Development and demonstration of a modeling framework for exploring the emission impacts of alternative future scenarios

D. Loughlin[1], W.G. Benjey[2], and C.G. Nolte[2]

[1]U.S. Environmental Protection Agency, National Risk Management Research Laboratory, 109 T.W. Alexander Drive, Research Triangle Park, NC 27711, USA (loughlin.dan@epa.gov)

[2]U.S. Environmental Protection Agency, National Exposure Research Laboratory, 109 T.W. Alexander Drive, Research Triangle Park, NC 27711, USA (benjey.william@epa.gov; nolte.chris@epa.gov)

ABSTRACT. This article presents an approach for creating anthropogenic emission scenarios that can be used to simulate future regional air quality. The approach focuses on energy production and use since these are principal sources of air pollutants. We use the MARKAL model to characterize alternative realizations of the U.S. energy system through 2050. Emission growth factors are calculated for major energy system categories using MARKAL, while growth factors from non-energy sectors are based on economic and population projections. The SMOKE model uses these factors to grow a base-year 2002 inventory to any year through 2050. The approach is demonstrated for two emissions scenarios. Scenario 1 extends current regulations through 2050, while Scenario 2 applies a hypothetical policy that limits carbon dioxide (CO_2) emissions from the energy system. Both scenarios show significant reductions in air pollutant emissions through time. These reductions are more pronounced in Scenario 2, where the CO_2 policy results in the adoption of technologies with lower emissions of both CO_2 and traditional air pollutants. The methodology is being refined and is expected to play an important role in investigations of linkages among emission drivers, climate and air quality by the U.S. EPA and others.

1 Introduction and Objectives

Anthropogenic emissions (including greenhouse gases or GHGs) are responsible for many current air quality problems, including photochemical smog, acid rain, and regional haze. Many of these emissions also contribute to climate change (Pachauri and Reisinger, 2007), which is associated with temperature increases, changes in precipitation patterns, water supply issues, reduced air quality, introduction of new disease vectors, and sea level rise (Peary et al, 2007). To address long-term air quality and climate concerns, decision-makers need to be able to anticipate future emissions and their impacts, as well as to develop and evaluate candidate management strategies.

The uncertainty inherent in projecting emissions decades into the future provides complications. Uncertain variables include population growth and migration, economic growth and transformation, energy resource supplies, climate change, land use change, technology change, future policy directions, and human behavior. One approach for projecting emissions is to combine best guesses about these many drivers, developing a single projection (Woo et al., 2008). Scenario analysis differs by developing of a range of very different, yet plausible, alternative futures (Schwartz, 1996). Using scenario analysis, future emissions and air quality can be evaluated over a wide range of demographic, economic, technological, regulatory and economic possibilities.

The U.S. EPA is developing scenario-based approaches for supporting climate and air quality decision-making. A central component of this effort is the implementation of an integrated modeling framework. The framework includes models that characterize global circulation patterns, regional meteorology, economic growth, land use changes, the energy system, and air quality. Parts of this framework were demonstrated in previous work that examined climate change impacts on air quality, independent of changes in anthropogenic emissions (U.S. EPA, 2009). The results suggested that climate change, under the modeled assumptions, could lead to a 20% increase in biogenic emissions and up to a 5 ppb increase in surface-level ozone (Nolte et al., 2008). For the next phase of that work, alternative emission scenarios through 2050 are being developed and the resulting air quality impacts will be evaluated. The results are expected to improve our understanding of the linkages and important relationships among emissions, climate, and air quality.

The mechanism by which these scenarios are translated into future emissions is a critical component in the evaluation of alternative emissions scenarios. The purpose of this paper is to describe a methodology for this translation. The methodology is demonstrated for two illustrative scenarios. Both national and regional emissions responses to the scenario assumptions are explored. Refinements to the methodology are ongoing, and short- and long-term improvements are discussed at the end of the paper.

2 General Methodology

The energy system is a major source of air pollutant emissions. Energy-related sources in 2005 contributed approximately 94% of anthropogenic CO_2, 95% of anthropogenic nitrogen oxides (NOx), 92% of anthropogenic sulfur dioxide (SO_2), and 10% of anthropogenic PM emissions of less than 10 μm in diameter (PM_{10}) (U.S. EPA, 2009a; U.S. EPA, 2010).

The MARKet ALlocation (MARKAL) model (Fishbone and Abilock, 1981; Rafaj et al, 2005) is an energy system optimization model. MARKAL represents energy supplies and demands over a time horizon, as well as current and anticipated technologies for meeting those demands. MARKAL optimizes investments in technologies and fuels over time, apportioning market share such that energy system costs are minimized and modeled constraints are met. By modifying model inputs or introducing constraints to represent a particular scenario, MARKAL can provide an estimate of the resulting impacts on technologies, fuels, and air pollutant emissions.

To analyze a particular energy system with MARKAL, a database that represents that system must be developed. The U.S. EPA has developed MARKAL databases that represent the U.S. energy system at the national and regional levels (U.S. EPA, 2006). Both databases cover the period 2000 through 2050 in five-year increments and represent the following sectors: resource supply, electricity production, residential, commercial, industrial and transportation. Characterizations of current and future energy demands, resource supplies, and technologies within the databases were developed primarily from the Energy Information Agency's 2006 Annual Energy Outlook (AEO06) report, extrapolated to 2050 (U.S. DOE, 2006; U.S. DOE, 2009). Additional sources of information include the EPA's AP-42 emission factors (U.S. EPA, 1995), the Integrated Planning Model (IPM) (U.S. EPA, 2010c), and Argonne National Laboratory's Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model (Burnham et al, 2006).

The level of technological detail within the EPA MARKAL databases differs by sector, depending on data availability and importance with respect to emissions and energy use. Data sources used to allocate effort include the U.S. EPA's Greenhouse Gas Inventory (U.S. EPA, 2009a), the U.S. EPA National Emission Inventory (NEI) (U.S. EPA, 2010), and the AEO06. Based on an analysis of these data sources, the electricity production and light duty transportation sectors have the highest level of specificity within MARKAL. In 2002, these two sectors together accounted for approximately 62% of U.S. anthropogenic CO_2 emissions and

53% of anthropogenic NOx emissions. We also have included considerable technological detail within the residential and commercial sectors of MARKAL. These sectors use large quantities of electricity, thus influencing emissions from the electric sector. The industrial sector is also a major user of electricity and accounts for approximately 15% of U.S. anthropogenic CO_2 emissions through fuel combustion. Detailed information about industry-specific energy use and technologies is not readily available, however, limiting how that sector has been represented. Specification of heavy duty vehicle, air, shipping, and rail technologies also is currently limited within the database. In 2002, these sectors together accounted for only 12% of transportation CO_2 emissions, but 32% of transportation NOx emissions. Development of the EPA MARKAL databases is ongoing, and these transportation categories are currently receiving additional attention.

Running MARKAL for a particular scenario using the national database requires only 1 to 5 minutes, depending on the options that are selected. The regional model, which represents the U.S. at the Census Division resolution, requires 20 to 45 minutes. A map showing the nine MARKAL regions is shown in Figure 1. Regionalization allows consideration of fuel transportation costs and regional differences in energy supplies, demands, and technology performance. Outputs, including technologies, fuel use, and emissions, are generated at the regional level. The EPA's nine-region MARKAL database was selected for this work because of this regional differentiation.

An approach was developed for converting MARKAL's regional emissions projections into state-level, Source Classification Code (SCC)-based emissions growth factors (U.S. EPA, 2010d). These factors can be used within the Sparse Matrix Operator Kernel Emission (SMOKE) model (Houyoux and Adelman, 2001) to grow a base-year inventory to a future year. SCCs represent specific types of emission sources within the NEI. Point sources are represented by 8-digit SCCs. Area and mobile sources are represented by 10-digit SCCs. The digits provide more specificity from left to right. For example, the code 10100201 represents a utility sector, wet-bottom boiler that burns bituminous coal. The left most digit, “1,” refers to external combustion. The next two digits specify the industry, with “01” representing electric utilities. The following three digits represent the fuel, with “002” being bituminous or sub-bituminous coal. The last two digits specify the type of process, a wet bottom boiler. If a set of digits within the code is replaced by zeros, those zeros are interpreted as a wildcard. For example, the code 10000000 refers to all external combustion point sources, regardless of industry.

The portion of the approach related to energy system emissions consists of the following steps, which are repeated for each pollutant (NOx, SO_2, and PM_{10}) and region:

1. Emissions are summed for each MARKAL emission category and time period.

2. The summed MARKAL emissions are allocated to the matching SCCs using the crosswalk provided in Table 1. SCC codes for point sources are aggregated to the 3-digit level, area sources to the 4-digit level, and mobile sources to the 7-digit level. The rationale for the degree of aggregation in each sector is provided later in this section. Since the SCC codes are generally more specific than the MARKAL codes, there are several one-to-many mappings. The entire summed MARKAL emissions for each category are allocated to each of the more detailed matching SCCs.

3. For each SCC, multiplicative emission growth factors are calculated by dividing the future-year value by the base-year value.

4. The resulting SCC-, pollutant- and region-specific growth factors are applied to each state within the region.

5. After repeating the procedure for each pollutant and region, the resulting emission growth factors are placed in a SMOKE growth and control factor file using the standard SMOKE growth packet format (CMAS, 2009).

Since MARKAL does not include full coverage of energy sector pollutant species, growth factors for CO_2, PM_{10} and NOx are used as surrogates for other species. For example, energy system carbon monoxide (CO), volatile organic compounds (VOC), and ammonia (NH_3) are assumed to grow at the same rate as CO_2. Growth factors for PM_{10} are applied to PM of 2.5 μm or less ($PM_{2.5}$). For mobile sources, NOx growth factors are used for CO, VOC and NH_3 emissions. Ongoing efforts to expand pollutant coverage within the MARKAL database will reduce the need for such surrogates.

Industrial process-related emissions are not modeled within MARKAL. National-scale growth rates for these emissions are generated from industry-specific growth projections produced by the EPA's Economic Model for Environmental Policy Analysis (EMPAX) (RTI International, 2008). Similarly, MARKAL also does not model non-combustion emissions from the residential and commercial sectors. Growth factors for these emissions are linked to county-level population growth projections. While there are alternative sources for such projections, we have used the Integrated Climate and Land Use Scenarios (ICLUS) model (U.S. EPA, 2009b). The resulting economic- and population-based growth factors are matched to SCCs and are inserted into the SMOKE growth and control factor file.

SMOKE carries out the following steps: the base-year inventory is grown to the future using the multiplicative factors within the growth and control file; NOx, PM, and VOC emissions are disaggregated into their constituent chemical species using a library of SCC-specific chemical speciation profiles;, emissions are spatially and temporally allocated into a three-dimensional modeling grid using spatial surrogates and SCC-specific temporal allocation profiles, respectively. In the spatial allocation process, point sources are allocated directly to the grid cell in which the source's coordinates lie. Non-point emission sources are characterized at the county level. SMOKE allocates these emissions to grid cells based on spatial surrogates. For example, residential emissions are allocated to the overlapping grid cells proportionally to the population in each grid cell. The resulting gridded file can be used within an air quality model such as the Community Multiscale Air Quality (CMAQ) model (Byun and Schere, 2006) to simulate regional air quality for the modeled scenario.

2.1 Important considerations

Aggregation of SCCs within the crosswalk in Step 3 is an important component of the methodology. Consider the example of a region that transitions from coal to natural gas as its primary fuel in the electric sector. Without SCC aggregation, multiplicative growth factors would result in natural gas emissions being increased only at the locations where gas turbines exist in the base-year inventory. In reality, the new turbines may be placed at other locations, including perhaps the sites of the decommissioned coal plants or at new sites entirely. Similarly, problems arise when a source category appears in a future year but not in the base year. For example, the 2000 emissions from integrated gasification combined cycle (IGCC) coal technologies effectively would be zero. A future-year multiplier, applied to a base-year value of 0, would therefore be meaningless. New emission sources in the inventory would need to be sited geographically, introducing additional spatial uncertainty. These issues cannot be addressed comprehensively except with the development of an algorithm for siting future-year emissions. The formulation and parameterization of such an algorithm would undoubtedly introduce uncertainties itself and is beyond the current scope of our work.

We instead introduce the simplifying approach of smoothing spatial allocation by mapping MARKAL categories to aggregated SCC codes. Point source SCCs are aggregated at the 3-digit level, area source SCCs at the 4-digit level, and mobile sources at the 7-digit level. For point sources, for example, 3-digit aggregation would include natural gas and IGCC emissions with other external combustion sources within the electric sector. Transportation sources use 7-digit aggregation because rail and shipping are not distinguished until the seventh digit.

Given these various aggregations, the resulting emissions factors must be interpreted carefully. These factors are intended to characterize regional trends for each class of sources, but they do not explicitly represent changes at any particular source. From the perspective of modeling several decades into the future, we believe that aggregation is more appropriate than detailed mappings given the large uncertainties in both long-term projections of emission drivers and the relationships between those drivers and emissions. This approach provides more detailed emission projections than some alternatives, such as modifying NOx emissions from all classes of sources by a single fraction.

Another consideration is related to industrial emissions. MARKAL calculates industrial emissions for each combination of technology category, fuel and industry. For example, emissions are estimated for coal-fired boilers within the paper industry. In contrast, entries within the NEI, to which emission growth factors are applied, do not uniformly include industrial specificity. Our methodology thus makes the simplifying assumption that boiler emissions will change at the same rate for all industries. This assumption can be revisited if future versions of the NEI include more universal coverage of industrial specificity.

3 Application

The EPA's 2002 modeling inventory was selected as the base inventory for this application (U.S. EPA, 2010d). The methodology described above was applied to grow the base inventory through 2050 for the two scenarios described below. The scenarios represent only two of a large number of potential futures and are not intended to be interpreted as predictions or to represent most likely outcomes. Instead, the scenarios were selected to demonstrate how technology and policy assumptions may impact emission growth factors and how these factors may differ by sector and region.

Scenario 1. The first scenario was based on the AEO06 "Business as Usual" case, but was extended from 2030 through 2050. To approximate the Clean Air Interstate Rule (CAIR), which restricts power plant emissions east of the Mississippi River, NOx and SO_2 emissions from electric generating units in MARKAL's regions 1, 2, 3, 5 and 6 (Figure 1) were constrained to meet projections from the EPA's regulatory impact assessment of CAIR, which were produced by the Integrated Planning Model (IPM) (U.S. EPA, 2005). Beyond 2020, electric sector NOx and SO_2 from these regions were capped at their 2020 levels. For all regions, new coal-fired boilers were assumed to use low-NOx burners, selective catalytic reduction (SCR), and flue gas desulfurization control technologies. Representations of the 2007 Corporate Average Fleet Efficiency (CAFE) standards for light-duty vehicles and the biofuels requirements of the Energy Independence and Security Act of 2007 (EISA) were included (H.R. 6, 2007). Emission factors for light duty vehicles were obtained from GREET. Emissions from hybrids and plug-in hybrids were reduced by the average fraction of the operating cycle that the vehicles are under electric power, as modeled by GREET. Heavy-duty vehicle emission factors were also obtained from GREET and include sulfur limits on diesel and on-road heavy-duty engine NOx limits (U.S. EPA, 2010b). Electric and hydrogen fuel cell vehicles were assumed to have no tailpipe emissions. Industrial sector emission factors were developed from GREET and incorporate predicted impacts of New Source Performance Standards (U.S. EPA, 2010a).

Scenario 2. In this scenario, a representation of a CO_2 policy was applied to Scenario 1. In addition, optimistic assumptions were made about the availability and growth potential for carbon capture and sequestration (CCS) and renewable energy technologies. The CO_2 policy was modeled as a decreasing trajectory of energy system CO_2 emissions, resulting in 25% reduction in cumulative CO_2 emissions from 2000 through 2050. Annual constraints on CO_2 emissions were patterned after the U.S. EPA's analysis of the Lieberman-Warner climate bill (U.S. EPA, 2008). The details of the bill were not modeled, however, so the simulated policy cannot be regarded as adhering to the Lieberman-Warner bill or any particular legislative proposal. Further, while MARKAL was allowed to select technologies to minimize the net present value of the energy system cost, behavioral responses such as conservation and changes in industrial output were not modeled. The system-wide CO_2 emissions for Scenario 1 and the constrained CO_2 trajectory for Scenario 2 are shown in Figure 2.

3.1 Scenario results

MARKAL optimized technology and fuel selections across all sectors, regions, and time periods for each scenario. Regional outputs are aggregated to the national level to illustrate some of the differences between the two scenarios. For example, Figure 3 shows the electricity produced by various technologies. In Scenario 1, pulverized coal combustion holds the largest market share for most of the modeled time horizon. Emission constraints on NOx and SO_2 limit the growth of coal, however, and its market share decreases. Output from wind, solar and nuclear technologies grows to meet additional electricity needs.

In Scenario 2, existing coal plants instead are phased out relatively quickly and replaced by new IGCC plants with CCS and additional wind capacity. The CO_2 constraints introduce price pressures that result in more efficient end-use technologies, reducing growth in electricity demand between 2015 and 2030. The availability of nearly carbon-free electricity supply after 2030, however, yields major increases in electricity output as other sectors reduce their carbon footprint by converting some fossil fuel demands to electricity.

An example of this transition to electricity use can be seen in Figure 4, which shows the market share of light-duty vehicle technologies. Through 2030, the distribution of light-duty vehicle technologies is similar between the two scenarios: conventional technologies surrender market share to moderately-improved and advanced internal combustion engines. The scenarios diverge considerably after 2030 as CO_2 limits, combined with the availability of a supply of low-carbon electricity, yield an abrupt transition to plug-in hybrids, electric, and hydrogen fuel cell vehicles.

Figure 5 shows trajectories for CO_2, NOx, and PM_{10} over the modeling horizon. CO_2 emissions in Scenario 1 increase steadily, driven by increases in energy demands. Other pollutant emissions through 2020 follow a decreasing trend, however, driven by air pollution regulations. CO_2 emissions in Scenario 2 decline in response to the CO_2 constraints. Emissions of NOx and PM_{10} decline even further in Scenario 2 relative to Scenario 1 because many technologies that are low in CO_2 emissions also are low in other pollutant emissions.

3.2 Calculated emission growth factors

Regional emission growth factors were developed for Scenarios 1 and 2 using the methodology described in Section 2. Tables 2 and 3 include multiplicative growth factors for major energy system categories in Regions 5 and 9, respectively. These regions correspond to the Southeast and Pacific U.S. Census Divisions, respectively. Some of these factors within these tables are similar to the national trends shown in Figure 2, while others are not, reflecting regional and sectoral differences.

For Region 5 (Table 2), the Scenario 1 results show large reductions in NOx and $PM_{2.5}$ emissions from the electric sector and from light- and heavy-duty transportation, signified by growth factors of less than 1.0. These reductions are due to current emissions regulations and to the retirement of a small portion of existing coal-fired power plants, combined with new capacity for nuclear and natural gas technologies. Scenario 2 results in additional reductions for many pollutants and sectors. The largest change is within the electric sector, where CO_2 emissions are reduced by 95% from Scenario 1 to Scenario 2. The model achieves this reduction primarily by replacing existing coal-fired power plants with nuclear power and with new coal gasification and natural gas facilities that both use CCS. Light-duty transportation also exhibits emissions reductions as a result of the CO_2 constraints. These reductions are driven by the market penetration of plugin-hybrid, fuel cell, and electric vehicle technologies.

While the trend is for Scenario 2 to result in emissions reductions relative to Scenario 1, there are a number of exceptions. For example, $PM_{2.5}$ emissions from the residential sector increase by 12%. This response is the result of a small increase residential wood heating, a major source of residential sector $PM_{2.5}$, Other than light-duty vehicles, the transportation sector does not respond to Scenario 2's CO_2 constraints. The EPA MARKAL database represents relatively limited technology and emission control options within these transportation categories.

Region 9 (Table 3) exhibits many of the same overall trends as Region 5. The most notable exceptions, however, are within the electric sector. For example, in Scenario 1, the growth factors for NOx and $PM_{2.5}$ are 1.26 and 0.72, respectively. These are considerably greater than Region 5's corresponding values of 0.23 and 0.54. These differences can be attributed to each region's initial mix of electric sector technologies, as well as to MARKAL's technology selections for meeting future electricity demands. In 2000, Region 9's electricity production was dominated by hydropower and natural gas. The ability to expand hydropower capacity was constrained in MARKAL, however, so the model opted to meet increases in electricity demands with natural gas, nuclear power, and a small amount of coal. The result was a net increase in NOx emissions even though the magnitude of the increase was small.

Growth factors for non-energy sources are shown in Table 4. In this initial application, the economic and population surrogates used to develop these factors were assumed to be the same for both scenarios and for all regions.

3.3 Spatially allocated emissions

In the previous section, we demonstrated that emission growth factors generated from MARKAL results may differ by scenario, source category, and region. Applying these growth factors to an existing inventory using SMOKE also yields grid cell-level differences. For example, reductions in power plant emissions will be modeled as occurring in the grid cells that contain power plants. Similarly, changes in highway emissions will be allocated proportionally to cells containing highway segments.

To demonstrate grid cell-level changes from one scenario to another, SMOKE was used to apply Scenario 1 and Scenario 2 growth factors for 2050 to the base year inventory. The resulting gridded emissions of NOx and PM2.5 for each scenario were then compared. Figure 5 provides an example of the resulting spatial differences (Scenario 2 minus Scenario 1) for Region 5. The greatest differences in NOx are associated with additional emission reductions from power plants and from light and heavy duty transportation. Many of the greatest emissions reductions are occurring in the grid cells that include power plants. Vehicle emissions reductions, in contrast, largely are correlated with vehicle miles traveled, and thus are spread more widely. Similarly, PM_{10} emission differences also principally reflect emission reductions within these categories. The PM_{10} results also show small increases in emissions in many cells as a result of additional use of wood for residential space heating (Table 2).

4 Summary and future directions

We describe and demonstrate an approach for generating future emission inventories for nine regions within the United States. The approach focuses on the energy system, allowing alternative future scenarios to be characterized and evaluated. By generating SCC-based emission growth factors, the approach is compatible with existing emission modeling tools, such as SMOKE. Ultimately, tools and methods such as this are expected to improve the ability of decision-makers to anticipate criteria and greenhouse gas emissions trends, understand how these trends are linked to underlying factors, and identify and evaluate alternative adaptation and mitigation policies.

The scenarios selected for evaluation in this paper do not represent specific projections or policies. Instead, they illustrate the application of the methodology for a case in which traditional pollutant (i.e., NOx and SO_2) emissions are expected to change in response to a GHG policy. The results demonstrate that traditional air pollutant reductions may accompany a GHG policy, and that there may be sectoral, regional, and grid cell-level differences in these reductions.

Refinements to the approach and its implementation are ongoing. Many of these refinements involve updates to the EPA MARKAL databases. For example, many technology assumptions are being updated to be consistent with the latest U.S. DOE Annual Energy Outlook. Also, pollutant coverage is being expanded to provide system-wide factors for $PM_{2.5}$, carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), VOCs, black carbon, organic carbon, and mercury (Hg). Further, the off-highway transportation technology representation is being enhanced to include additional advanced technology options. Planned longer-term improvements to the MARKAL databases include an update to the industrial sector to include greater technological detail and control information, as well as the development of an improved representation of existing coal-fired electric utilities to differentiate existing facilities by factors such as age and size.

From the methodological standpoint, we also plan to investigate a number of refinements. For example, we will explore in more detail the implications of SCC aggregation, including comparing the results of different levels of aggregation. We will also examine the advantages and disadvantages of producing industry-specific emission growth rates. For the application presented here, population projections and economic growth rates were not adjusted to reflect impacts that the CO_2 policy might have. In future work, we will develop more widely ranging scenarios that incorporate not only technological and policy assumptions, but also consistent assumptions about population, economy, land use, and other factors. Development of a better capability to generate future land cover scenarios will also improve the spatial distribution and resolution when used in conjunction with the methodology presented here.

An advantage of using MARKAL is its fast runtime, which is only 20-45 minutes for the nine-region model, allowing the development of many alternative future scenarios. Emission modeling with SMOKE and air quality modeling with CMAQ have much greater computational time requirements, however, limiting the number of emission scenarios that can be used in air quality simulations. Computational requirements also limit the ability to consider feedbacks, such as the impact of GHG mitigation efforts on radiative forcings and the resulting changes in temperatures and energy demands. The U.S. EPA is developing screening tools that incorporate MARKAL to facilitate the evaluation of the air quality impacts of a larger number of future scenarios, as well as examining the implications of those scenarios for mitigating climate change.

Acknowledgements

To be added

Disclaimer

This paper has been subjected to the Agency's peer and administrative review and has been cleared for publication. The views and opinions of authors expressed herein do not necessarily state or reflect those of the EPA. The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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U.S. EPA: Technology Transfer Network Clearinghouse for Inventories and Emission Factors, U.S. Environmental Protection Agency, Washington, D.C., available at: http://www.epa.gov/ttn/chief/eiinformation.html. Code tables available in the file http://www.epa.gov/ttn/chief/net/neip/appendix_6.mdb, 2010d.

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Figure Captions

Figure 1. The nine regions used within the U.S. EPA MARKAL database.

Figure 2. National emissions of CO_2 for Scenarios 1 and 2.

Figure 3. Production of electricity by technology for Scenarios 1 and 2. Formatted for color reproduction only.

Figure 4. Market share of light duty vehicle technologies for Scenarios 1 and 2. Formatted for color reproduction only.

Figure 5. Changes in national emissions of CO_2, NOx and PM10, relative to 2000, for Scenarios 1 and 2. Formatted for color reproduction only.

Figure 6. Example gridded plots of scenario differences in annual NOx and $PM_{2.5}$ emissions for the Southeastern United States. Formatted for color reproduction only.

Table 1. Crosswalk linking MARKAL emission categories with matching SCC codes.

Sector	MARKAL Category	Matching SCC codes
Electric	Pulverized coal boilers	10100000, 2101000000
	Gasified coal combined cycle turbines	10100000, 20100000
	Biomass combustion	10100000, 20100000, 2101000000
	Diesel turbine, combined-cycle, and Combined Heat and Power	10100000, 20100000, 2101000000
	Natural gas turbine, combined-cycle, and CHP	10100000, 20100000, 2101000000
	Residual fuel oil boilers	10100000, 2101000000
	Landfill gas turbines	10100000, 20100000, 2101000000
	Waste-to-energy	10100000, 10200000, 10300000, 2101000000
Industrial	All except refineries	10200000, 10500000, 20200000, 2102000000, 2390000000, 2199000000
	Refineries	2306000000
Commercial	All combustion	10300000, 10500000, 2103000000, 2199000000
Residential	All combustion	2104000000
Transportation	Airplanes	2275000000
	Buses and heavy duty trucks	2201070000, 2230070000
	Light duty vehicles	2201001000, 2201020000, 220140000, 2230001000, 2230060000
	Off-highway	2260000000, 2270000000
	Rail	2285000000
	Shipping	2282000000, 2280001000, 2280002000, 2280003000, 2280004000

Table 2. EPA MARKAL Region 5* emissions growth factors, 2000 to 2050, for major energy system source categories

	Scenario 1			Scenario 2			Difference (percent)		
	CO_2	NOx	$PM_{2.5}$	CO_2	NOx	$PM_{2.5}$	CO_2	NOx	$PM_{2.5}$
Electric sector	0.96	0.23	0.54	0.04	0.23	0.55	-95	0	2
Industrial combustion	1.75	1.68	1.52	1.15	1.07	0.68	-34	-36	-55
Residential combustion	1.11	1.17	0.95	1.01	1.08	1.06	-9	-8	12
Commercial combustion	1.65	1.64	1.52	1.21	1.17	0.90	-27	-29	-41
Light duty transportation	1.54	0.19	2.07	0.76	0.08	1.74	-51	-58	-16
Heavy duty transportation	1.88	0.07	0.12	1.87	0.07	0.12	-1	0	0
Airplanes	1.81	1.81	1.81	1.81	1.81	1.81	0	0	0
Rail	1.90	1.91	1.91	1.90	1.91	1.91	0	0	0
Domestic shipping	1.27	1.27	1.27	1.27	1.27	1.27	0	0	0

*Southeast U.S. Census Division; see Figure 2.

Table3. EPA MARKAL Region 9* emissions growth factors, 2000 to 2050, for major energy system source categories

	Scenario 1			Scenario 2			Difference (percent)		
	CO_2	NOx	$PM_{2.5}$	CO_2	NOx	$PM_{2.5}$	CO_2	NOx	$PM_{2.5}$
Electric sector	0.99	1.26	0.72	0.03	0.45	0.56	-97	-64	-22
Industrial combustion	1.72	1.52	1.30	1.31	1.04	0.65	-24	-32	-50
Residential combustion	1.12	1.13	0.89	0.81	0.83	0.96	-28	-27	8
Commercial combustion	1.68	1.72	1.91	1.07	1.05	0.86	-36	-39	-55
Light duty transportation	1.26	0.15	1.70	0.80	0.09	1.52	-37	-40	-11
Heavy duty transportation	1.91	0.07	0.12	1.87	0.07	0.12	-2	0	0
Airplanes	1.81	1.81	1.81	1.81	1.81	1.81	0	0	0
Rail	1.90	1.91	1.91	1.88	1.91	1.91	-1	0	0
Domestic shipping	1.27	1.27	1.27	1.27	1.27	1.27	0	0	0

*Pacific U.S. Census Division; see Figure 2.

Table 4. Non-energy, surrogate-based emission growth factors, 2000 to 2050

Surrogate	Sector Category	Scenarios 1 and 2
Value of shipments	Non-manufacturing industrial sector	1.13
	Food sector	1.52
	Primary metals sector	1.15
	Non-metallic minerals sector	1.23
	Paper sector	1.12
	Transportation equipment sector	1.27
	Chemical sector	0.76
	Other manufacturing demands	4.04
	Other industrial sectors	3.11
Population	Commercial sector	Growth factors vary by county in accordance with the ratio of projected population to 2000 population
	Residential sector	
	Agricultural operations	
	Fugitive dust sources	Fugitive dust source sectors by county vary proportional to projected county population

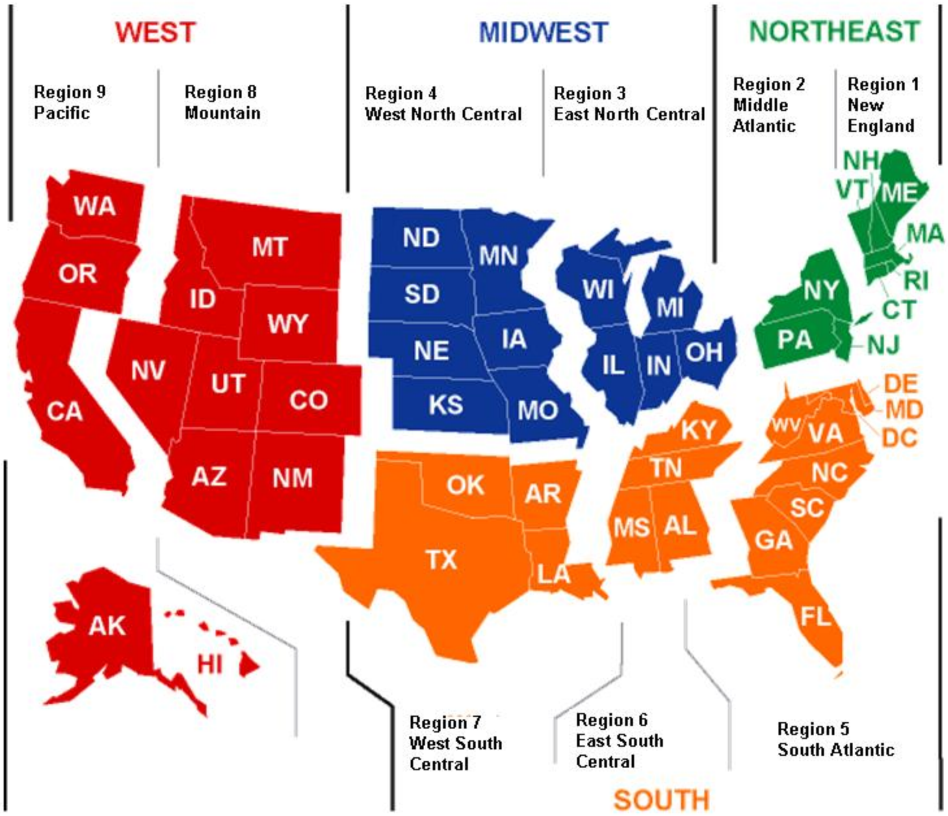
WEST
MIDWEST
NORTHEAST
Region 9
Pacific
Region 8
Mountain
Region 4
West North Central
Region 3
East North Central
Region 2
Middle
Atlantic
Region 1
New
England
WA
OR
CA
MT
ID
WY
NV
UT
CO
AZ
NM
AK
HI
ND
SD
NE
KS
MN
IA
MO
WI
MI
IL
IN
OH
NH
VT
ME
MA
RI
CT
NY
PA
NJ
DE
MD
DC
WV
VA
NC
SC
GA
FL
KY
TN
MS
AL
OK
AR
TX
LA
Region 7
West South
Central
Region 6
East South
Central
Region 5
South Atlantic
SOUTH

FIGURE 1

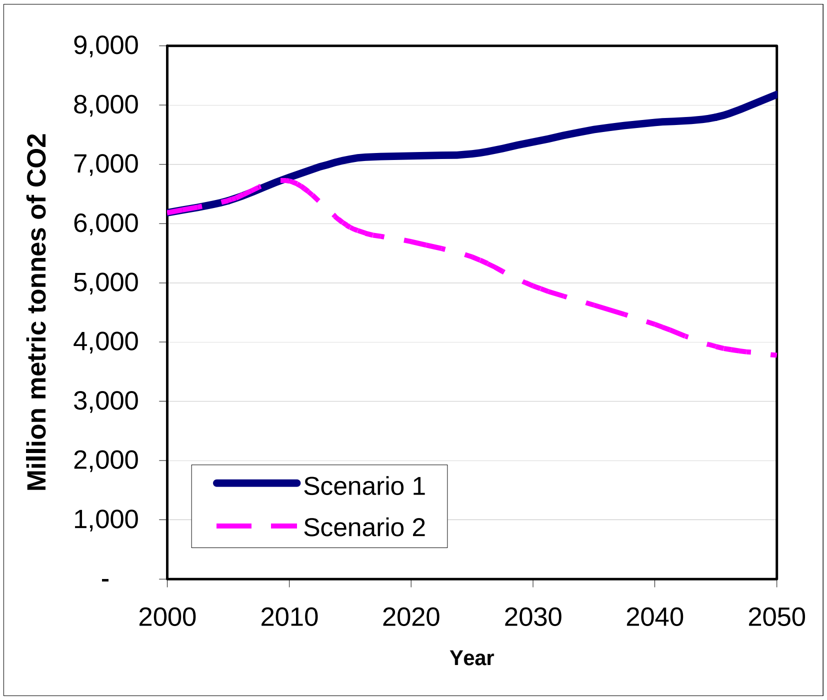
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-
Million metric tonnes of CO2
2000
2010
2020
2030
2040
2050
Year
Scenario 1
Scenario 2

FIGURE 2

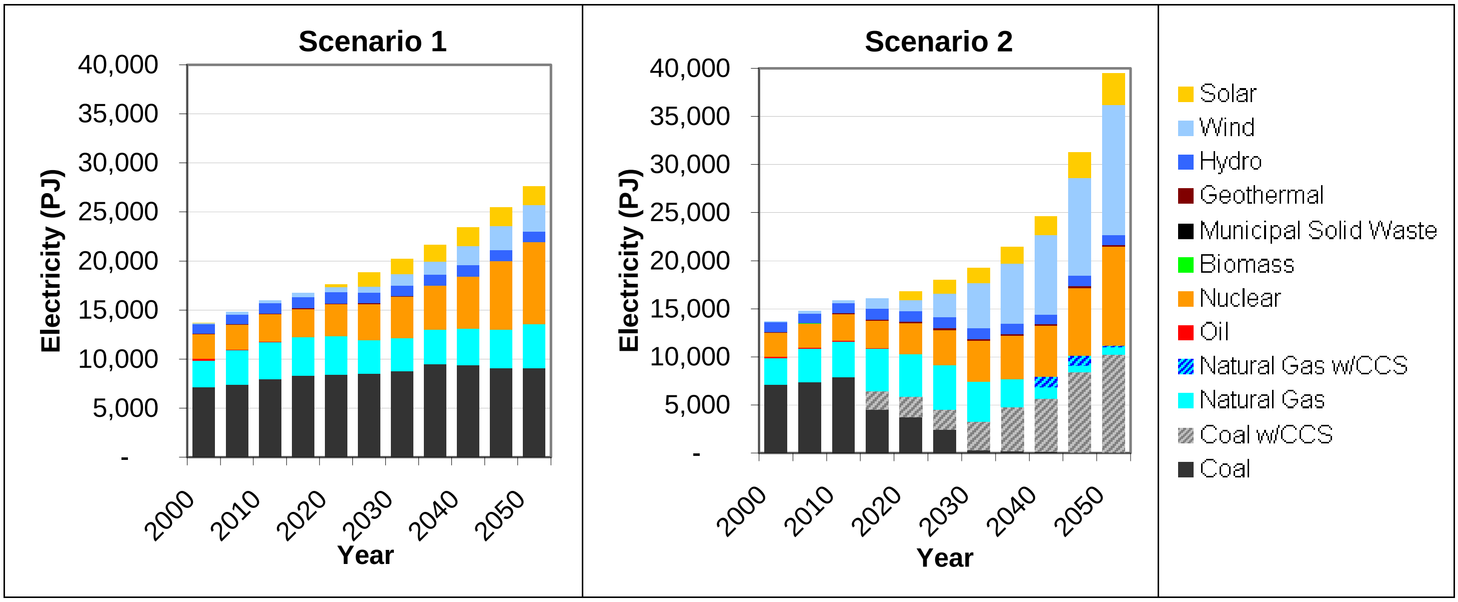
Scenario 1
Scenario 2
Electricity (PJ)
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
-
2000
2010
2020
2030
2040
2050
Year
Solar
Wind
Hydro
Geothermal
Municipal Solid Waste
Biomass
Nuclear
Oil
Natural Gas w/CCS
Natural Gas
Coal w/CCS
Coal

FIGURE 3

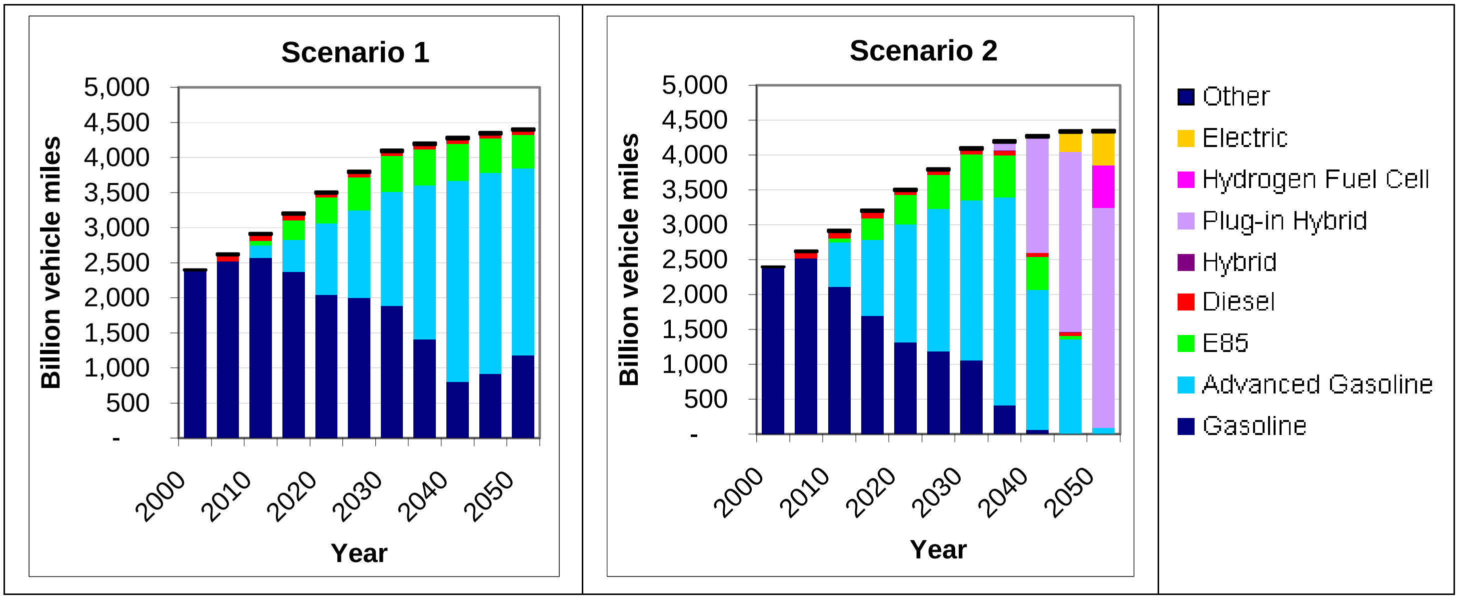
Scenario 1
Scenario 2
Billion vehicle miles
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
2000
2010
2020
2030
2040
2050
Year
Other
Electric
Hydrogen Fuel Cell
Plug-in Hybrid
Hybrid
Diesel
E85
Advanced Gasoline
Gasoline

FIGURE 4

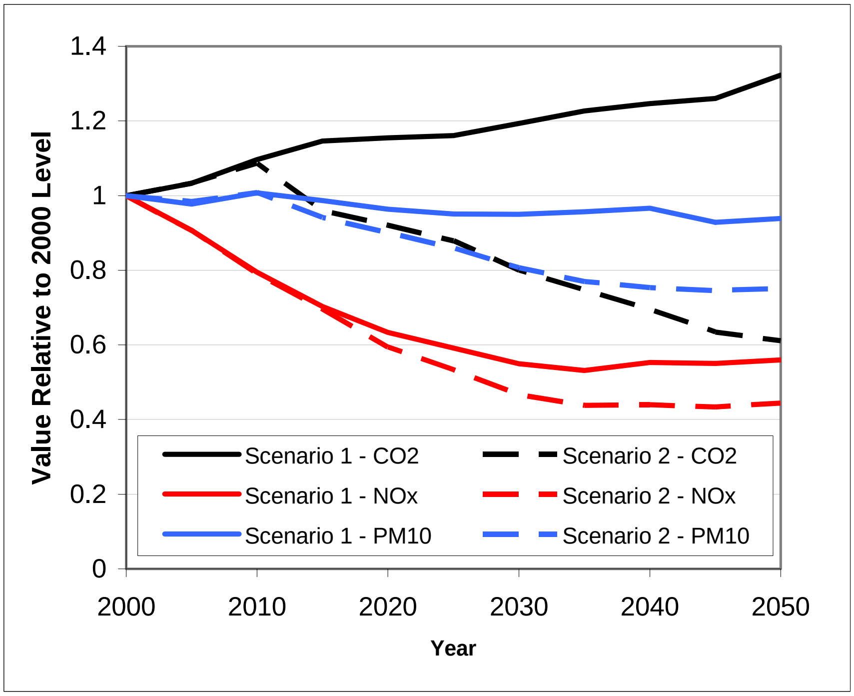
Value Relative to 2000 Level
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2000
2010
2020
2030
2040
2050
Year
Scenario 1 - CO2
Scenario 1 - NOx
Scenario 1 - PM10
Scenario 2 - CO2
Scenario 2 - NOx
Scenario 2 - PM10

FIGURE 5

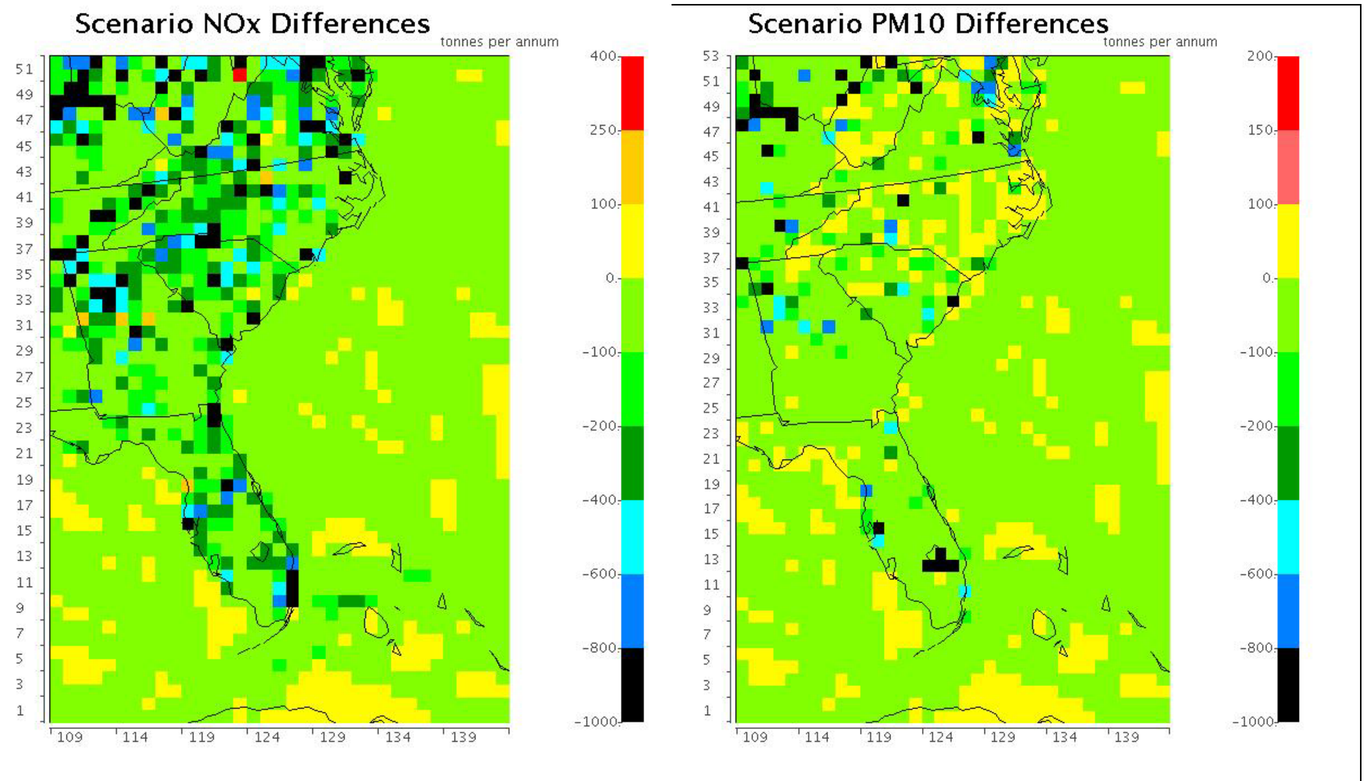
Scenario NOx Differences
tonnes per annum
400
250
100
0
-100
-200
-400
-600
-800
-1000
Scenario PM10 Differences
tonnes per annum
200
150
100
0
-100
-200
-400
-600
-800
-1000

FIGURE 6