Does Natural Gas Make Sense for Freight? Environmental Implications of the “Pickens Plan”

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The "Pickens Plan" is a highly promoted U.S. energy strategy, proposing to use natural gas as a transportation fuel to displace imported oil and, simultaneously, to increase renewable contributions to national electricity production. While the principal goal of the Pickens Plan is to improve domestic energy security and its associated foreign trade imbalance, we investigated the proposed strategies for their environmental benefits. We simulated a variation of the Pickens Plan across a seven-state Midwestern U.S. region to evaluate the greenhouse gas (GHG) and air quality implications of the plan. In this scenario, liquefied natural gas (LNG) is used to replace 100 percent of long-haul, diesel-powered freight, while wind-power is roughly doubled over the anticipated 2020 levels under existing renewable portfolio standards. Relative to a business-as-usual (BAU) reference case, the Pickens scenario reduces NO_x, SO_2, and GHG emissions. Most reductions occur within the electricity sector versus the freight sector: 73 percent of NO_x reductions, 99 percent of SO_2 reductions, and 94 percent of GHG reductions occurred within the power sector. While the LNG truck is estimated to have 21 percent lower GHG emissions than its diesel counterpart, methane leakage from the natural gas fuel cycle significantly reduces the GHG benefit from LNG trucking. Thus, LNG-powered freight only slightly reduces greenhouse gas emissions relative to the diesel-powered freight. To assess the benefits of natural gas in the transportation sector (Pickens Plan) versus the electricity sector, we considered a scenario where natural gas is increased in the electricity sector instead of the freight sector. This scenario yielded greater emissions reductions than the Pickens plan for all species, suggesting that natural gas fuel switching has more impact as an emissions mitigating measure within the electricity sector, rather than within the freight sector. To assess how emissions reductions would affect ambient pollutant concentrations, and the formation of secondary air pollutants, we employed a regional air quality model. Under the Pickens scenario, ambient concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$ were all reduced relative to BAU. In general, the largest reductions were simulated near metro areas, along major highways, and in the Ohio River Valley.</td></tr>
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Executive Summary

The Pickens Plan was introduced in 2008 by American financier T. Boone Pickens as a means to reduce foreign oil imports, and has since become one of the most talked about U.S. energy strategies. The proposal suggests using natural gas as a transportation fuel to displace imported oil and, simultaneously, to increase renewable contributions to national electrical power production. While the principal goal of the Pickens Plan is to improve domestic energy security and its associated foreign trade imbalance, the proposed strategies seemingly have environmental benefits to offer as well. It is not clear, however, whether environmental benefits would be maximized by using natural gas in the transportation sector. For instance, the same characteristics that make natural gas attractive as a "clean" fuel for the freight sector also apply in the electricity sector, especially as a substitute for coal-burning power plants. It is therefore important to examine how the environmental impacts of increasing natural gas compares between the electricity and freight sectors.

We estimated NO_x, SO_2, and GHG emissions for future 2020 scenarios for a seven-state Midwestern U.S. region. In the business-as-usual (BAU) scenario, the vast majority of long-distance highway freight vehicles are powered by diesel fuel, while the electricity fuel mix represents an extrapolation of current trends and regulatory requirements (as characterized by established national modeling efforts). In the Pickens scenario, liquefied natural gas (LNG) is assumed to replace 100 percent of long-haul, diesel-powered freight trucks, while wind-powered electricity is roughly doubled. Relative to the BAU, the Pickens scenario resulted in reduced NO_x, SO_2 and GHG emissions. Most of the reductions result from doubling wind power within the electricity sector, with the Pickens scenario achieving 73 percent of its NO_x reductions, 99 percent of its SO_2 reductions, and 94 percent of its GHG reductions by displacing coal from the electricity sector. LNG-powered freight only slightly reduced greenhouse gas emissions relative to diesel-powered freight. While the LNG truck is estimated to have 21 percent lower GHG emissions than its diesel counterpart, methane leakage from the natural gas fuel cycle significantly reduced the GHG benefit for LNG trucking.

We further compared the Pickens and BAU emissions to an alternate scenario, where wind-powered electricity is similarly doubled and natural gas is increased in electricity sector at the same level used in the Pickens Plan. In other words, the natural gas that would have been required for the 100 percent long-haul diesel freight substitution is instead put toward electricity, while freight trucks continue to be powered largely by diesel fuel. This "Electricity-Only" (EO) scenario yielded much greater reductions in all emissions than the Pickens Plan. Whereas Pickens reduced NO_x emissions by 25 percent relative to BAU, EO reduced NO_x by 39 percent relative to BAU. Similarly, SO_2 was reduced 18 percent by Pickens and 44 percent by EO; GHG was reduced 14 percent by Pickens and 26 percent by EO (all relative to BAU).

We modeled regional air quality resulting from the Pickens scenario, and compared pollutant concentrations to those resulting from BAU. As expected, emission reductions from the Pickens scenario reduced concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$. In general, deeper reductions were projected in metro areas, along major highways, and along the Ohio River Valley. A potentially important exception is for O_3, where slight increases were projected in select metro areas, due to the known nonlinear response of O_3 to NO_x in urban areas. Both $PM_{2.5}$ and O_3 exceed air quality

standards in certain counties across the Midwest, with the greatest exposure risk occurring in metro areas, and the Pickens plan (or the EO scenario, not shown) would both reduce these pollutants across the region.

The stated motivation of the Pickens Plan is to reduce U.S. dependence on imported oil as a matter of increased national economic security. With this objective, the optimal use of natural gas is to displace petroleum, for which imported supply meets roughly half of U.S. demand. Our estimates of regional emissions demonstrate emission reduction benefits from deployment of LNG-trucking at the scale proposed by the Pickens Plan. The freight sector, however, is not the optimal end-use for natural gas from an environmental perspective, in part because of increasingly cleaner diesel technology. As an emissions mitigating measure, increasing natural gas in the electricity sector is likely to be more efficient than a comparable increase within the freight sector. From an infrastructure perspective, increasing natural gas within the electricity sector is seemingly far easier than comparable changes to freight transportation. Whereas LNG freight requires a transformation of truck inventory and fuel infrastructure, much of the requisite power plant infrastructure already exists. For the 7-state study region, gas-fired power plants comprise 25 percent of installed generated capacity. These gas-powered plants are often idle and could generate more electricity under the appropriate market conditions, as evidenced by the surge in natural gas generation associated with recently depressed gas prices.

1. Introduction

As the reliable and efficient movement of freight remains vital to the economic wellbeing of the United States, recognition of the environmental and resource costs of diesel trucks has motivated the search for viable alternatives. One option is natural gas (NG), which offers a technologically viable option for reducing foreign oil demand, greenhouse gas (GHG) emissions, and health-damaging air pollution associated with heavy-duty trucks. Although transportation currently accounts for just 0.1 percent of U.S. natural gas consumption (1), this demand may increase rapidly if NG is promoted for use in heavy-duty vehicles, as suggested by the highly visible "Pickens Plan," among others. A 2013 New York Times article reported that "Citigroup recently forecast that 30 percent of the heavy truck fleet would shift to natural gas by the end of the decade, but some in the transportation industry put that figure much lower" (2).

The Pickens Plan was introduced by American financier T. Boone Pickens in 2008 as a means to reduce foreign oil imports, and has since become one of the most talked about U.S. energy strategies in recent times (3). Pickens proposes using NG as a transportation fuel to displace imported oil and, simultaneously, to increase renewable contributions to the electricity sector. While the principal goal of the Pickens Plan is to improve domestic energy security and its associated foreign trade imbalance, the proposed strategies would be expected to yield environmental benefits as well. It is not clear, however, that those environmental advantages are best achieved by using natural gas in the transportation sector. For instance, the same characteristics that make natural gas attractive as a "clean" fuel for the freight sector also apply in the electricity sector, especially as a substitute for coal-burning power plants. Therefore, it is important to analyze how the environmental impact of increased natural gas use differs when deployed for electricity as opposed to transportation, as recently suggested by Alvarez et al (4).

We examined the "Pickens Plan" as implemented in a seven-state region of the Upper Midwestern United States covering Minnesota, Iowa, Wisconsin, Illinois, Indiana, Michigan, and Ohio. This region represents 19 percent of U.S. truck shipments (5), and 18 percent of U.S. retail electricity consumption (6). Long-haul highway freight transport is responsible for approximately 13 percent of total transportation energy use in the Midwest region. We examined emissions from freight and electricity sectors, including emissions from associated fuel production. We considered nitrogen oxides (NO_x), sulfur dioxide (SO_2), and greenhouse gases (GHG) occurring as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). For freight only we calculate emissions of non-methane hydrocarbons (NMHC), carbon monoxide (CO), and particulate matter (PM).

For the three scenarios described below (see also Table 1), we estimated emissions from electricity generation, freight transport, as well as emissions from the associated fuel cycles:

- Business As Usual (BAU) – In the BAU scenario, the vast majority of long-distance highway freight vehicles are powered by diesel fuel. The electricity fuel mix for the Midwestern United States is based on projected use of existing and new power plants, including compliance with state renewable portfolio standards (RPS). Fuel price assumptions were consistent with the U.S. Environmental Protection Agency's (EPA) Integrated Planning Modeling (version 4.10) (7), which have a major impact on the resulting fuel mix within the electricity sector (8).[1] We did not assume that coal plants were required to comply with recent proposals under the Clean Air Act, which are not currently in effect due to a 2012 court ruling (9).[2]

- Pickens – In the Pickens scenario, liquefied natural gas (LNG) trucks are assumed to replace 100 percent of all long-haul, diesel-powered freight trucks within the region. In the electricity sector, wind-powered electricity is doubled relative to BAU; the additional wind displaces 16 percent of the coal required for electricity generation.
- Electricity-Only (EO) – In the EO scenario, wind-powered electricity is increased to the same extent as the Pickens scenario. In addition, the NG that would have been required to power 100 percent of long-haul diesel freight is instead used for electricity. The combination of wind and natural gas displaces 42 percent of the coal required for electricity generation. Long-distance highway freight is transported mostly by heavy-duty diesel vehicles as in the BAU scenario.

Using the emission inventories developed for the scenarios above, we used an advanced air quality model to simulate regional air quality changes that would result from the Pickens scenario versus BAU. We employed the U.S. Environmental Protection Agency (EPA) Community Multiscale Air Quality (CMAQ) model, along with the Lake Michigan Air Directors' Consortium (LADCO) regional emissions inventory, both at a 12 km x 12 km horizontal resolution. These simulations allowed us to compare ambient concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$ throughout the Midwest, and evaluate spatial and temporal impacts of the Pickens Plan on air quality.

[1] For the BAU scenario, price assumptions for 2020 favor coal generation (at $2.1/MMBtu) over natural gas (at $4.5/MMBtu) in the heavily coal-dependent Midwest. The combination of fuel prices and RPS requirements greatly diminish the contributions from natural gas in the BAU forecast to just one percent of the fuel mix. Recently, a substantially higher natural gas contributions have occurred (e.g., 18 percent nationally in January 2013) as a result of very low natural gas prices. This demonstrates the sensitivity of the fuel mix to the relative price of coal and gas.
[2] The impact of these rules would slightly diminish the contribution of coal to the fuel mix as a result of increased operational costs, as well as potential retirement of some existing coal-fired power plants.

2. Background

The Pickens Plan was proposed by American financier T. Boone Pickens, who launched a self-funded public relations campaign in July 2008 to promote his idea. Since then, thousands of news stories and editorials have referenced the Plan, although no official documentation is available to provide detail to the plan beyond its relatively basic concepts (3).

The premise of the Pickens Plan is to displace imported oil by using domestic natural gas as a transportation fuel, with particular concentration in “over-the-road trucks.” This transformation in the transportation sector would occur simultaneously with an expansion of electricity powered by wind turbines located in the Great Plains region of the United States. This addition of renewable energy is meant to displace natural gas consumption in the electric power sector, thereby balancing the increase in the transportation sector (10). The Pickens Plan also suggests improvements to the electrical transmission grid and incentives to improve the insulation of residential and commercial buildings to increase their efficiency.

The potential emissions benefits of natural gas are well known, with NG emitting less CO_2, NO_x, or SO_2 per unit energy than either petroleum or coal. Thus, NG would be expected to benefit climate and air quality as a substitute for petroleum in the transportation sector and as a substitute for coal in the electricity sector. It should be noted that there are additional emissions associated with NG extraction, from both conventional and hydraulic fracturing extraction methods. We include “upstream” emissions from fuel production in our estimates. In considering the relative environmental benefit of NG in transportation versus electricity, there are a number of complicating issues. First, the marginal benefit of NG will depend in part on the characteristics of the fuel substitution, with relatively higher benefits substituting for coal versus substituting for oil. In addition to the differential per-unit-energy emissions, transportation and electricity have different spatial emission characteristics. Whereas electricity emissions are concentrated at power plants, and released through high stacks, trucking emissions are concentrated on highways and in cities, released at ground-level. Thus, while NG has a higher per-unit benefit relative to coal-fired electricity, it is conceivable that its benefit to air quality and public health may be greater when applied to trucking.

It is worth noting that the environmental benefits of the Pickens Plan are not a major part of its self-promoted message. Rather, trucking is the focus of NG implementation because there are few alternative fuels to support our current freight transport system. Other than biodiesel, NG is the only fuel that offers a viable near-term alternative to diesel fuel. It is worth noting, however, that the growth in U.S. oil production has been increasing since 2008. Thus, the argument that NG would offer a path to domestic fuel independence not currently offered by diesel fuel may no longer be viewed with the same urgency.

From an air quality perspective, several factors may compel policy-makers and fleet managers to start investing in natural gas infrastructure: 1) the U.S. Environmental Protection Agency (EPA) is tightening standards on multiple criteria pollutants, 2) urban areas and ports are struggling to meet regulated air quality thresholds, and 3) major increases in freight are projected in coming decades. Freight trucks contribute 18 percent of man-made NO_x emissions, the largest single source (11); these NO_x emissions generate direct health impacts and also react with other compounds to form ozone (O_3) and nitrate particulates, an important contributor to total fine particulate ($PM_{2.5}$), especially in the Upper Midwest. Both $PM_{2.5}$ and O_3 pose major challenges for regulators and public health officials in the Midwestern United States, where over 28 million people live in areas not meeting the National Ambient Air Quality Standards (NAAQS) for these two pollutants (12). Natural gas powered freight has been demonstrated to successfully reduce fleet emissions for the UPS Corporation, with a study by UPS concluding that for trucks of a similar age, switching to natural gas fuel from diesel reduced NO_x emissions by 49 percent and PM emissions by 95 percent (13). Increasingly stringent rules for heavy duty vehicles and diesel fuel, however, will greatly reduce incremental benefits between natural gas and cleaner-burning diesel technology (14).

In addition to regulated pollutants with direct health impacts, carbon dioxide (CO_2) from trucking contributes significantly to total U.S. GHG emissions. Trucking contributes 4.9 percent of U.S. CO_2 emissions (11), with contributions growing at nearly three times the rate of the total transportation sector: between 1990 and 2007, CO_2 from trucking increased 80 percent versus 29 percent for all transportation activities (15). In the absence of control technology for CO_2 exhaust, freight transport emissions can only be mitigated by either reducing fuel consumption or by switching to a lower carbon-content fuel such as natural gas. Because we are interested in high-efficiency long-haul trucking, this study considers liquefied natural gas (LNG) technology, which offers longer range than compressed natural gas (CNG). Specifically, we consider the High Pressure Direct Injection (HPDI) approach to LNG, which, unlike spark-ignition LNG, retains the diesel-like efficiency advantage of compression-ignition, using natural gas as its primary fuel along with a small percentage of diesel fuel to enable compression ignition (16).

3. Methodology

3.1 Scenario Development

We examined three 2020 scenarios with identical freight transport demand over our seven-state study region. Fuel contributions for the three scenarios are summarized in Table 1 and Figure 1. In the BAU and EO scenario, long-haul freight transport is powered exclusively by diesel fuel. In the Pickens scenario, long-haul freight transport is powered exclusively by LNG. In the EO scenario, an equivalent amount of NG is instead used within the electricity sector.

Fuel-shifting assumptions were designed such that changes in electricity sector were of a comparable magnitude (on an energy basis) to changes in the transportation sector. The BAU scenario required 807 million MMBtu of diesel for freight transport. The Pickens scenario required 867 million MMBtu of LNG to satisfy the same transport demand due to the slightly lower efficiency of LNG-powered vehicle relative to a diesel-powered vehicle. In addition, the Pickens and Electricity-Only scenarios increased wind generation from 12 percent to 23 percent, such that a comparable amount (roughly 829 million MMBtu of coal and gas) were displaced from the electricity sector. The presumed intent of the Pickens Plan's is for wind energy to diminish the net natural gas demand by displacing its use from the power sector. In our analysis, however, wind power mainly displaces coal in the highly coal-dependent Midwest.

Freight demand, in terms of vehicle miles traveled (VMT), was based on a roadway-by-roadway inventory of heavy-duty diesel vehicles from the Federal Highway Administration's Freight Analysis Framework (FAF) (17). To reflect 2020 freight demand, we assumed a linear growth rate between FAF reported vehicle miles travelled (VMT), corresponding to a 33 percent increase in freight VMT between 2007 and 2020. Diesel fuel consumption was estimated using FAF-reported freight activity and speeds along with speed-dependent fuel efficiency reported by Oak Ridge National Laboratory (ORNL) (18). Natural gas consumption for freight was estimated using methods reported by Luedke (19), wherein speed-dependent diesel vehicle efficiencies from ORNL are scaled by the relative efficiency of diesel vs. LNG. For this study we used the diesel and LNG efficiencies reported by engine-maker Westport (20). The resulting average vehicle fuel efficiency used as the basis for this work was 6.4 miles per gallon for diesel vehicles and 6.0 miles per gallon (diesel equivalent) for LNG vehicles.

Table 1. Comparison of Midwestern Fuel-switching Scenarios for 2020.

2020 Fuel Mix	Business As Usual	Fuel-switching Scenarios: Pickens	Fuel-switching Scenarios: Electricity-Only
Long-Haul Freight Fuel Mix			
LNG Percentage Long-Haul Freight	0%	100%	0%
Diesel Percentage Long-Haul Freight	100%	0%	100%
Electricity Fuel Mix			
Wind Percentage of Electricity	12%	23%	23%
Natural Gas Percentage of Electricity	1.4%	0.9%	15%
Coal Percentage of Electricity	61%	51%	36%
Other Percentage of Electricity	26%	25%	25%

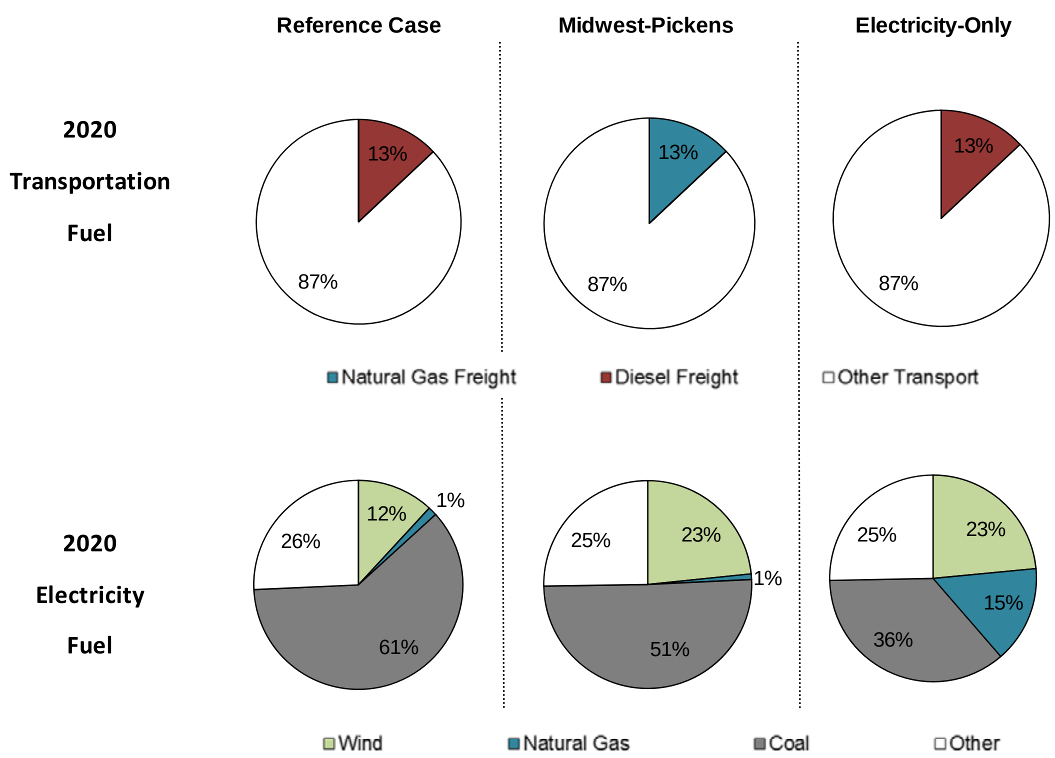

Figure 1. Percent Fuel Contributions for 2020 Scenarios.

Data and assumptions characterizing the electricity sector in 2020 were based on EPA's IPM v4.10 modeling documentation (7). Each electricity generating unit (EGU) in the study area was characterized using data from the U.S. EPA National Electric Energy Data System (NEEDS), as well as related information from IPM v4.10, and historical generation data from U.S. Energy Information Administration. Electricity demand for the study area (i.e., load shapes) were based on 2007 historic data reported by EPA and scaled to represent 2020 electricity demand using an 0.8 percent/year growth rate for energy and a 1.2 percent/year growth rate for peak demand.

This study used the MER electricity-sector model[3] to estimate power plant performance (electricity generation, fuel requirements, and emissions) on a plant-by-plant basis, using a least-cost dispatch routine that satisfies the electricity demand forecast represented by seasonal load duration curves (21). With the RPS required capacity additions, a 20-percent capacity reserve (the total amount of installed summer capacity) was maintained over forecast peak demand for the study region. To increase gas-powered generation in the Electricity-Only scenario, the relative price of natural gas versus coal was decreased (from 2.11 times coal price to 1.35 times coal price) such that generation from the least-efficient coal plants was replaced by generation from the most efficient natural gas plants.

3.2 Emissions Estimation

We considered system-wide emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), and greenhouse gases (GHG) occurring as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). We report GHG emissions as CO_2-equivalent tonnes based on 100-year global warming potentials of 25 for CH_4 and 298 for N_2O. We employed three types of emission calculations discussed below. For freight only we calculate emissions of non-methane hydrocarbons (NMHC), carbon monoxide (CO), and particulate matter (PM).

3.2.1. Tailpipe Emissions from Freight. We estimated diesel tailpipe emissions by multiplying speed-dependent FAF activity by speed-dependent emission factors generated using EPA's MOBILE 6.2 emissions factor model Class 8 trucks (22). The MOBILE 6.2 model does not provide emission factors for LNG trucks; in fact, LNG truck emission factors and tests are sparse. We relied on a comparison of HDPI LNG and diesel engine configurations (23), which (after conversion to a grams-per-mile comparison) demonstrated 38 percent reduction in NMHC, 46 percent increase in CO, and a 46 percent decrease in both NO_x and PM emissions. Consistent with Luedke's approach (19), we used the ratio of the LNG to diesel emissions to scale the MOBILE 6.2 generated diesel emission factors, in order to generate speed-dependent emission factors for LNG-powered freight transport for NMHC, CO, NO_x, and PM. CO_2 emission factors were calculated based on each fuel's carbon content as reported in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model 1.8 (24). Because the LNG fuel blend was assumed 6 percent diesel (23), we assumed that SO_2 emissions from LNG were 6 percent of the diesel rate. We assumed methane emissions from LNG to be 1.6 g/mile based on the approximately 1 g/bhp-hr reported by Westport (20). When applied to the regional

[3] Dr. Paul Meier is principal owner of Meier Engineering Research LLC (MER) which develops and owns the power sector model used as part of this investigation.

speed-dependent FAF data, the weighted average emission factors used for this study are shown in Table 2 below.

Table 2. Weighted Average Emission Rate for All Speeds (g/mile).

Pollutant	Diesel Truck	LNG Truck
Non-Methane Hydro Carbon	0.18	0.068
Carbon Monoxide	0.34	0.498
Nitorgen Oxides	1.86	0.85
Carbon Dioxide	1625	1238
Methane	0	0.161
Total Particulate	0.03	0.014
Sulfur dioxide	0.01	0.0006

3.2.2. Stack Emissions from Power Plants. We calculated 2020 power plant emissions as a function of electricity generation (kWh), heat rate (MMBtu/kWh), and emission factor (tonnes/MMBtu) for each generating unit reported in the NEEDS database. The MER model estimated generation (kWh) by dispatching each power plant in order of increasing marginal operating cost to satisfy peak season (May to September) and off-peak season (October – April) load duration curves representing 2020 annual electricity demand. The NEEDS database provided emission factors for CO_2, NO_x, and SO_2; however, actual 2009 emission rates were substituted based on data from U.S. EPA 2009 Clean Air Markets (CAM) database wherever generating units from the NEEDS and CAM databases could be directly correlated (7, 25).

The 2020 BAU emissions estimates were compared against CAM-reported historic emissions from 2007 and 2009. In general, simulated emissions for the BAU scenario showed good overall agreement to historic emissions at the state level, with the exception of Ohio where simulated emission rates were considerably higher than historic rates. We therefore assumed NOx control additions for 72 Ohio EGUs (34 percent state level reduction) and SO2 control additions at 8 EGUs (17 percent state level reduction) to reduce simulated emissions to levels comparable to historic reporting. We made no reductions in power plant emission rates to reflect potential regulatory limits occurring between 2009 and 2020. Therefore, while the SO_2 and NO_x emissions results are relevant for comparing scenarios, they are higher than would have been anticipated prior to the U.S. Court of Appeals for the D.C. Circuit vacating EPA's Cross-State Air Pollution Rule (9). Detailed comparisons were made between simulated and historic emissions at the facility level as part of air quality modeling efforts described later.

3.2.3. Fuel-Cycle Emissions. A considerable fraction of fossil fuel related emissions occurs during the "upstream" life-cycle; this is particularly true for natural gas (26). We accounted for fuel-cycle emissions occurring during fuel extraction, refinement, and transport. Life-cycle emissions were included for fuels only (not for materials or equipment) using default emission factors from GREET Model Version 1.8 (24). The GREET model provided emission factors for CO_2, CH_4, N_2O, SO_2, NO_x for the following upstream fuel-cycle processes: 1) coal production and delivery to power plants, 2) natural gas recovery, processing, transmission and distribution, and 3) crude petroleum recovery (conventional, oil sands, and oil shale), crude oil transportation to refinery, low-sulfur diesel refining, and diesel transportation and distribution. We estimated life-cycle GHG emissions for wind power based on CO_2-equivalent values from White and Kulcinski (27). We estimated SO_2 and NO_x emissions for wind power by multiplying the White and Kulcinski GHG values by the ratio of SO_2/GHG and NO_x/GHG from GREET for "Energy Use and Emissions for Power Plant Infrastructure" (24).

3.3 Hourly Power Plant Emissions Distribution

As discussed in previous sections, emissions estimates were generated using a load duration curve (LDC) model. In general, LDC models are used to generate seasonal or annual performance estimates, not hourly performance estimates. LDC modeling approaches are capable of estimating hourly emissions as discussed below. However, the limitations of this approach should be appreciated. Applying state-of-the-art modeling is not typically viable for studies such as this one, as the requisite software license fees potentially range from $30,000 to $200,000 annually, in addition to considerable staff and consulting time (28). With such state-of-the-art tools, hourly power plant performance is evaluated and optimized over small time-steps, typically from several minutes to a few hours. In practice this involves evaluating generating units, transmission system interconnections, and market interactions, while incorporating operational constraints such as startup and cycling costs, ramping restrictions, minimum up and down time, spinning reserves, and energy limits (29, 30, 31).

Our approach to hourly emissions estimation is considerably simpler. By definition, a load duration curve model will sort the system electricity demand from highest to lowest. The MER model was used to determine the range of LDC hours, for which each power plant is estimated to operate. For example, most power plants will be operated during Hour #1, representing the peak demand of the year. A power plant that is continuously operated for the peak season (lasting 3672 hours) would operate for Hour #1 through Hour #3672. A peaking power plant operating for only the ten highest hours of demand would operate for Hours #1 through Hour #10. The hours of operation (based on LDC electricity demand rank) can be correlated to the historical calendar hour, for which that demand occurred. For example, if the tenth highest demand hour occurred on July 7 at 4:00 pm, the previously mentioned peaking unit would be assumed to operate during that hour. In this way, every hour of the Load Duration Curve can be matched with its corresponding calendar hour. Using this approach, hourly emissions estimates were generated for every power plant for the month of July (the month for which air quality analysis was performed.)

The limitations of this approach are as follows: 1) the MER model de-rates (reduces) power plant capacity to account for planned and forced outages. Therefore, the output of operating plants is slightly underestimated; 2) the MER model relies on average power plant efficiency and emission factors, which neglects the variability in fuel consumption and emissions that may vary on an hourly basis; 3) the MER model does not consider the transient conditions that affect short-term unit dispatch as discussed above. For example, a unit with a high startup cost may not be operated if it is only required to meet increasing demand for an hour or two. The MER ignores startup cost and would assume this plant operates if it is the next unit in the merit order based on its average operating cost. Given the limitations of our modeling approach, we performed a facility-specific comparison of simulated 2020 July emissions to historic 2007 and 2011 emissions, included as Appendix A.

3.4 Freight Transport Emissions Scaling

The methods described in Section 3.2.1 are used to generate annual emissions estimates for FAF reported in Section 4. These same emissions estimates, however, cannot be directly incorporated into the air quality modeling analysis. The air quality analysis uses as its baseline a temporally and spatially distributed database of 2007 emissions for the northeastern United States developed by the Lake Michigan Air Directors Consortium (LADCO), hereafter referred to as the "LADCO inventory" (32). The LADCO inventory includes all highway and metro freight in the region, from which July emissions are used for air quality modeling and analysis, as discussed below. To adjust the LADCO inventory to represent our scenarios of interest, we generated scaling factors for each pollutant of interest. We adjusted 2007 emissions values to 2020 emissions estimates for two cases: 1) assuming 100 percent LNG-powered freight (applied to the Pickens scenario), and 2) assuming 100 percent diesel-powered freight (applied to the BAU and Electricity-Only scenarios).

The LNG-freight scaling factors were created by dividing the 2020 LNG-based freight emissions from the Pickens scenario by a 2007 diesel-based freight emissions estimate. Scaling factors for the BAU and Electricity-Only scenarios were created by dividing the 2020 diesel-based freight emissions from those scenarios, by the same 2007 diesel-based freight emissions estimate. For the diesel-based scenarios, a nine percent increase resulted (i.e. 1.086 scaling factor) as a combined result of a 33 percent increase in total VMT (2.2 percent annual growth) and an 18 percent improvement in per mile pollutant rates between 2007 and 2020.[4] The net result is that 2007 freight emissions from the LADCO inventory are scaled upward by 8.6 percent to represent 2020 freight emissions for diesel-powered scenarios. Pollutant-specific scaling factors for each scenario are shown in Figure 2.

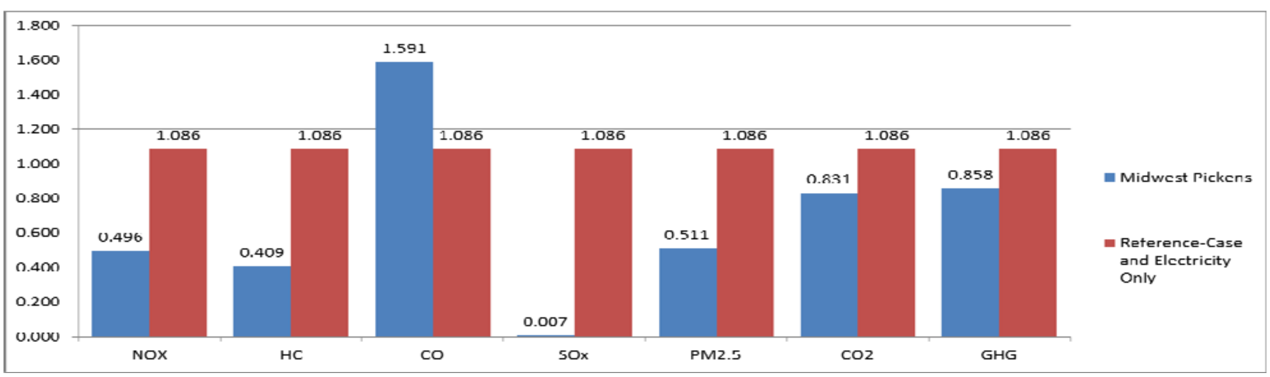

Figure 2. Scaling Factors to Adjust 2007 Freight Emissions to 2020 Scenario Emissions.

[4] Emission rate reductions are due largely to improvements in fleet-average fuel efficiency. An average annual rate of improvement of 1.56 percent per year was assumed based on simulation with U.S. EPA MOVES model for years 2010 through 2020.

3.5 Air Quality Modeling Approach

To estimate the air quality impacts resulting from switching trucks from diesel to natural gas, the BAU and Pickens scenarios were modeled using EPA's Community Multiscale Air Quality Model (CMAQ) (33). CMAQ is a state-of-the-science photochemical model that takes meteorological data and emission inventories as inputs, and calculates ambient air pollutant concentrations based on atmospheric chemistry, meteorological transport and numerical processes. The CMAQ model is widely used for policy, and many states use CMAQ to develop their state implementation plans (SIP) in accordance with the Clean Air Act (34, 35, 36, 37). This type of complex numerical model is the only way to effectively estimate how energy and transportation choices affect health-relevant air pollution (38).

As required for processing through the CMAQ model, the freight and electricity emissions inventories were parsed into their component pollutant sub-species (e.g., NO_x emissions were sub-divided into NO and NO_2 emissions). Using GIS software, the freight and electricity emissions were assigned to grid-cells corresponding to the 12 km x 12 km 2007 LADCO emissions inventory (32). The speciated and gridded emissions for freight truck and electricity sectors were then substituted into the LADCO inventory. Emissions data for all other sectors (including gasoline vehicles, industrial facilities, agriculture, natural emissions) are taken directly from LADCO.

Air quality modeling was performed for July 2007, using associated (July only) sub-sets of emission inventories and meteorology. Meteorology inputs for CMAQ were generated using the Weather Research and Forecasting (WRF) model with North American Regional Reanalysis (NARR) input data to simulate meteorology for June and July 2007. Daily meteorology files output by WRF were processed for CMAQ using the Meteorology-Chemistry Interface Processor (MCIP) version 3.6.

3.6 Related Analysis

For quality control purposes, we compared air quality modeling results for BAU July emissions (2020) against the 2007 LADCO inventory, included in Appendix A. Air quality modeling was also performed for the Electricity-Only scenario; however, errors were founding the model set-up, so results were not available for this report. Preliminary cost assessment was also performed to examine the financial pay-back from switching from diesel to LNG trucks. This assessment was deemed too superficial for inclusion in this report, and interested readers should refer to Deal (16) for more comprehensive analysis.

4. Results

4.1 Annual Emissions Results and Scenario Comparison

We estimated NO_x, SO_2, and GHG emissions for future 2020 scenarios for a seven-state Midwestern U.S. region. In the business-as-usual (BAU) scenario, long distance highway freight vehicles are powered exclusively by diesel fuel, while the electricity fuel mix represents an extrapolation of current trends and regulatory requirements. In the Pickens scenario, liquefied natural gas (LNG) is assumed to power 100 percent of long-haul freight, while wind-powered electricity is roughly doubled. Relative to the BAU, the Pickens scenario reduces NO_x, SO_2 and GHG emissions. We further compared the Pickens and BAU emissions to an alternate scenario, where wind-powered electricity is similarly doubled and natural gas is increased in electricity sector at the same level used in the Pickens Plan. As shown in Table 3, the "Electricity-Only" (EO) scenario yielded much greater reductions in all emissions than the Pickens Plan. Whereas Pickens reduced NO_x emissions by 25 percent relative to BAU, EO reduced NO_x by 39 percent relative to BAU. Similarly, SO_2 was reduced 18 percent by Pickens and 44 percent by EO; GHG was reduced 14 percent by Pickens and 26 percent by EO (all relative to BAU).

Table 3. Comparison of Scenario Emission Totals and Percent Change from BAU Scenario.

		Fuel-switching Scenarios	
Pollutant	**Business As Usual**	**Pickens**	**Electricity-Only**
Nitrogen Oxides (NO_x) K-Tonnes	575	433 (-25%)	353 (-39%)
Sulfur Dioxide (SO_2) K-Tonnes	1,810	1480 (-18%)	1020 (-44%)
Greenhouse Gases (GHG) M-Tonnes	654	560 (-14%)	485 (-26%)

Tables 4 through 6 compare annual NO_x, SO_2, and GHG emissions, respectively, for the BAU and the two fuel-switching scenarios. Table 7 provides a sensitivity analysis around reported rates of methane losses occurring both during the fuel cycle and during vehicle operation. Both fuel-switching scenarios result in reductions in NO_x, SO_2 and GHG. In the case of all three pollutants, emissions are reduced more significantly for the Electricity-Only scenario than for the Pickens scenario. Fuel-cycle emissions comprise a significant portion of NO_x emissions (up to 22 percent) and GHG emissions (up to 13 percent), but only a small portion of SO_2 emissions (up to 5 percent).

As shown in Table 4 and Figure 3, NO_x emissions improve under both fuel-switching scenarios. Relative to the BAU scenario, the Pickens scenario reduced freight-related NO_x emissions by 39,000 tonnes, while surplus wind generation reduced electricity-sector NO_x emissions by 103,000 tonnes (fuel cycles included). Using more electricity generated from both wind and natural gas, the Electricity-Only scenario lowered NO_x emissions even further, by 222,000 tonnes below the BAU scenario and 80,000 tonnes below the Pickens scenario.

The NO_x emissions from the LNG trucks were roughly half that of the diesel trucks, resulting in a 40,000 ton reduction in roadway NO_x emissions. When life-cycle emissions were included, however, the net NO_x emissions from LNG trucking, relative to diesel, were moderated to only a 36 percent reduction. Life-cycle fuel production and distribution rates from GREET (24) increase NO_x contributions by 46 percent per MMBtu for diesel, but more than double (104 percent) NO_x emission per MMBtu for LNG. Within the GREET model, 36 percent of the NO_x emissions occur from natural gas recovery, 32 percent from liquefaction, and 18 percent from transportation and distribution.

As shown in Table 5 and Figure 4, both fuel-switching scenarios reduced SO_2 dramatically, with the vast majority of SO_2 reductions result from fuel-switching in the electricity sector. Natural gas combustion has extremely low sulfur emission, as almost all sulfur is removed during natural gas processing. Limited SO_2 reductions result from converting from diesel to LNG trucking, however, because newer diesel-powered freight vehicles emit very little SO_2 as a result of ultra-low-sulfur diesel fuel and emission-controls. Fuel switching in the electricity sector, however, results in significant SO_2 emissions reductions from the power sector—300,000 tonnes in the Pickens scenario and more than 788,000 tonnes in the Electricity-Only scenario.

Total GHG emissions (Table 6 and Figure 5) are reduced in both the Pickens (by 93 million tonnes) and Electricity-Only scenarios (by 168 million tonnes). Major GHG emissions reductions occur in the power sector by using wind power (in the Pickens scenario) and both wind and natural gas power (in the Electricity-Only scenario) to reduce emissions from coal-powered electricity generation. Perhaps surprisingly, LNG-powered freight in the Pickens scenario only reduces GHG emissions by 8 percent relative to the diesel-powered freight in the BAU scenario. There are two main explanations for why the resulting GHG reduction is not larger: 1) fuel efficiency of the two truck types and 2) methane leakage from the natural gas fuel cycle. Though the LNG fuel itself is less carbon-intensive than diesel, the less efficient LNG vehicle requires slightly more fuel per mile. Looking at truck operations in isolation, LNG does provide a net 21 percent lower GHG emissions than diesel. However, GHG emissions from the fuel cycle are significantly higher for LNG trucking, due in large part to methane leakage as discussed below.

GHG emissions reported for LNG freight has three distinct components: vehicle fuel combustion, methane losses during vehicle operation (as leakage or as incomplete combustion), and fuel-cycle emissions including leakage. There is little available information for methane emissions from the LNG vehicle. We estimated that the methane emission rate for LNG trucks reported by Westport (20) corresponds to 0.34 percent of vehicle fuel supply. The reported methane emissions from Chandler et al. (39) correspond to a surprisingly high loss rate of 2.7 percent of vehicle fuel. Importantly, the high-pressure LNG system is designed to vent emissions as the fuel warms. According to Deal (16), this venting is minimized for applications where "trucks have very little down-time so that new cold LNG is continually added to the system. If a tank sits idle, the gas inside will warm and expand; after about five days it will begin to vent into the atmosphere."

Table 4. Comparison of 2020 Nitrogen Oxide (NO_x) Emissions (tonnes).

Emission Source	Business As Usual	Fuel-switching Scenarios: Pickens	Fuel-switching Scenarios: Electricity-Only
LNG Long-Haul Freight Vehicle	-	33,400	-
Diesel Long-Haul Freight Vehicle	73,100	-	73,100
Transportation Fuel Life-Cycle	33,800	34,900	33,800
Electricity from Coal	415,000	322,000	188,000
Electricity from Natural Gas	8,980	6,470	13,730
Electricity Fuel Life-Cycle	44,200	36,500	44,700
Total	575,000	433,000	353,000
Change from Business As Usual	**-**	**-142,000**	**-222,000**

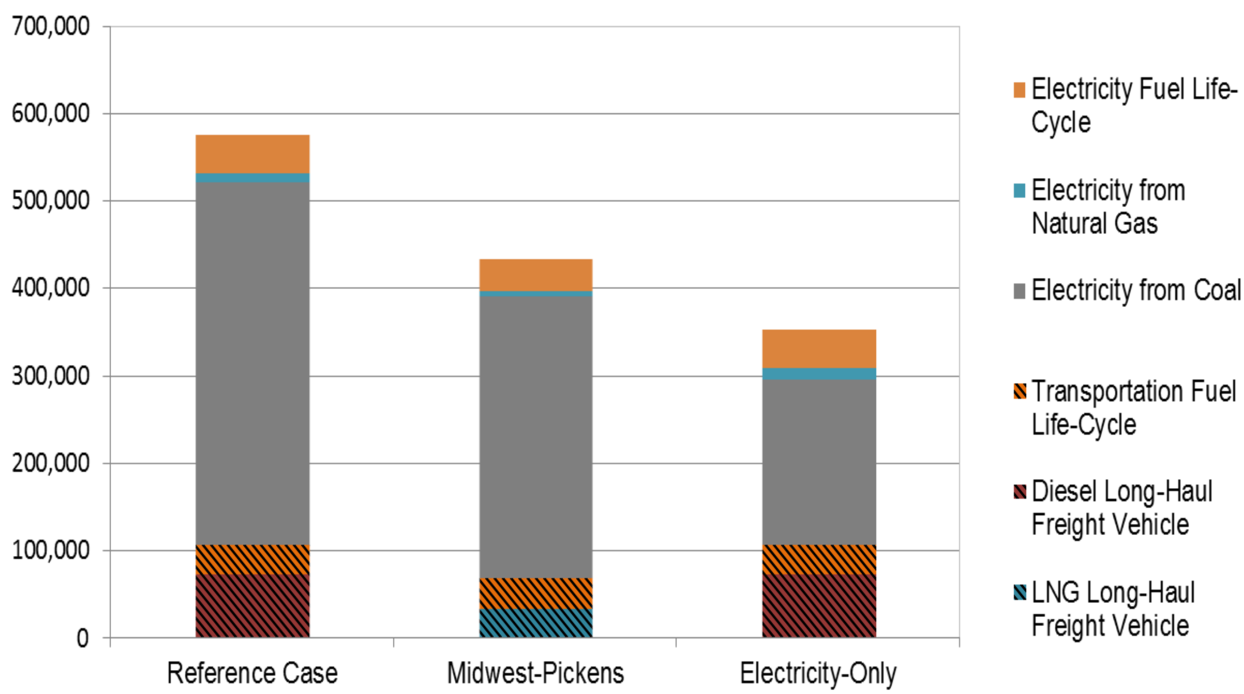

Figure 3. 2020 Nitrogen Oxide (NOx) Emissions (tonnes).

Table 5. Comparison of 2020 Sulfur Dioxide (SO2) Emissions.

Emission Source	Business As Usual	Fuel-switching Scenarios: Pickens	Fuel-switching Scenarios: Electricity-Only
LNG Long-Haul Freight Vehicle	-	-	-
Diesel Long-Haul Freight Vehicle	374	2.4	374
Transportation Fuel Life-Cycle	17,800	14,400	17,800
Coal-Powered Electricity	1,750,000	1,430,000	970,000
Gas-Powered Electricity	104	18	283
Electricity Fuel Life-Cycle	37,400	31,100	32,900
Total	1,810,000	1,480,000	1,020,000
Change from Business As Usual	**-**	**-330,000**	**-784,000**

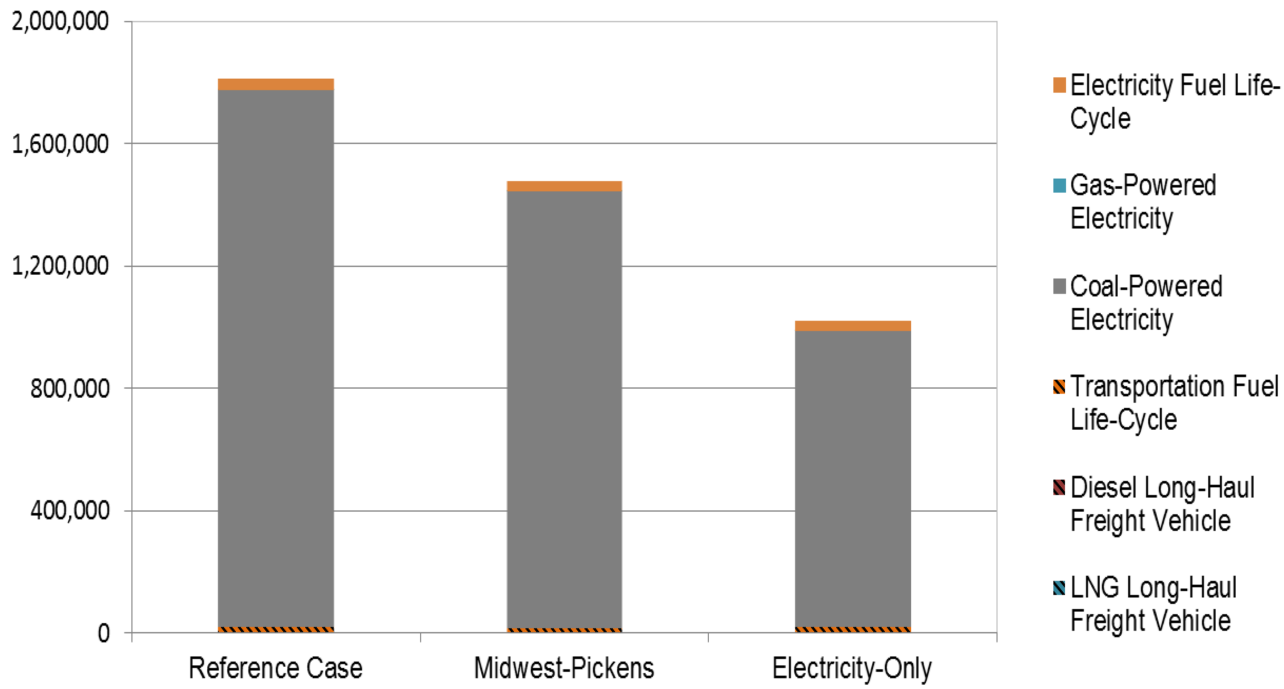

Figure 4. 2020 Sulfur Dioxide (SO2) Emissions (tonnes).

Table 6. Comparison of 2020 Greenhouse Gas Emissions (CO2-equivalent tonnes).

		Fuel-switching Scenarios	
Emission Source	**Business As Usual**	**Pickens**	**Electricity-Only**
Methane Leakage Rate	**2.4%**	**2.4%**	**2.4%**
LNG Long-Haul Freight Vehicle	-	46,900,000	-
Diesel Long-Haul Freight Vehicle	59,400,000	-	59,400,000
Transportation Fuel-Cycles	15,800,000	22,600,000	15,800,000
Coal-Powered Electricity	532,000,000	444,000,000	309,000,000
Gas-Powered Electricity	5,378,937	3,424,830	55,057,053
Electricity Fuel-Cycles	41,100,000	43,400,000	46,200,000
Total	654,000,000	560,000,000	485,000,000
Change from Business As Usual	**-**	**-93,400,000**	**-168,000,000**

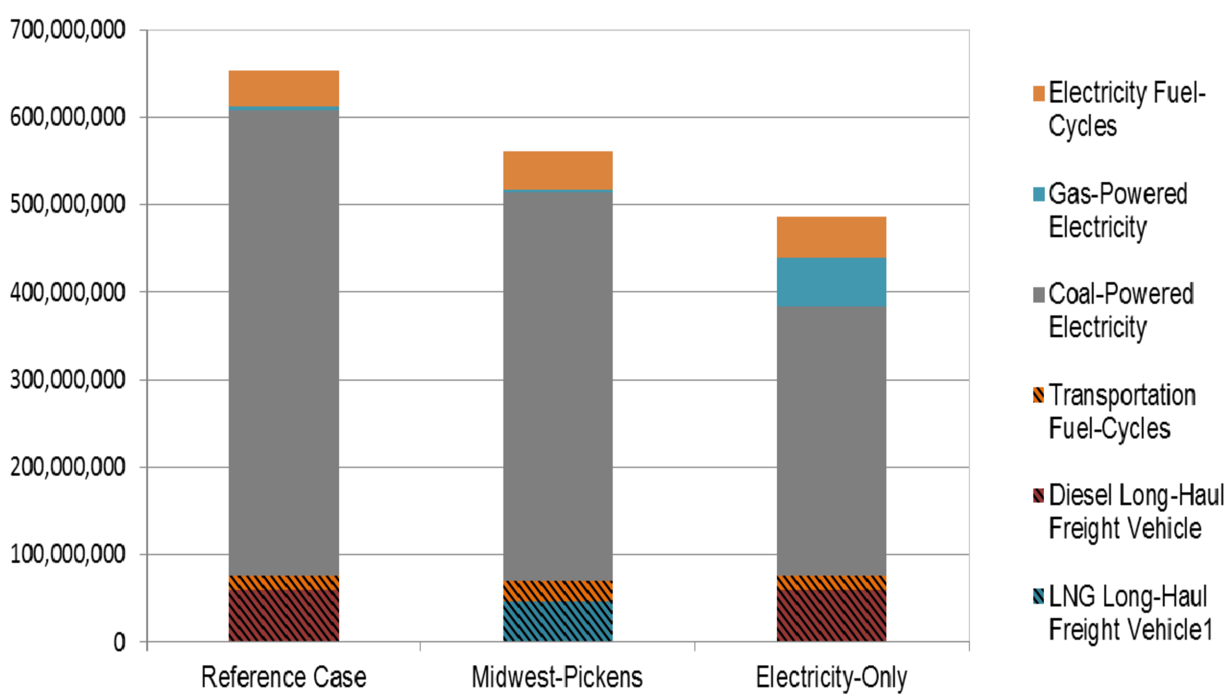

Figure 5. 2020 Greenhouse Gas (GHG) Emissions (CO2-equivalent tonnes).

Leakage from the natural gas fuel cycle is also an important source of GHG emission. As reported by Alvarez et al. (4), there is a "paucity of empirical data addressing CH_4 emissions through the natural gas supply network." We examined emissions under four estimates for fuel-cycle losses, expressed as a percentage of production: 0.9 percent based on the GREET default assumption (24), 2.4 percent based on U.S. EPA estimates (40), 3.9 percent based on the median rate estimated by Howarth et al. for conventional gas, and 5.8 percent based on the median rate estimated by Howarth et al. for shale gas (i.e., hydraulic fracturing) production (41). Table 7 provides a limited sensitivity analysis for these cited methane losses occurring both during the fuel cycle and during vehicle operation. In Table 6, we assume a fuel-cycle methane leakage rate of 2.4 percent and a vehicle methane emission rate of 0.34 percent, resulting in 69.5 million tons of GHG emission. As shown in Table 7, the worst case scenario (94.4 million tonnes GHG) is 36 percent higher than the LNG transport value (69.5 million tonnes GHG including fuel cycle) and 26 percent higher than the diesel-based transport emissions (75.2 million tonnes GHG including fuel cycle) estimated in Table 6.

Table 7 - Comparison of 2020 Greenhouse Gas Emissions under Various Methane Leakage Assumptions (CO_2-equivalent tonnes).

Emission Source	Midwest Pickens Scenario with Various Leakage Rates			
Fuel-Cycle CH_4 Leakage Rate (% of fuel)	0.9%	2.4%	3.9%	5.8%
Transportation Fuel-Cycles	16,000,000	22,600,000	29,200,000	37,500,000
Vehicle CH_4 Loss Rate (% of fuel)	0.34%	0.34%	1.0%	2.7%
LNG Long-Haul Freight Vehicle	46,900,000	46,900,000	49,700,000	56,900,000
Total LNG Transport GHG Emissions	**62,900,000**	**69,500,000**	**78,900,000**	**94,400,000**

4.2 Air Quality Modeling Results

Air quality modeling results are shown in Figures 6 through 9, comparing the Pickens scenario to the BAU scenario. The mean July SO_2 concentrations are shown in Figure 6. The general distribution is similar in both scenarios, with the highest concentrations (2 to 10 ppb) extending along the Ohio River Valley and several metro areas having higher concentrations (Sioux City, Omaha, Kansas City, St. Louis, Chicago, Detroit). Figure 6 illustrates the absolute (ppb) and relative (percent) difference between BAU and Pickens scenarios. As a result of natural gas trucking and wind-powered electricity, we see a general reduction in SO_2 concentrations over the entire study region. The most substantial reductions (ranging from 0.5 to 3.0 ppb) occur in metropolitan areas, along the Ohio River Valley, and along major highways. We assume that LNG trucks replace all diesel trucks, including older and higher emitting trucks resulting in visible reductions along study area interstates and metro areas. A similar effect would be expected if new diesel trucks (with ultra-low sulfur diesel and advanced emission controls) were substituted for the entire truck fleet.

Figure 7 illustrates projected NO_2 concentration ranging from 0 to 30 ppb, with metro areas exhibiting the greatest reductions between the two cases. The percent difference between the two scenarios is greater for NO_2 than SO_2, with 15 to 35 percent reductions in ambient NO_2 covering much of the study area.

Ozone concentrations (O_3) are reduced by 1.0 to 4.0 ppb (Figure 8) for much of the study area, which constitutes a 2 to 6 percent reduction relative to BAU. Slight ozone increases are projected in metro areas. Due to its rate limiting chemistry in these regions, NO_2 reductions in urban areas often result in increased O_3 formation.

Fine particulate ($PM_{2.5}$) show the greatest decrease in metro areas as well as an area broadly covering most of Indiana and extending southwest to Illinois and northeast to southern Michigan (Figure 9). In general, simulated $PM_{2.5}$ reductions for the Pickens scenario are between 6 and 20 percent less than BAU.

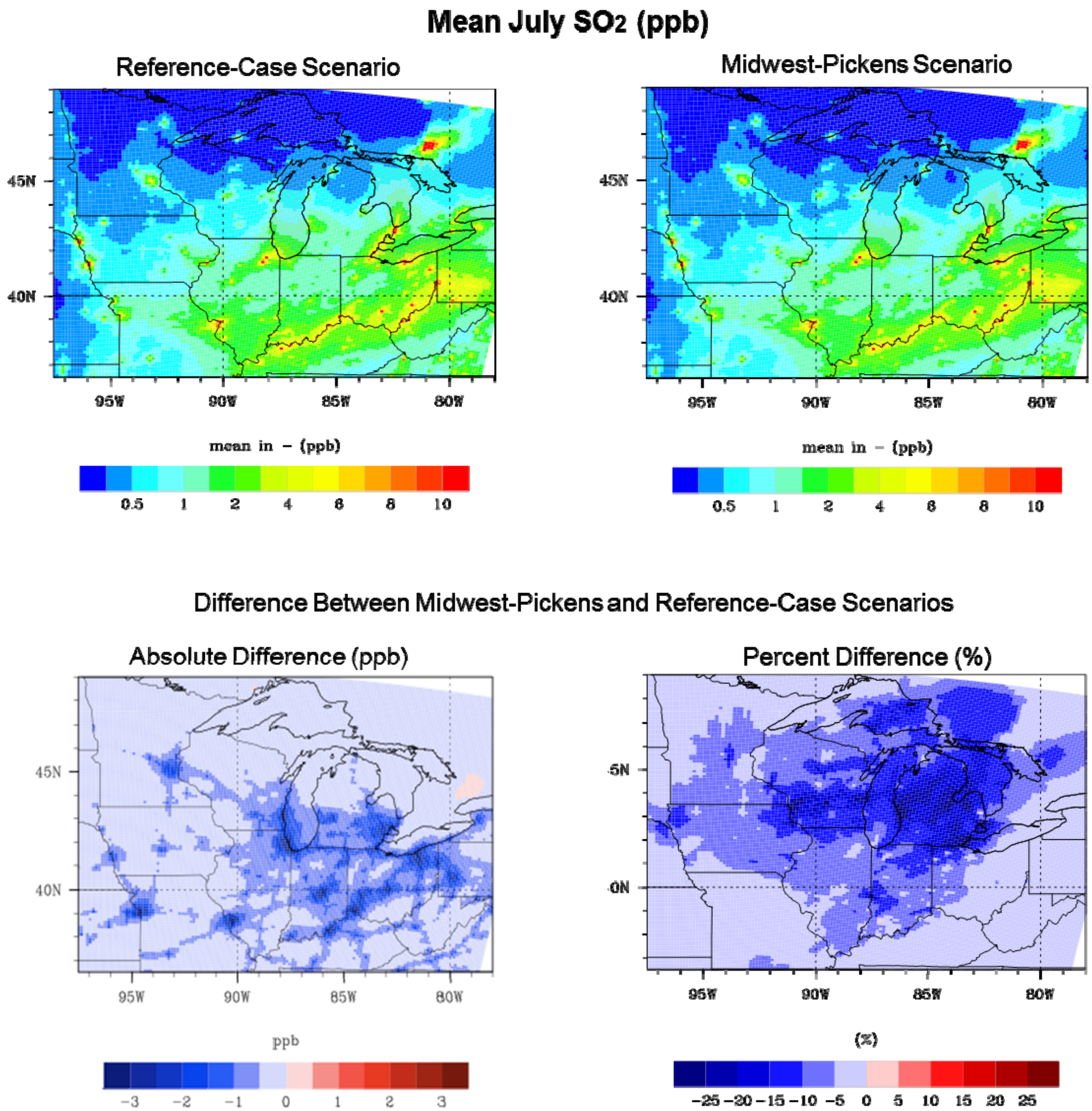

Figure 6. Comparison of Mean July SO_2 Concentrations (ppb) for BAU and Pickens Scenarios.

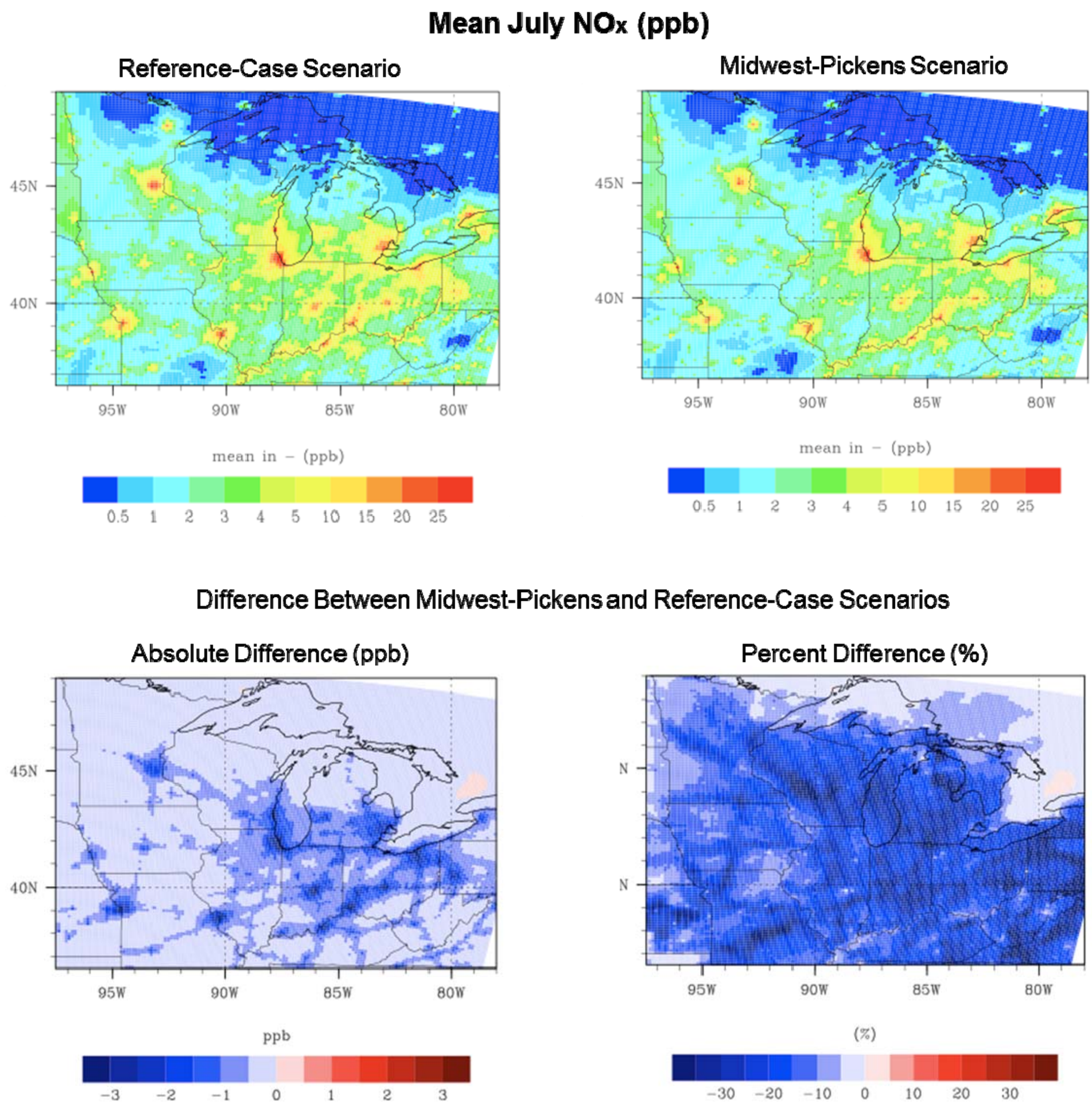

Figure 7. Comparison of Mean July NO_x Concentrations (ppb) for BAU and Pickens Scenarios.

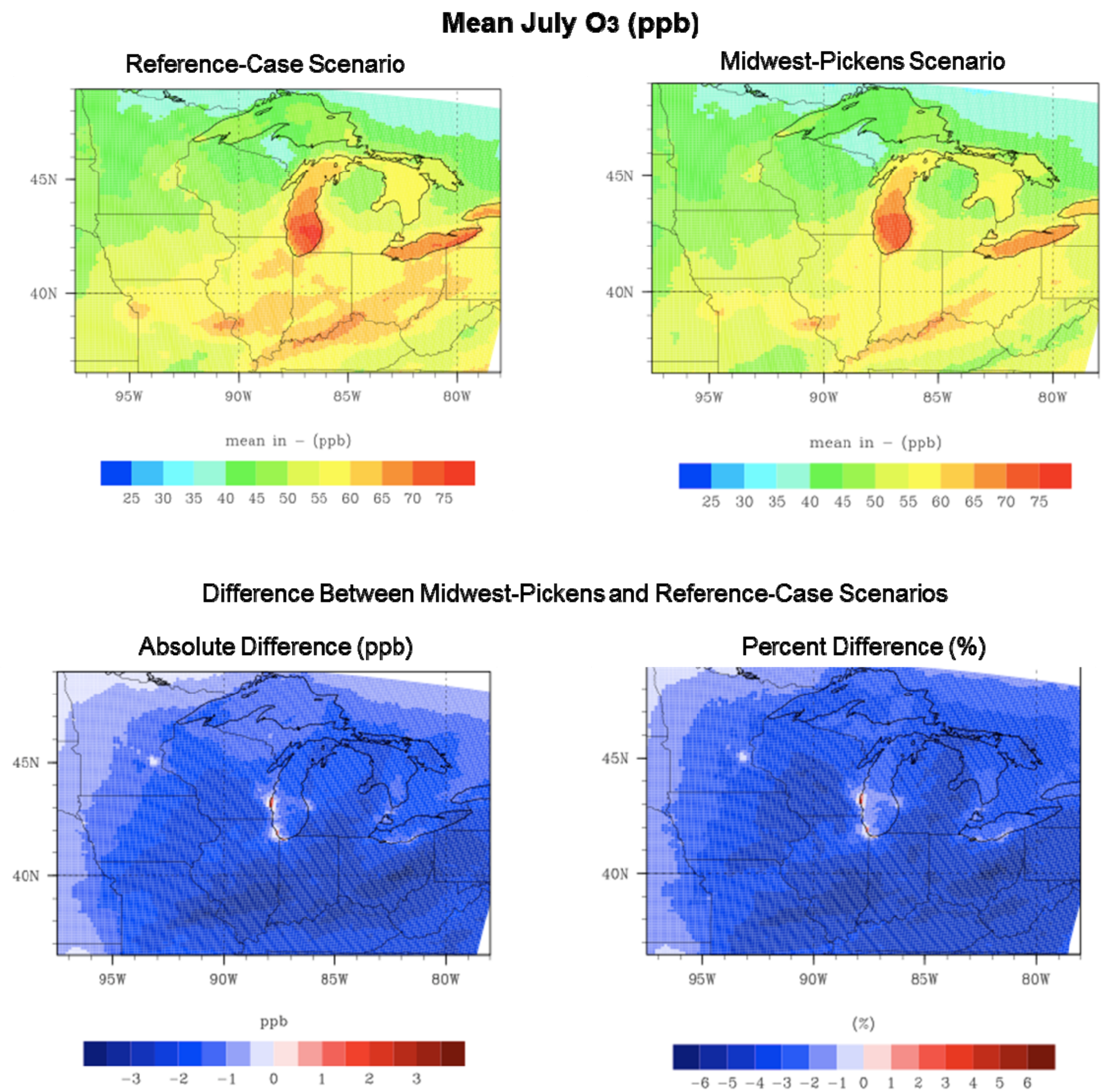

Figure 8. Comparison of Mean July O_3 Concentrations (ppb) for BAU and Pickens Scenarios.

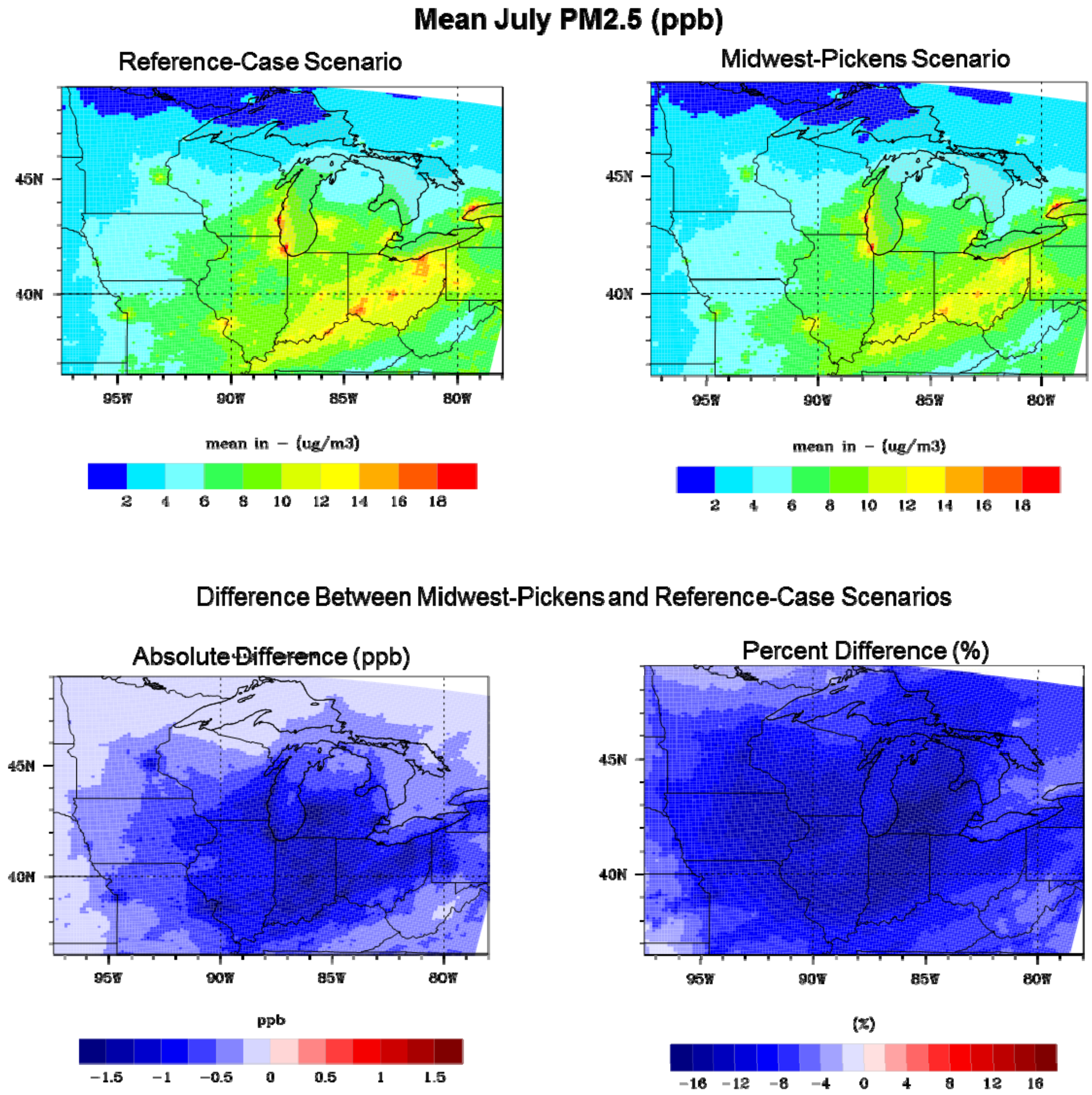

Figure 9. Comparison of Mean July $PM_{2.5}$ Concentrations (ppb) for BAU and Pickens Scenarios.

5. Discussion

We examined whether a Midwestern version of the Pickens Plan might contribute to meaningful emissions reductions. We found that powering freight transport using high-pressure direct-injection LNG technology, while simultaneously doubling contributions of wind power to the electricity grid, resulted in lower regional emissions of SO_2, NO_x, and GHG. The majority of emissions benefits occur within the power sector, however, with fewer reductions occurring within the transportation sector. Emissions benefits occurring within the electricity sector are the result of roughly doubling wind power contributions. Of the emissions reductions achieved by the Pickens scenario (as reported in Tables 4 through 6), 73 percent of NO_x reductions, 99 percent of SO_2 reductions, and 94 percent of GHG reductions were the result of increasing the wind power contributions to 23 percent of the electricity fuel mix, roughly double the 12 percent we anticipated from existing RPS standards.

Life-cycle emissions diminish the GHG emissions reductions achieved from converting from diesel to LNG trucks. Assuming the LNG truck mileage is only 6 percent lower than the diesel truck, we estimate that a 21 percent reduction is achieved considering roadway emissions alone. The GHG benefit is reduced to only 8 percent, however, when assuming a 2.4 percent leakage rate from the natural gas fuel cycle. The GHG benefits from LNG trucking are highly contingent on methane leakage assumptions for both the truck and the fuel cycle, ranging from 10 percent lower to 36 percent higher than diesel trucking.

Even deeper emissions reductions resulted when natural gas was increased within the electricity sector (Electricity-Only scenario) instead of the transport sector (Pickens scenario). Relative to BAU, the Electricity-Only scenario achieved 56 percent more NO_x reductions, 236 percent more SO_2 reductions, and 80 percent more GHG reductions than the Pickens scenario. These reductions occur as a result of displacing coal combustion with cleaner burning natural gas at higher efficiency combined-cycle power plants. Some of this reported benefit has occurred in recent years due to the dramatic reduction of natural gas prices, brought on in large part by increasing shale gas production. (Our estimated 2020 emission benefits would diminish somewhat if the assumed price of BAU natural gas were based on recently low natural gas prices - down to $2.77/MMBtu in 2012 from $4.02 in 2011) (42). As the markets demonstrated in response to this decline, increasing natural gas within the electricity sector is seemingly far easier than comparable changes to freight transportation. Whereas LNG freight requires a transformation of truck inventory, much of the requisite power plant infrastructure already exists. For the 7-state study region, gas-fired power plants comprise 25 percent of installed generated capacity. These gas-powered plants are often idle and could generate more electricity under the appropriate market conditions.

We modeled regional air quality to estimate pollutant concentrations resulting from the Pickens scenario relative to BAU. As expected, the Pickens scenario's emission reductions described above reduced concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$. In general, deeper reductions were projected in metro areas, along major highways, and along the Ohio River Valley. A potentially important exception is for O_3, where slight increases were projected along metro areas on Lake Michigan and Lake Erie. It is unfortunately ironic there NO_x reductions have the potential to exacerbate O_3 formation in metro areas – the same areas for which natural gas-powered transport is increasingly cost-competitive. This does not necessarily mean that the Pickens scenario has a net negative health impact in these metro areas. Both $PM_{2.5}$ and O_3 exceed air quality standards in the Midwest (12), with the greatest exposure risk occurring in metro areas. In the case of $PM_{2.5}$, the Pickens scenario resulted in widespread reductions throughout the study area, with deeper reductions occurring in metro areas.

While this work is interested in emissions impacts, the stated motivation of the Pickens Plan is to reduce U.S. dependence on imported oil as a matter of increased national economic security. With this objective, the optimal use of natural gas is to displace petroleum, for which imported supply meets roughly half of U.S. demand (43). While we show that major deployment of LNG-trucking reduces regional emissions, we further show that natural gas is even more efficient at reducing emissions within the electricity sector. A similar magnitude shift of natural gas and wind into the electricity sector provides deeper emission cuts while requiring a less dramatic shift in energy infrastructure.

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Appendix A - Comparison of Simulated 2020 July Emissions to Historic 2007 and Historic 2011 July Emissions

July emissions estimates for each scenario were used as the basis of air quality modeling assessment. Providing reasonably realistic simulation requires that the modeling approach adequately estimates the performance and emissions from freight vehicles and power plants, and subsequently simulates the fate and transport of these pollutants in a way that is realistic relative to real-world observation. To validate our approach, we compared Madison-area (2007) observations for ozone and fine particulate to the values simulated for the 2020 BAU scenario. In general we see very good agreement between the simulated and observed $PM_{2.5}$ concentrations (shown in orange in Figure 10), both in magnitude and in timing. The timing of simulated ozone concentrations also agrees closely with observation. As shown in Figure 11, the magnitude of ozone concentration was frequently higher in the simulated projections relative to the observed concentrations (shown in orange), by roughly 15ppb in magnitude.

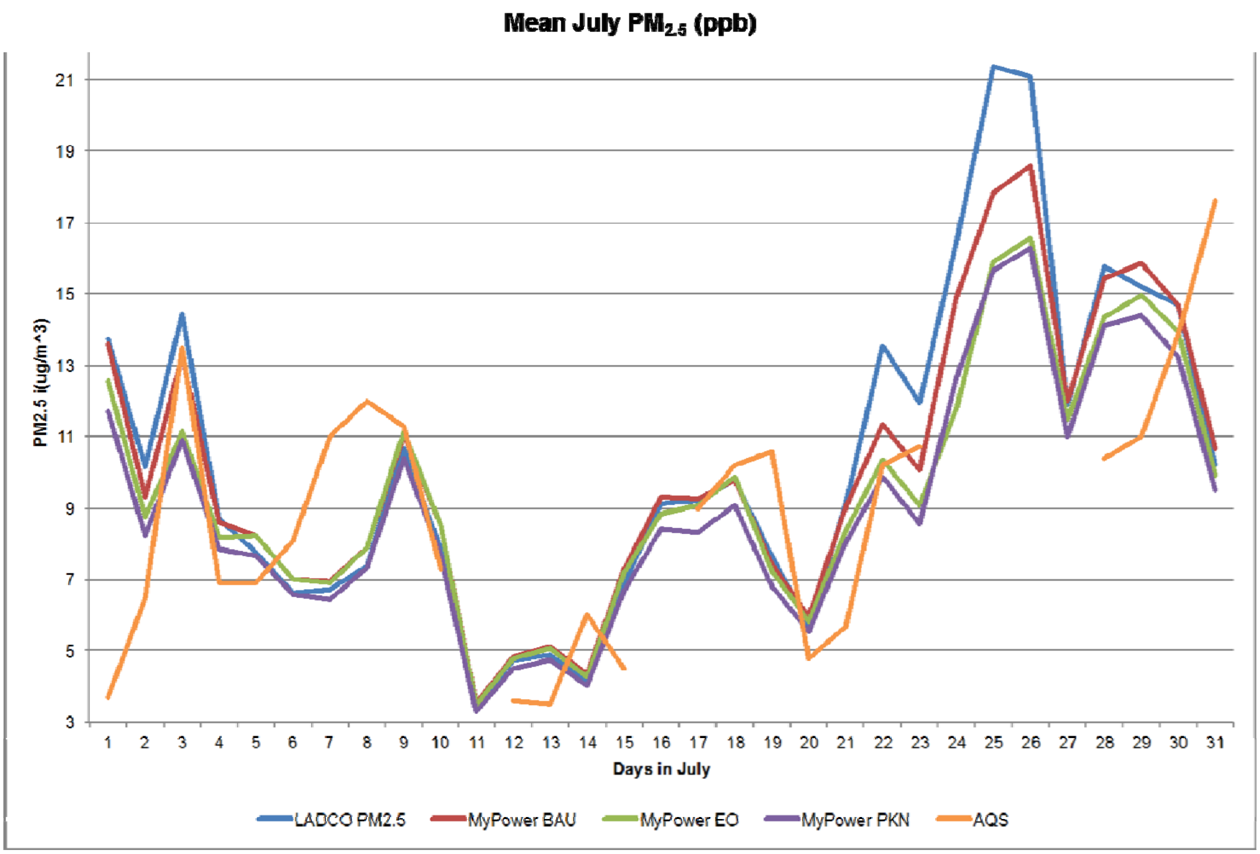

Figure 10. A Comparison of Simulated and Observed Mean July Concentration of Fine Particulate $PM_{2.5}$ for the Madison, WI Area.

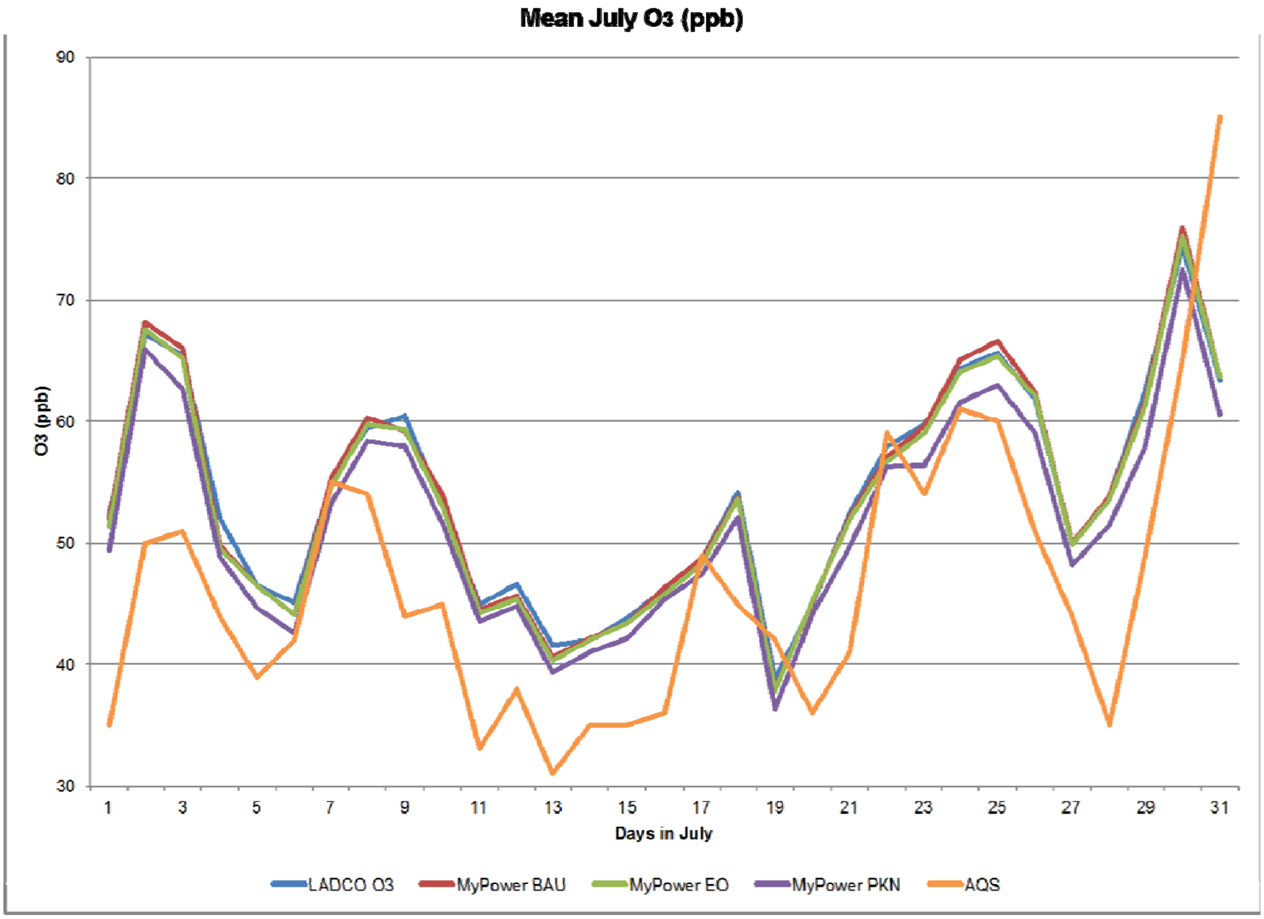

Figure 11. A Comparison of Simulated and Observed Mean July Concentration of Ozone (O_3) for the Madison, WI Area.

To ensure that the power sector modeling was realistic, we compared the 2020 BAU scenario estimates for July to historic July emissions for 2007 and 2011 as reported by U.S. EPA Clean Air Markets (CAM) Database. (25). We compared historic and simulated SO_2 and NO_x emissions in two ways: 1) at the state level comparing cumulative emissions for all units, and 2) at the facility level for the largest emitting units – those comprising 95 percent of each state's emissions. In general, emissions estimates show good agreement at the state level. The source of these emissions does vary when evaluated at the facility level. Most of the observed differences between simulated and historic emissions result from system changes occurring between 2009 and 2020 as part of the BAU scenario. These changes include additions of renewable power resources to comply with Renewable Portfolio Standards, additions of new power plants to maintain system reserve capacity (peak demand is assumed to grow by 18 percent for the region between 2007 and 2020), and differences between historic and forecast natural gas and coal fuel prices. Some emission factor discrepancies are likely to result due to the lack of correlation between the NEEDS and CAM databases. In some cases, emission factors discrepancies result from the recent addition of pollution control equipment between 2009 and 2011, which would not have been reflected in the NEEDS database or 2009 CAM data. While these discrepancies create variance between simulated and historic emissions, they are consistent across all scenarios. Therefore, we assert we have provided valid comparisons of the relative change of emissions between BAU and Pickens scenario (wherein we make large additions of wind power) and the Electricity-Only scenario (wherein we add large amounts of wind power and natural gas power).

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