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Effects of recent energy system changes on CO_2 projections for the United States

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Abstract

Recent projections of future United States carbon dioxide (CO_2) emissions are considerably lower than projections made just a decade ago. A myriad of factors have contributed to lower forecasts, including reductions in end-use energy service demands, improvements in energy efficiency, and technological innovations. Policies that have encouraged these changes include renewable portfolio standards, corporate vehicle efficiency standards, smart growth initiatives, revisions to building codes, and air and climate regulations. Understanding the effects of these and other factors can be advantageous as society evaluates opportunities for achieving additional CO_2 reductions. Energy system models provide a means to develop such insights. In this analysis, the MARKet ALlocation (MARKAL) model was applied to estimate the relative effects of various energy system changes that have happened since the year 2005 on CO_2 projections for the year 2025. The results indicate that transformations in the transportation and buildings sectors have played major roles in lowering projections. Particularly influential changes include improved vehicle efficiencies, reductions in projected travel demand, reductions in miscellaneous commercial electricity loads, and higher efficiency lighting. Electric sector changes have also contributed significantly to the lowered forecasts, driven by demand reductions, renewable portfolio standards, and air quality regulations.

Keywords

energy system; energy modeling; emissions projections; carbon dioxide

1. Introduction

Recent U.S. carbon dioxide (CO_2) emission projections are considerably below what was estimated only 10 years ago. For example, in 2005, the U.S. Department of Energy's (DOE) Energy Information Administration (EIA) projected U.S. CO_2 emissions in 2025 to be 8,062 million metric tons (Mt) (U.S. EIA, 2005). Ten years later, EIA estimated 2025 emissions to

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be 5,511 Mt, a 31.6 % reduction (U.S. EIA, 2015). What factors led to this change? The answer may inform future emission reduction efforts – both by helping us more fully understand the factors that have influenced future emission baselines and by identifying additional reduction opportunities.

We applied the MARKet ALlocation (MARKAL) (Loulou et al., 2004) energy system model, using a database representation of the U.S. energy system called the EPAUS9r, to evaluate how various factors contribute to lower projections. This differs from typical energy system modeling applications, which generally involve one of the following: developing scenarios of the evolution of the energy system and estimating the resulting emissions into the future (e.g., IPCC 2000, Clarke at al., 2007, IEA 2015b); identifying least cost technology pathways to meet air pollutant and greenhouse gas reduction targets (e.g., GEA 2012, IEA 2015a, IPCC 2014); and, evaluating the energy and emissions implications of specific energy technologies for various policy scenarios (e.g., Sweeney et al., 2005, Loughlin et al., 2012).

Energy system models are also sometimes used in retrospective analyses. In one type of retrospective application, past energy and emission forecasts are compared to the historical record to evaluate how well the forecasts predicted observed conditions (e.g., EEA 2011, US EIA 2015b, Zafeiratou and Spataru 2014). Alternatively, contemporary energy system models can be used to re-develop forecasts over the historic period (Beckman et al., 2011), which can be then used for model evaluation and validation.

The approach presented here is most similar to this second type of retrospective analysis. However, instead of evaluating the forecast against real-world data for an historic year, we use MARKAL to produce a set of 2025 emission forecasts. The set includes a 2025 Reference Case projection, as well as sensitivity runs in which a subset of the energy system transformations of the past 10 years are backed out individually and in combination. This sensitivity analysis allows us to associate reductions in CO_2 emissions forecasts to specific post-2005 energy system changes and the underlying factors that are driving those changes.

2. Background

We define the U.S. energy system as encompassing all of the processes, fuels, and technologies that meet the country’s demands for energy. Thus, the system includes resource extraction, electric power production, refining, manufacturing, construction and agriculture, as well as the technologies that meet lighting, space conditioning, transportation, and other demands. Defined as such, the energy system has many environmental impacts. For example, fuel combustion is the primary anthropogenic source of U.S. greenhouse gas and air pollutant emissions (U.S. EPA 2016a). Furthermore, electric power production is responsible for 38 % of freshwater withdrawals and 45 % of all water withdrawals (Maupin et al., 2014). Here, we focus on CO_2 emissions, but the approach could be extended readily to examine additional environmental metrics.

Societal demands for energy have historically been highly correlated with population and economic growth (U.S. EPA 2016a). Considering these factors in isolation, our growing energy demands would yield increasing emissions. However, many other factors also influence energy and emissions. Population migration across the U.S. and climate change, for example, can increase or decrease heating and cooling demands. Land use change and urbanization can impact driving patterns and household energy footprints. Also, the desire to lower energy expenses can result in energy efficiency improvements. Conversely, a proliferation of electronic gadgets or electric vehicles would increase demands for electricity. Energy and emission trends can also be influenced by environmental, climate and energy policies and regulations.

Evaluating the net effect of these various factors is very complicated. One approach is to represent the energy system within a computer model, providing a computational laboratory for exploring the evolution of the energy system and the resulting emissions through time. A number of such models have been developed, including the National Energy Modeling System (NEMS) (U.S. EIA, 2009a), MARKAL (Loulou et al., 2004), the Global Change Assessment Model (GCAM) (Kim et al, 2006), and the Applied Dynamic Analysis of the Global Economy (ADAGE) model (Ross, 2008).

These models can be used to develop baseline energy and emission projections based on a single set of input assumptions. They also are often applied within parametric sensitivity and scenario analyses to explore alternative assumptions. In parametric sensitivity analyses, inputs to the model are varied from their baseline values individually or in combination. The sensitivity of the model outputs to these input changes can then be assessed (Saltelli et al., 2004). Scenario analyses also involve modifications to model inputs, but typically seek to find more extensive combinations of inputs that represent a range of diverse but plausible conditions (Schwartz, 1996; Gamas et al., 2015).

One of the most well-known projections of the U.S. energy system is the Annual Energy Outlook (AEO), developed by EIA using NEMS. EIA, which has been releasing forecasts of the energy system since 1979, states: “Because of the uncertainties inherent in any energy market projection, the Reference case results should not be viewed in isolation” (U.S. EIA, 2015a). To address uncertainty, EIA also releases alternative scenarios that accompany the AEO Reference Case. These scenarios explore a wide range of situations, such as more rapid technology improvements and high oil prices.

The underlying data and assumptions in the AEO Reference Case are often used by other groups in projecting energy demands and emissions, as well as in developing, calibrating, and providing boundary conditions for other modeling exercises. For example, AEO electricity demands are used as input to the Integrated Planning Model (U.S. EPA 2013b) in U.S. EPA regulatory impact analyses.

The AEO Reference Case thus receives considerable attention, including within retrospective analyses. For example, O’Neill and Desai (2005) assessed the accuracy of past AEO projections of energy consumption and found that they are relatively accurate within a time horizon of less than 10 years, under-projecting by approximately 2 %. However, the errors climb to 4 % beyond that time horizon. Furthermore, energy intensity assumptions are over-projected by 3–7 % in the shorter time frame and under-projected by 10–20 % when the time horizon goes beyond 10 years. In the AEO projections reviewed by O'Neill and Desai, the under-projected energy intensity assumptions are offset to a large degree by an over-projection in Gross Domestic Product (GDP). Winebrake and Sakva (2006) took the analysis further to look at projection errors in the individual sectors. They found that while the overall consumption numbers vary only slightly from actual, there were much larger, often off-setting, differences in the end-use sectors. For example, the transportation sector was systematically underestimated while the industrial sector was overestimated.

Other researchers have also assessed projection uncertainties and bias. Bezdek and Wendling (2002) noted that "even the most sophisticated energy forecasts are strongly influenced by events and trends of the time of the forecast." They provide the example that projections made in the 1970s and early 1980s, influenced by the oil crisis, predicted dramatic increases in oil prices that did not come to pass. Craig et al. (2002) observed the importance of documenting assumptions, of not assuming fixed human behavior, and of using a set of scenarios to improve the usefulness of projections being provided to decision makers.

As uncertainties are realized, new knowledge is incorporated, and the modeling platform is improved, CO_2 projections change from one release of the AEO to another. These changes can be dramatic, as shown in Figure 1 below, in which CO_2 projections from every other AEO annual release since 2005 are plotted.

EIA periodically releases documentation describing changes in assumptions and methodology from the previous year AEO (e.g., U.S. EIA 2015c). Comparing these assumptions provides information that can be used to identify some of the drivers leading to projection changes in CO_2 emissions. The assumptions document does not indicate the effect of each individual assumption, however.

3. Approach

We use an energy system model to evaluate how energy system changes made after the release of AEO2005 have affected the AEO2015 reference case projection. Our focus is on the year 2025, which is the last projection year that both AEO2005 and AEO2015 have in common.

Our experimental design involves iteratively backing out individual and combinations of various post-2005 energy system changes. The general approach is illustrated in Figure 2. The solid black line represents the AEO2005 projection. Our modeled Reference Case using the EPAUS9r database, the solid grey line, approximates AEO2015. Backing out a single post-2005 energy system change, "x", from the database yields a line such as the dashed black line. Thus the quantitative impact of this factor can be approximated and compared to others. Backing out all modeled post-2005 changes simultaneously produces the dashed grey line, which represents our attempt to revert the EPAUS9r database to AEO2005 assumptions. The difference between the grey and dashed grey lines provides an estimate of how much of the difference between the AEO2005 and AEO2015 projections can be explained by the post-2005 changes included in our analysis.

Instead of using the NEMS model itself to back out the changes, we use MARKAL and EPAUS9r, which is largely derived from inputs to NEMS. This combination results in a linear programming formulation with a runtime of approximately 1 hour on a typical desktop computer. In contrast, NEMS would require 6 to 12 hours per run (U.S. EIA 2016). Using a simplified representation has tradeoffs, however. For example, demands for energy services are assumed to be inelastic to the cost of meeting those services. Therefore, in our MARKAL formulation, the quantity of lumens needed for lighting, the watts per square meter needed for heating, and the vehicle miles traveled needed for passenger transportation would not be reduced endogenously if the costs of meeting those demands increased. The technologies that MARKAL selects to meet these demands could become more efficient, however, as the model seeks to minimize the net present value of total energy system costs. Other limitations of the MARKAL framework include the assumption of linearity which may not capture some of the dynamics of the system, the lack of a representation of technological learning which could reduce the costs of new technologies as they increase their market penetration, and the lack of feedback from economic activity like changes in GDP.

The following subsections describe the MARKAL model and database, as well as the methodology for their use here.

3.1. Model

MARKAL is a technology rich, bottom-up linear optimization model that solves for the least-cost technological and fuel pathway for meeting the energy demands while simultaneously taking into account constraints such as emissions limits and available energy resources. It was originally developed in the 1970s and has undergone continued development since that time. A number of country specific and multi-national databases have been developed for use with MARKAL and have been applied to wide ranging applications such as assessments of carbon mitigation strategies (Chiodi et al., 2013; Lu et al., 2016; Reikkola et al., 2011), analyses of the impacts of sectoral changes on the total energy system (Dodds, 2014; Nichols and Victor, 2015; Rosenberg et al., 2010), and the air quality impacts of technology change (Brown et al., 2013; MacKinnon et al., 2016; Rudokas et al., 2015). Trutnevyte et al. (2016) included the UK MARKAL in a retrospective review of energy projections. The authors are not aware of any applications in which MARKAL was used to evaluate the factors underlying how future projections have changed.

The EPAUS9r database is used to tailor MARKAL to the U.S. energy system. Many of the important database assumptions for this analysis are documented below. The full set of assumptions are detailed in the database documentation (Lenox et al., 2013). The EPAUS9r represents resource supply extraction and import, refinery and electric power sector conversion technologies, and residential, commercial, transportation, and industrial end-use sector technology choices, efficiencies, and demands. The database covers a time horizon stretching from 2005 to 2055 in 5-year increments. Spatial resolution is the 9 U.S. Census Division level. Regions can interact with one another by trading electricity and other energy resources such as coal and natural gas.

We use a modified version of the database, the EPAUS9r_v14.1.5. The database includes resource supply curves, technology costs and efficiencies, and end-use demands that were drawn primarily from the AEO2014 (U.S. EIA, 2014). Subsequent modifications to the database were made to reflect some of the key aspects of AEO2015, including updated costs for wind and solar power in the electric sector, updated projections for solar photovoltaic installations in the buildings sector, and updated cost and efficiencies for light-duty vehicle technologies.

Along with technology costs and efficiencies and resource supply curves, the EPAUS9r includes technology- and fuel-specific emission factors. Emissions factors are obtained from a number of sources, including the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (U.S. EPA, 2013a), EPA WebFire emission factor database (U.S. EPA, 2014a), National Emissions Inventory (U.S. EPA, 2014b), Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA, 2015a), and Argonne National Laboratory’s Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model (Wang, et al., 2007).

In addition, the database includes representations of a variety of air pollution and energy efficiency policies and regulations. For example, the database includes constraints to approximate the Clean Air Interstate Rule (CAIR) (Federal Register, 2005; U.S. EPA, 2004) and the Mercury Air Toxics Standards (MATS) (Federal Register, 2011; U.S. EPA, 2015c). The transportation sector includes constraints intended to reflect the National Highway Traffic Safety Administration (NHTSA) and EPA joint rulemaking to establish vehicle Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) emissions standards from 2012 to 2016 (Federal Register, 2010) and the later model year GHG and CAFE standards for light-duty vehicles (Federal Register, 2012). Also, air pollutant emission factors account for the Tier 3 mobile source emission standards (U.S. EPA, 2014c). State-level Renewable Portfolio Standards (RPSs) are approximated by aggregating their requirements to the regional level. These various policies and regulations are included in the Reference Case used in the analysis presented here. The Reference Case does not include a representation of the Clean Power Plan (CPP) (U.S. EPA, 2015b) since the AEO2015 Reference Case also did not include the CPP.

The formulations used to approximate various policies and regulations are limited by the temporal and spatial resolution of the MARKAL model and database. For example, CAIR introduces state-level budgets, or caps, on electric sector NOx or SO_2 emissions for thirty states. Since the resolution of the database is the census region, these state-level budgets must be mapped to regions. The regulated states do not necessarily match each U.S. Census Division, and assumptions must be made about how to handle regions with some states that have limits and others that do not. With such simplifications, there are unavoidable discrepancies between MARKAL results and the regulatory development and assessment modeling activities that utilize more detailed sector-specific models, such as the EPA Power Sector Modeling Platform (U.S. EPA, 2013b) and the MObile Vehicle Emission Simulator (MOVES)(U.S. EPA 2015d).

Even so, the set of input assumptions for fuels, technologies, and demands, along with the representation of the policies and regulations detailed above, result in a Reference Case model run that closely aligns with the AEO2015 predicted fuel use, technology penetration, and emissions out to the year 2040. This Reference Case database is the starting point for the sensitivity runs detailed below.

3.2. Sensitivity Runs

In this parametric sensitivity analysis, various sectoral input values are perturbed from the baseline values in the MARKAL Reference Case. This includes changes in the electric, building, transportation, and industrial sectors. The perturbations back out specific technology- and policy-related energy system changes that occurred between 2005 and 2015.

Two sets of runs were evaluated. The first set involved a series of runs evaluating the overall effects of the changes in the different sectors, where the changes in individual sectors were run by themselves and in combination with one or more of the other sectors. In the second set of runs, the changes within specific sectors were disaggregated to explore their impacts. For each run, energy system CO_2 emissions were recorded. A list of the perturbations made to approximate the AEO2005 view of the world is given in Table 1, and a detailed discussion of the perturbations made follows below.

3.2.1. Electric Sector Changes—Between 2005 and 2015, a number of factors have had a direct effect on the way the electric sector is evolving. Many of these factors are related to the adoption of energy policies, such as state-level RPSs, and air quality regulations, including CAIR and MATS. Concurrently, there have been changes in the availability and price of fuels, as well as rapidly declining renewable costs and escalating construction costs for coal and nuclear plants. Here, we focus on examining the impacts of policies and regulations since 2005 as opposed to changes in fuel and technology costs. Air quality regulations are lumped together as their development and implementation were highly dependent upon each other.

Perturbations related to each are discussed below. Runs involving removal of all of these perturbations are referred to as having “2005 Electric” or as having no “Post-2005 Electric Sector Regulations.”

RPS: In the late 1990s, states and counties began to implement standards requiring a minimum percentage of electricity generation that must come from either a subset or the full range of renewable generation options. Today there are 29 states with a RPS in place. In the Reference Case, the electric sector has a set of regional constraints that represent these state RPSs aggregated to the regional level. The data were drawn from the U.S. Department of Energy’s Database of State Incentives for Renewables and Efficiency (DSIRE, 2010). In 2005 the number of states with an RPS was significantly lower and many of the standards did not come into play until later on the time horizon; therefore, we represent a state of the electric sector without any RPS constraints and refer to these runs as having “No RPS.”

Air Quality Regulations: The Reference Case includes representations of CAIR, and MATS. We use simplified representations that are derived from the emission results of other models (e.g., U.S. EPA 2004), but do not include all of the technical details of the regulations. As mentioned previously, aggregation of emission constraint to the U.S. Census Regions also introduces uncertainty. Information about regulations follows.

CAIR, which was finalized in March 2005, was designed to improve air quality by bringing deep reductions to NO_x and SO_2 emissions from the electric power sector, both of which contribute to the formation of fine particles. NOx also contributes to the formation of ground-level ozone. CAIR has recently been replaced by the Cross-State Air Pollution Rule (CSAPR), but this change was not in place at the time the EPAUS9r version 14.1.5 was developed. Similarly, AEO2015 includes a representation of CAIR instead of CSAPR. CAIR is parameterized through a set of regional constraints on the NO_x and SO_2 emissions allowed from the electric sector.

The MATS rule was finalized in December 2011. The rule placed technology-based limits on mercury and other pollutants, including $PM_{2.5}$. MATS is parameterized through a set of regional $PM_{2.5}$ and SO_2 control requirements, both of which have been shown to be effective for reducing mercury emissions.

We represent the 2005 electric sector air pollutant regulations by removing the representations of the CAIR and MATS, and refer to these runs as “No Air Quality.”

3.2.2. Buildings Sector Changes—Between AEO2005 and AEO2015, the projected energy intensity for the residential and commercial buildings in the year 2025 had dropped by 8 % and 19 %, respectively. For this analysis, we backed out changes in buildings that led to the greatest reductions in energy use from AEO2005 to AEO2015, including increased efficiency in lighting, space conditioning, commercial office equipment, and miscellaneous commercial energy demands. Runs that back out all of these changes simultaneously are referred to as “2005 Buildings.” Each type of perturbation is described below.

Lighting: In the AEO2015, lighting accounts for over 6 % of the projected energy use in buildings in 2025. Over the past ten years, the AEO projection for lighting-per-square-foot in 2025 has declined over 50 % in residential buildings and over 35 % in commercial buildings. This decrease is attributable primarily to the lighting standards put into place by the 2007 Energy Independence and Security Act (EISA) (HR6 2007). The standards required incandescent lights to reduce wattage 28 % by 2014, and 65 % by 2020 (U.S. EIA, 2008), which also led to increasing competition from compact fluorescent lightbulbs (CFLs) and light-emitting diodes (LEDs). Runs labeled as having “2005 Lighting” have the lighting efficiency to pre-EISA levels and do not have LEDs as an end-use technology option.

Space conditioning: In the AEO2015, space heating and cooling demands account for 37.4 % of the projected energy use in the buildings sector in the year 2025. These demands have changed as the weather has warmed and the population has migrated south and west (U.S. EIA, 2008). AEO projections of space cooling per square foot in 2025 have increased over 30 % in residential buildings and over 11 % in commercial buildings. The higher increase in residential cooling is also due in part to an increase in homes with central air systems (U.S. EIA, 2006). In contrast, projections for space heating per square foot in 2025 have decreased almost 20 % in residential buildings and 5 % in commercial buildings. The runs labeled as having “2005 Heating,” and “2005 Cooling” set the respective space conditioning per square foot trends back to the AEO2005 levels.

Office equipment: In the AEO2015, commercial office equipment accounts for 1.6 % of the projected buildings energy use in 2025. AEO2005 predicted that energy use for office equipment would have an annual growth of 3.8 % from 2012 through 2025. AEO2015 predicts an annual decrease over that same period of 0.3 %. This change in use is due to a number of factors including an increase in the purchase of Energy Star compliant products, reductions in computer processor power requirements, and a shift from desktop systems to mobile devices (U.S. EIA, 2014). Runs labeled as having “2005 Office Equipment” have an annual growth rate on commercial office equipment set to the 2005 levels.

Miscellaneous electricity demands: In the AEO2015, miscellaneous commercial energy use accounts for 19 % of the projected buildings energy use in 2025. This commercial energy use includes energy demands for distribution transformers, water use, kitchen ventilation systems, laboratory refrigerators and freezers, and medical imaging machines. A 2011 study done by Navigant Consulting for IEA (2013) analyzed the top contributors to this miscellaneous category and found that a number of new and proposed efficiency standards and the replacement of older equipment with newer, more efficient versions would lead to an overall improvement in the energy demands for these items. The projected average annual increase in demand for miscellaneous electricity use from 2012 to 2025 dropped from 3.3 % in AEO2005 to 2.6 % in AEO2015. Runs labeled “2005 Miscl. Commercial” set miscellaneous commercial energy use back to the projected levels and annual growth in AEO2005.

3.2.3. Transportation Sector Changes—The analysis modeled two different representations of the transportation sector. Between AEO2005 and AEO2015, the projected energy use for the transportation sector in 2025 dropped 34 %. For this analysis we looked at four changes in the transportation sector that contributed to this reduction: improvements in light- and heavy-duty vehicle efficiency, and reductions in light- and heavy-duty vehicle miles traveled. Runs labeled “2005 Transportation” adjust each of these factors to align more closely with AEO2005. Each change was also evaluated individually.

Vehicle efficiency: Over the past ten years, the AEO projection for 2025 average light-duty vehicle (LDV) stock efficiency has increased 37 %, from 21.0 mpg to 28.7 mpg due primarily to CAFE and GHG tailpipe standards, which now require car manufacturers to meet a projected average fleet efficiency rating of 54.5 mpg for new vehicles by 2025 (Federal Register 2012a). During the same time period, the AEO projection of 2025 heavy-duty vehicle stock efficiency has increased from 8.6 mpg to 10.1 mpg, or 17.4 %. Heavy-duty efficiency improvements are due to NHTSA reforms to CAFE for light trucks published in August 2005 and new standards promulgated in the Heavy-Duty (HD) national program. The runs labeled “2005 LDV Efficiency” and “2005 HDV Efficiency” assume fleet average efficiencies for both light- and heavy-duty vehicles that match the AEO2005 projections.

Travel demand: AEO2005 projected that light-duty vehicle miles traveled (VMT) would grow continuously at an average annual rate of 2 %. But in reality, VMT leveled off between 2008 and 2012, then began climbing again at a projected annual rate of only 1.4 %. The leveling off occurred due to higher fuel costs and the economic downturn. The slower rise since then is based on demographic studies which show that there has been a decrease in licensing and travel among younger age groups, while the total driving pool also includes a larger proportion of older drivers who tend to drive less (U.S. EIA, 2014). Heavy-duty VMT dropped in 2008 and 2009 due to the economic downturn, but subsequently has seen a small increase due to the recovery and increases in industrial output. Runs labeled “2005 LDV VMT” and “2005 HDV VMT” utilize projected growth trends from AEO2005.

3.2.4. Industrial Sector Changes—Runs labeled “2005 Industry” incorporate modifications that include selected industrial demands and roll back motor efficiency to reflect AEO2005 projections. Each is described below.

Industrial demands: Growth in domestic resources of natural gas and natural gas liquids have led to an expansion in several U.S. manufacturing industries, including a 58 % increase in energy demand in 2025 for iron and steel and a 72 % increase in energy demand for bulk chemical feedstocks. However, reductions in mining energy use have led to reductions in energy demand of 33 % in the non-manufacturing sectors.

Motor efficiency: EISA 2007 set standards for industrial electric motor efficiency. These standards have led to improvements in the overall efficiency of the industrial sector.

Considering runs with aggregated industrial, transportation, and buildings perturbations, a total of 11 sensitivity runs were made. An additional 11 sensitivity runs were made to investigate the response to non-aggregated changes, such as “2005 Lighting” and “2005 LDV Efficiency.” Results of all runs are summarized in the next section.

4. Results

MARKAL produces estimates of energy system fuel use, technology adoption, and emissions through 2055. Figure 3(a) shows sectoral CO_2 emissions for the Reference Case, and Figure 3(b) shows results for the case with all post-2005 changes omitted, referred to as EPAUS9r_05. In these graphs, emissions resulting from the production of electricity for use in the end-use sectors is accounted for in the electric power production sector. Figures 3(c) and 3(d) represent these same model runs, but the electric sector CO_2 has been apportioned to the sectors by how much electricity each used. These emissions are represented by the hashed areas on the graph. The total CO_2 ascribed, then, to each sector is the total of the solid area and the hashed area of the chart.

Comparing Figure 3(a) and 3(b) highlights the importance of post-2005 transportation and electric sector changes in reducing projections. Table 2 illustrates the importance of these sectors by showing the underlying sectoral emissions data for 2025, and the percentage each sector changed from (a) to (b).

Apportioning CO_2 from electricity to end-use sectors, however, highlights the contribution of the end-use sectors to those electric sector reductions. While the buildings sector contribution appears small in Figures 3(a) and 3(b), its contribution is considerably more prominent in Figures 3(c) and 3(d). In (c) in 2025, the industrial and buildings sectors produce 18 and 10 % of system-wide CO_2, respectively. In (d), however, the sectors' contributions rise to 23 and 33 %, respectively. This change in contribution percentage is due to both changes in electric sector emissions intensity and reductions in use in those sectors.

The difference in total emissions between the two cases was 1,690 Mt, which is 66 % of the total CO_2 emissions decrease of 2,551 Mt between the AEO2005 and AEO2015 projections. This result indicates that the post-2005 changes outlined in Section 3 may explain approximately two-thirds of the difference between AEO2005 and AEO2015 projections.

Next, we examine how post-2005 changes in each sector individually and in combination affect system-wide CO_2. Table 3 shows the 2025 total system CO_2 emissions for the subset of model runs involving sector-level changes.

By omitting each sector's post-2005 changes individually, the impacts of electric, industry, buildings and transportation changes on reducing 2025 projections were estimated to be 6 %, 1 %, 8 %, and 16 %, respectively. Interestingly, when multiple sector changes are omitted together, their combined impacts are approximately additive. For example, backing out post-2005 electric and transportation sector changes resulted in an increase of 21 %, roughly equivalent to the sum of each sector's impact. MARKAL is a sectoral model, and sectors interact during model runs. Changes in fuel use in one sector could lead to changes in another. An emissions reduction in one sector could lead to an emissions increase in another. For example, and large increase in electric vehicles would reduce the CO_2 emissions from the transportation sector, but would also lead to an increase in electricity production and CO_2 emissions from the electric sector. The post-2005 changes that we addressed in this analysis do not appear to have resulted in any interactions that changed the results in sectors other than the one being addressed. The large reductions in electricity use in the buildings sector did not lead to an uptake of electricity in other sectors. The removal of RPS requirements in the electric sector did not lead to an increase in the use of less expensive electricity in the buildings sector. The improvement in vehicle efficiencies in the transportation sector were met primarily through improvements in gasoline powered vehicles; there was not an uptake of electric vehicles which affected electricity production. Even as late as the AEO2015, electric vehicles were not projected to have a huge penetration in the light-duty vehicle market.

Next, sector responses were disaggregated to examine specific sub-sector changes. Figures 4, 5 and 6 show the contributions of individual components of the transportation, buildings and electric sectors, respectively.

The effect of the CAFE standard on changes in the efficiency of light-duty vehicles had the greatest impact on 2025 CO_2 emissions. A similar impact came from the change in light-duty vehicle VMT. The heavy-duty vehicles had much smaller changes in both efficiency and VMT and therefore had less of an impact on CO_2 emissions.

In the buildings sector, the changes in efficiencies and demands in miscellaneous commercial electricity use had the greatest impact on CO_2 emissions, followed by lighting, and commercial office equipment. It is a challenge to know how much of the change in demand for miscellaneous commercial electricity is due to actual changes in the efficiency of equipment and how much results from changes in how demand is calculated from older to more recent AEOs. Building space cooling demand has a negative signal since this demand has grown faster than past projections.

In the electric sector, removal of post-2005 RPSs and air quality regulations each produced a 3 % increase in CO_2 system-wide emissions.

Discussion

Of the 31 % reduction in system-wide CO_2 emissions from result (b) to result (a) in Table 3, changes in transportation sector emissions accounted for more than half. This response is not surprising as both the VMT reductions and the more stringent CAFE standard directly reduce fuel use and the corresponding emissions.

Table 3 indicates that the building sector was responsible for a little more than a quarter of the 31% reduction in the 2025 projection. This is a result of the overall building sector electricity demands decreasing by more than 25 % from the EPAUS9r_05 case to the Reference Case.

From Table 3, electric sector changes resulting from CAIR, MATS, and state RPSs, produced approximately one-fifth of the 31% CO_2 reductions. Roughly half of this fraction can be attributed to the RPSs, and the other half to the technology and fuel changes made to meet air quality regulations.

The post-2005 changes addressed in this model were not regionally specific, with the exception of the RPS’s and air quality regulations looked at in the electric sector. All regions received the same changes in demand and efficiency trends, therefore we focused on results at a nationally aggregated level. Some of the system-wide impacts that were analyzed represent real-world changes that were observed between 2005 and 2015, including improvements to vehicle and lighting efficiencies, increases in renewable generation in the electric power sector, and the adoption of emissions reduction policies like CAIR, MATS, and CAFE. However, some of the emission improvements in 2025 came from changes in assumptions about the future, such as whether the observed trend of increasing VMT per person would continue. Other emission changes come from methodological changes, such as in how miscellaneous commercial electricity demands are calculated. Methodological and demand-driven changes may continue out to 2025, potentially altering the CO_2 projections even further.

While the results bear out that we examined many of the most important energy system changes over the past ten years, an important caveat is that there were additional changes that we did not have the resources, data, or readily available modeling tools to examine. For example, we did not look at larger economic changes, such as the trends in primary fuel prices, changes in imports and exports, the effects of tax credits, or recent dramatic price decreases for solar power. We also did not look at the expansion of domestic natural gas resources resulting from increased access to shale gas. All of our scenarios are run with current projections of natural gas price and availability. There have been other large scale efforts to look at the transition in the natural gas markets (Huntington 2013), and the 2005 AEO actually had very comparable natural gas prices and natural gas use levels to the values assumed in the AEO2015.

Additional changes that we did not address include appliance efficiency improvements and state-level appliance standards, the implementation of Tier 2 and Tier 3 light-duty emissions standards, changes in housing stock and commercial floorspace, and changes in consumer behavior. We also did not include the reductions that could come from the implementation of the CPP. Further insights could be gained by doing an analysis that takes into account these additional changes. Future work could also be done to explore geographically specific emission reduction policies and the effects of trend reductions (i.e. a reduction in light-duty vehicle miles traveled) at a regional scale given population migration trends.

5. Conclusions

Recent projections of U.S. CO_2 emissions report trajectories that are considerably lower than projections made just ten years ago. Reviewing past and current modeling assumptions provides information about what has led to this change. We apply an energy system model, MARKAL, to explore and quantify emission changes due to specific changes in the energy system over the past 10 years. A wide range of factors was explored in this analysis, including sectoral energy efficiency improvements, changes in travel demand projections, and the introduction of policies that drive technology- and fuel-switching in electricity production.

Of the sector changes examined, changes in transportation brought about the greatest reduction in the 2025 CO_2 forecast, representing approximately half. The tightened CAFE standard on light-duty vehicles and reduced light-duty travel demand were two important reasons behind this result. The buildings sector provided a quarter of the overall reductions, with Miscellaneous office equipment, lighting and office equipment having major roles. The electric sector provided a fifth of the overall CO_2 reductions, six to seven times those of the industrial sector.

Through these results, we are able to understand more fully the factors that have led to reduced CO_2 forecasts. Most of these factors would have been impossible to predict and model in 2005. These past 10 years have brought an economic downturn and subsequent recovery, the rise in domestic natural gas and oil, and policies that are driving technological advances such as the switch to LED lighting. None of these were incorporated into AEO2005 because they were not known at the time. Furthermore, just as the 2025 forecast has changed from 2005 to 2015, we can expect that 2025 emissions may be very different from what we project today.

This result does not negate the utility of forecasts. Instead, it emphasizes the need to think about forecasts from a scenario perspective, examining a wide range of plausible outcomes and understanding what factors could push future emissions in different directions. Further emphasizing the utility of a scenario-based approach are the large number of factors and assumptions that changed just between 2005 and 2015. Since these changes were not known or anticipated in 2005, a typical parametric sensitivity analysis conducted in 2005 may have had limited value. In contrast, a scenario analysis, organized around key uncertainties and involving very different realizations of the future, could provide broader insights regarding relationships among sectors and policies.

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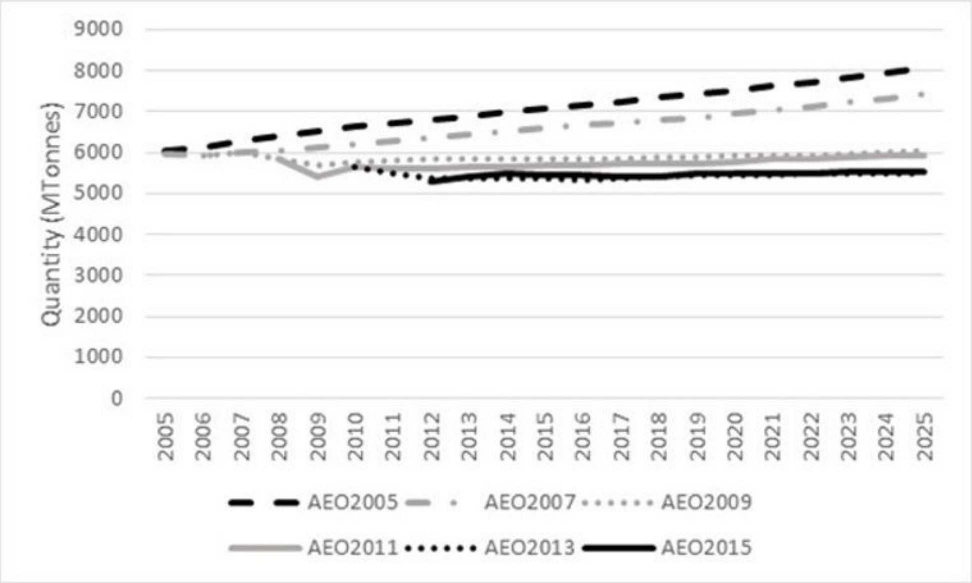

Fig. 1.

Projected total system CO2 emissions (MTonnes) from every other Annual Energy Outlook: 2005–2015

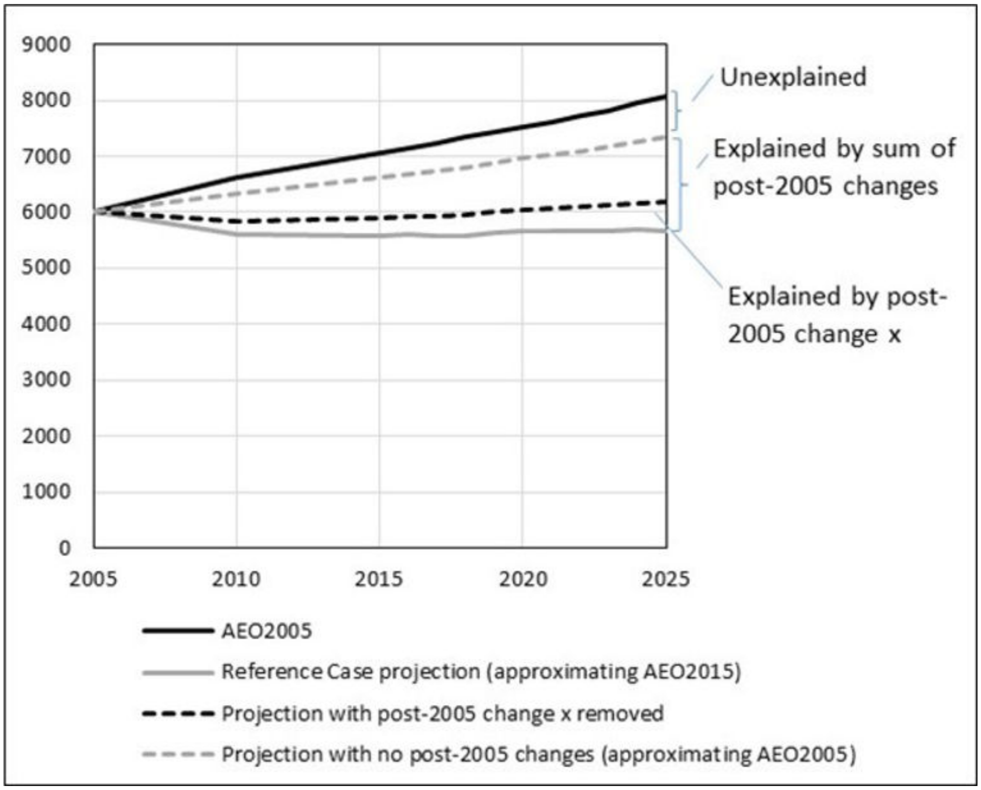

Fig. 2.

Conceptual diagram of total system CO_2 emissions indicating how individual and combined post-2005 energy system changes are evaluated

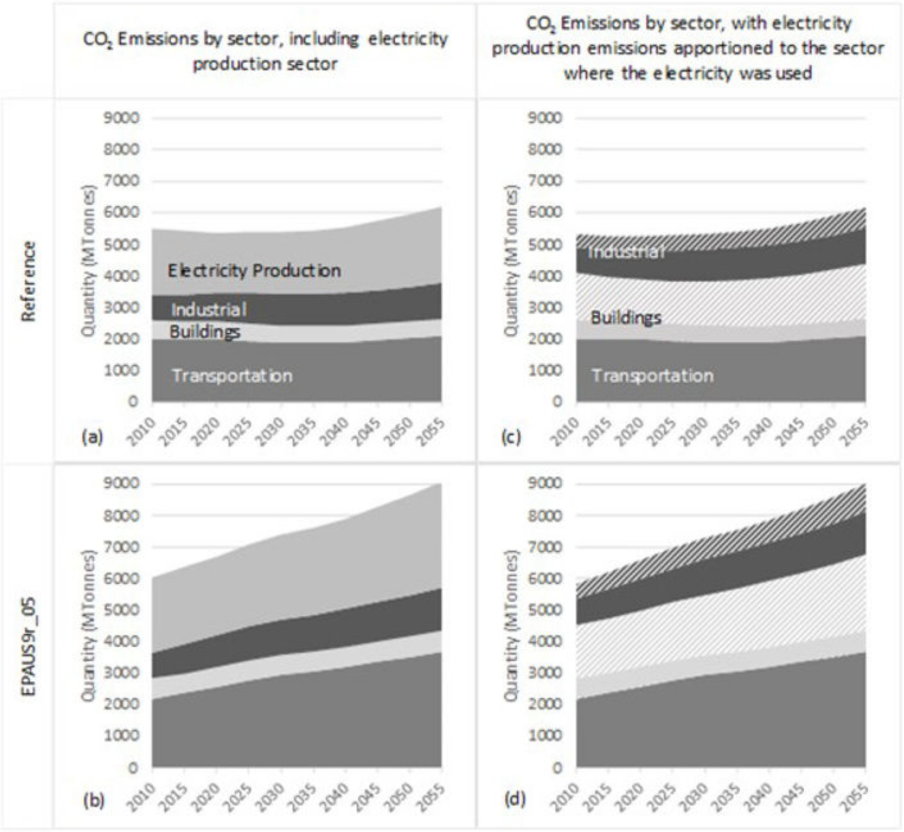

Fig. 3.

Sectoral CO2 emissions for the Reference Case and for the EPAUS9r_05. In (a) and (b), electricity production is included as one of the sectors. In (c) and (d), electric sector emissions are apportioned to the specific end-use sectors where the electricity was used.

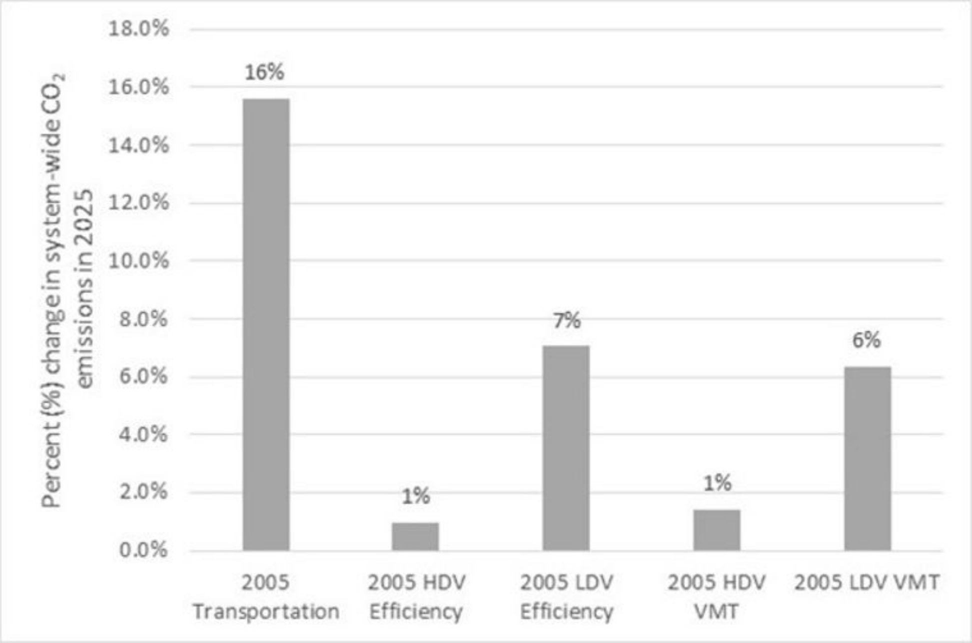

Fig. 4.

Percent change in year 2025 system-wide CO2 emissions in response to approximating selected AEO2005 assumptions in the transportation sector

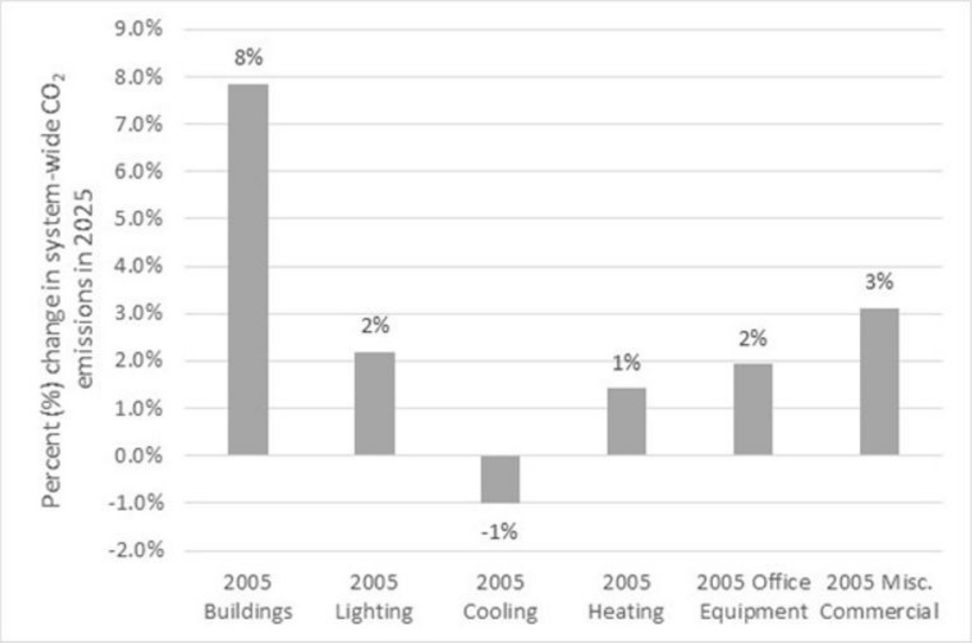

Fig. 5.

Percent change in year 2025 system-wide CO_2 emissions in response to approximating selected AEO2005 assumptions in the buildings sector

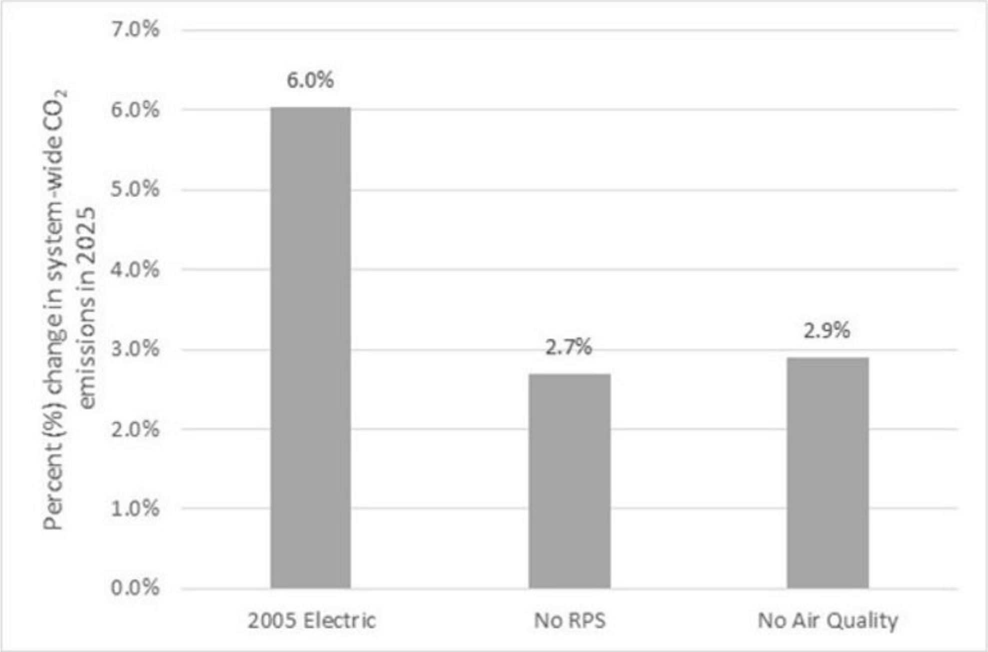

Fig. 6.

Percent change in year 2025 system-wide CO_2 emissions in response to approximating selected AEO2005 assumptions in the electric sector

Table 1

Perturbations made by sector to the EPAUS9r to reflect the AEO2005

Sector	Variables Perturbed
Electric	Removed regionally aggregated state RPS rules
	Removed representations of CAIR and MATS
Buildings	Adjusted lighting efficiency to pre-EISA levels, LED lighting technologies removed
	Adjusted space heating and space cooling requirements to reflect AEO2005 projections
	Adjusted miscellaneous commercial electricity and office equipment requirements to reflect AEO2005 projections
Transportation	Adjusted heavy-duty and light-duty vehicle fleet average efficiencies to reflect AEO2005 projections
	Adjusted heavy-duty and light-duty vehicle travel demand to reflect AEO2005 projections
Industrial	Rolled back motor efficiency improvements to reflect AEO2005 projections
	Adjusted industrial demands to reflect AEO2005 projections

Table 2

Sectoral CO2 emissions (Mt) in 2025 for the Reference Case and EPAUS9r_05. Lettering (a) and (b) is consistent with the results shown in Fig. 3.

Sector	(a) Reference Case	(b) EPAUS9r_05	% Change [(b−a)/a*100]
Electricity production	1,940	2,620	35 %
Industry	966	1,080	12 %
Buildings	558	623	12 %
Transportation	1,950	2,770	42 %
Total	5,410	7,100	31 %

Table 3

System-wide CO2 emissions (Mt) in 2025 for the Reference Case and each sensitivity run, as well as % change for each result versus the Reference Case. Lettering (a) and (b) is consistent with the results shown in Fig. 3.

	System- wide CO2 emissions (Mt)	**% increase from (a)**
Reference Case 2025 projection (a)	5410	–
Post-2005 sectoral changes NOT included		
Electric	5720	6 %
Industrial	5480	1 %
Buildings	5840	8 %
Transportation	6260	16 %
Electric and industrial	5770	7 %
Electric and buildings	6140	13 %
Electric and transportation	6560	21 %
Buildings and transportation	6690	24 %
Buildings, industrial and transportation	6810	26 %
Electric, buildings and transportation	7010	30 %
EPAUS9r_05 (Electric, industrial, buildings, transportation) (b)	7100	31 %