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# Modeling framework for exploring emission impacts of alternative future scenarios

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## 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 pollution. We use the MARKAL model to characterize alternative realizations of the US 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 future years through 2050. The approach is demonstrated for two emission scenarios: Scenario 1 extends current air regulations through 2050, while Scenario 2 applies a hypothetical policy that limits carbon dioxide ($CO_2$) emissions from the energy system. Although 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 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 linked to increasing temperature, changes in precipitation patterns, 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 develop and evaluate candidate emission management strategies.





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There is uncertainty inherent in projecting emissions decades into the future because of uncertainties in accurately predicting 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 (e.g., Woo et al., 2008). In contrast, scenario analysis involves the development 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; Weaver et al., 2009). 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 emission 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 emission 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





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paper. From an energy modeling standpoint, the primary contribution of this work is to provide an avenue for geographically allocating regional emissions to a grid. From an air quality modeling perspective, the methodology provides a way to generate internally-consistent emission inputs that conform to assumptions about specific future scenarios.

## 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 ($NO_x$), 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, 2009b, 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 specified 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 US 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 (US DOE, 2006, 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, 2009b), 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 US anthropogenic $CO_2$ emissions and 53% of anthropogenic $NO_x$ 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 US anthropogenic $CO_2$ emissions through direct fuel combustion. Detailed information about industry-specific energy use and technologies is not readily available, thereby 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 $NO_x$ 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 min of computational time, depending on the options that are selected. The regional model, which represents the US at the Census Division resolution, requires 20 to 45 min. A map showing the nine MARKAL regions is shown in Fig. 1. Regionalization





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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 emission projections into state-level, Source Classification Code (SCC)-based emission growth factors (US 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. For area source SCCs, a "2" proceeds the 8-digit structure, while a tenth digit is appended to the end to allow additional specificity. Zeros within SCC codes are interpreted as wildcards. The code 10000000 therefore 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 ($NO_x$, $SO_2$, 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



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later in this section. Since the SCC codes are generally more specific than the categories used to distinguish source types in MARKAL, 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 database does not include full coverage of energy sector pollutant species, growth factors for $CO_2$, $PM_{10}$ and $NO_x$ are used as surrogates for other species. For example, energy system emissions of carbon monoxide (CO), volatile organic compounds (VOC), and ammonia ($NH_3$) for most source categories 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, $NO_x$ 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, 2009c). The resulting economic-



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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; $NO_x$, 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





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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 $NO_x$ 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.





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## 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, $NO_x$ and $SO_2$ emissions from electric generating units in MARKAL's regions 1, 2, 3, 5 and 6 (Fig. 1) were constrained at the regional level 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 $NO_x$ and $SO_2$ from these regions were capped at their 2020 levels. For all regions, new coal-fired boilers were assumed to use low-$NO_x$ 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 $NO_x$ 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





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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 approximately in a 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 recent proposed climate bills, including the Lieberman-Warner Climate Security Act of 2008 (U.S. EPA, 2008) and the American Clean Energy and Security Act of 2009 (U.S. EPA, 2009a). The details of the bills were not modeled, however, so the simulated policy cannot be regarded as representing any specific 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. Emission trading was not modeled explicitly. Since MARKAL optimizes $CO_2$ reductions under a system-wide cap, however, the model is effectively simulating the cost-minimization behavior associated with trading.

The system-wide $CO_2$ emissions for Scenario 1 and the constrained $CO_2$ trajectory for Scenario 2 are shown in Fig. 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, Fig. 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 $NO_x$ and $SO_2$ limit the growth of coal, however, and its market





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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 Fig. 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. Such a rapid transition would face some barriers not represented explicitly in the model, such as the development of a charging infrastructure.

Figure 5 shows trajectories for $CO_2$, $NO_x$, and $PM_{10}$ emissions, normalized to year 2000. $CO_2$ emissions in Scenario 1 increase steadily because of continuing increases in energy demands with only limited drivers for reductions in $CO_2$ intensity. Other pollutant emissions through 2020 follow a decreasing trend, however, driven by air pollution regulations. Scenario 2 also experiences increases in energy demands. $CO_2$ emissions decline in response to the $CO_2$ constraints. Emissions of $NO_x$ 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.



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## 3.2 Calculated emission growth factors

Regional emission growth factors were developed for Scenarios 1 and 2 using the methodology described in Sect. 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 US Census Divisions, respectively. Some of these factors within these tables are similar to the national trends shown in Fig. 2, while others are not, reflecting regional and sectoral differences.

For Region 5 (Table 2), the Scenario 1 results show large reductions in $NO_x$ 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-in hybrid, fuel cell, and electric vehicle technologies.

While the trend is for Scenario 2 to result in emission 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 in 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,





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the growth factors for $NO_x$ 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 modeled $NO_x$ 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 Scenarios 1 and 2 growth factors for 2050 to the base year inventory. The resulting gridded emissions of $NO_x$ and $PM_{2.5}$ for each scenario were then compared. Figure 6 provides an example of the resulting spatial differences (Scenario 2 minus Scenario 1) for Region 5. The greatest differences in $NO_x$ 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.





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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 emission 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., $NO_x$ 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





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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 min 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.

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**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 |





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

| | Scenario 1 | | | Scenario 2 | | | Difference (percent) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $PM_{2.5}$ | $CO_2$ | $NO_x$ | $PM_{2.5}$ | $CO_2$ | $NO_x$ | $PM_{2.5}$ |
| 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 US Census Division; see Fig. 2.





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**Table 3.** EPA MARKAL Region 9* emissions growth factors, 2000–2050, for major energy system emission categories.

| | Scenario 1 | | | Scenario 2 | | | Difference (percent) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | $NO_x$ | $PM_{2.5}$ | $CO_2$ | $NO_x$ | $PM_{2.5}$ | $CO_2$ | $NO_x$ | $PM_{2.5}$ |
| 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 US Census Division; see Fig. 2.



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**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<br>Residential sector<br>Agricultural operations and fugitive dust | Growth factors vary by county in accordance with the ratio of projected population to 2000 population |





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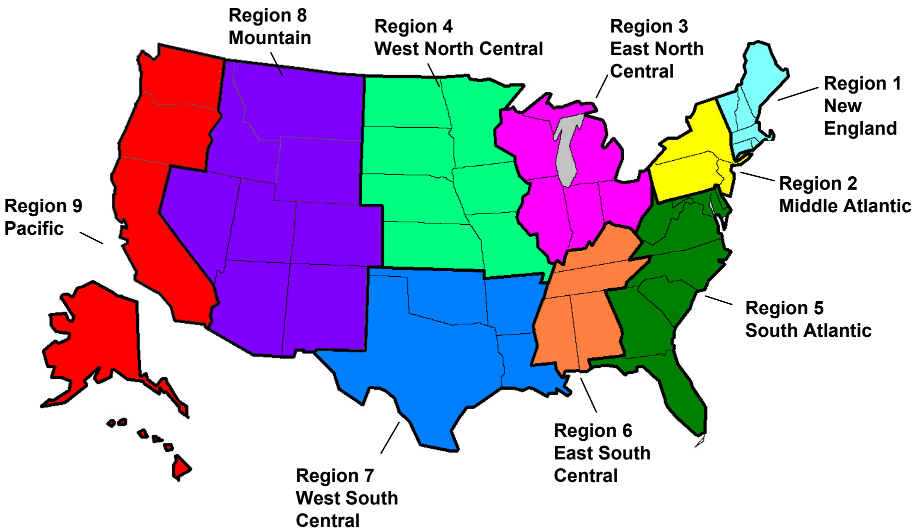


**Fig. 1.** The nine regions used within the U.S. EPA MARKAL database.





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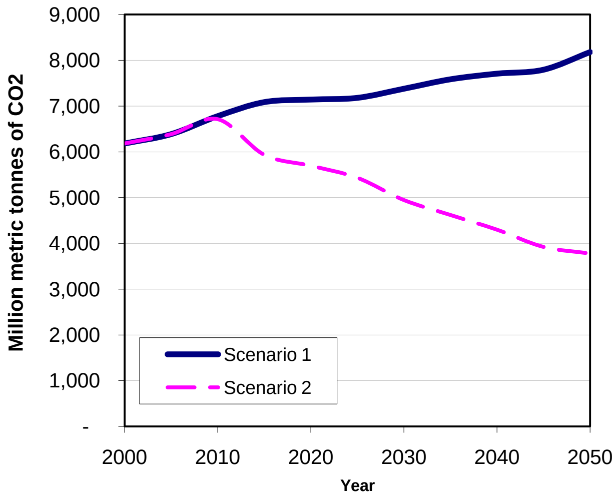


**Fig. 2.** National emissions of $CO_2$ for Scenarios 1 and 2.





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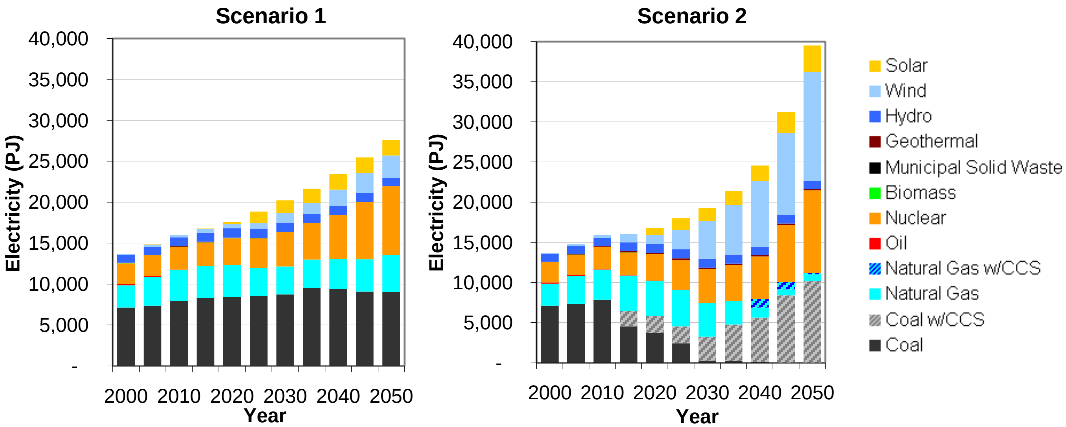


**Fig. 3.** Production of electricity by technology for Scenarios 1 and 2. Formatted for color reproduction only.





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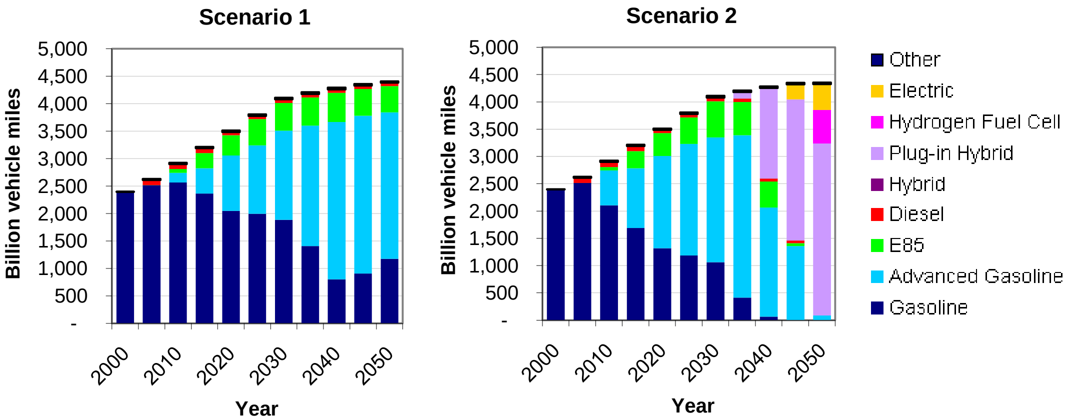


**Fig. 4.** Market share of light duty vehicle technologies for Scenarios 1 and 2. Formatted for color reproduction only.





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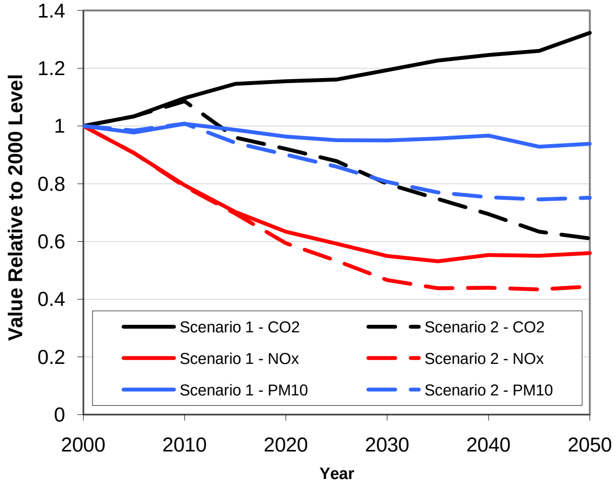


**Fig. 5.** Changes in national emissions of $CO_2$, $NO_x$ and $PM_{10}$, relative to 2000, for Scenarios 1 and 2. Formatted for color reproduction only.





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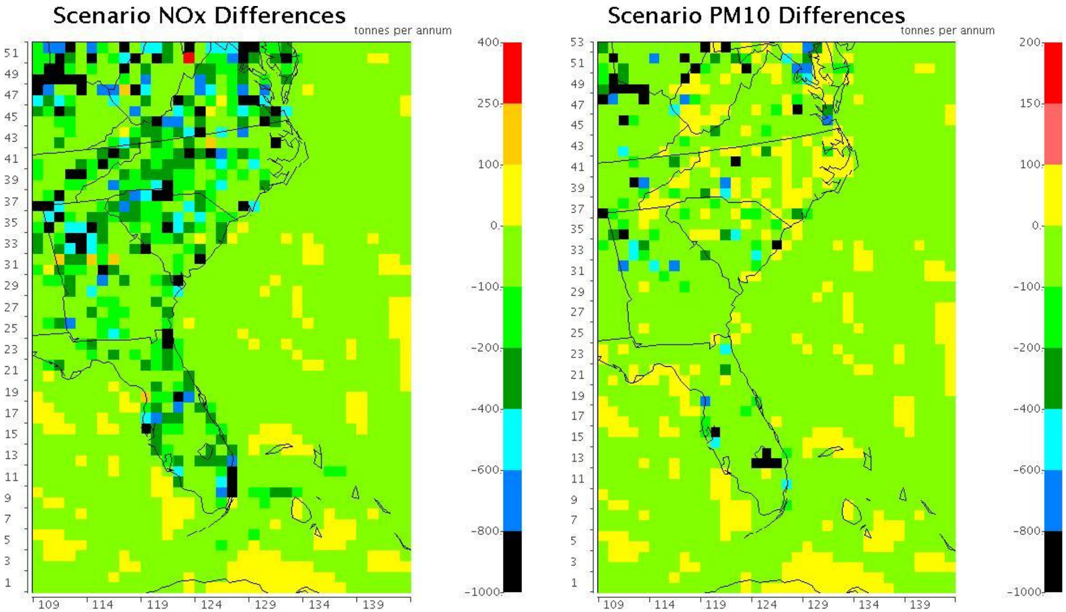


**Fig. 6.** Example gridded plots of scenario differences (Scenario 2 minus Scenario 1) in annual $NO_x$ and $PM_{10}$ emissions for the Southeastern United States. Formatted for color reproduction only.





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