GLIMPSE: a rapid decision framework for energy and environmental policy

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Over the coming decades, new energy production technologies and the policies that oversee them will affect human health, the vitality of our ecosystems, and the stability of the global climate. The GLIMPSE decision model framework provides insights about the implications of technology and policy decisions on these outcomes. Using GLIMPSE, decision makers can identify alternative techno-policy futures, examining their air quality, health, and short- and long-term climate impacts. Ultimately, GLIMPSE will support the identification of cost-effective strategies for simultaneously achieving performance goals for these metrics. Here, we demonstrate the utility of GLIMPSE by analyzing several future energy scenarios under existing

air quality regulations and potential CO_2 emission reduction policies. We find opportunities for substantial co-benefits in setting both climate change mitigation and health-benefit based air quality improvement targets. Though current policies which prioritize public health protection increase near-term warming, establishing policies that also reduce greenhouse gas emissions may offset warming in the near-term and lead to significant reductions in long-term warming.

1 Introduction

Atmospheric pollutants endanger human health, threaten ecosystems and exacerbate climate change. For example, both tropospheric ozone and fine particulate matter are cardiovascular and respiratory irritants when inhaled[1-3], can reduce crop yields by inhibiting vegetative growth[4], and perturb regional and global climate patterns by absorbing or scattering incoming and outgoing solar radiation[5]. Greenhouse gases (GHG) also contribute to climate change, which in turn impacts human health and ecosystems[6, 7]. Emissions of greenhouse gases, as well as the precursors of ozone and particulate matter can be largely attributed to a common source – the combustion of fossil fuels for use in the energy system.

In past decades, the U.S. Environmental Protection Agency (EPA) has led a successful campaign to reduce many of the impacts of air pollution by setting National Ambient Air Quality Standards (NAAQS) and implementing regulations to achieve those standards[8]. Historically, each air quality and climate policy often targets a specific source type or pollutant[9, 10]. There are three advantages to developing policy for the entire energy system rather than an individual pollutant or source type. First, individual pollutants have multiple impacts; for example, black carbon aerosol impairs human health and warms the atmosphere[11]. Second, emission control strategies impact multiple pollutants at once. For example, light-scattering organic aerosol is co-emitted with black carbon aerosol, hence emission control technologies can both increase or decrease radiative forcing based upon the relative amount of emitted organic and black carbon[12]. Finally, the interconnectedness of fuel sources and energy use means implementing an emission control strategy on one component of the energy system has effects on emissions from other parts of the energy system. For example, increased use of electric automobiles could re-distribute emissions from car tailpipes to power plants[13-16]. Therefore, there are considerable opportunities to make environmental policies more effective by assessing pollution control strategies in a framework that considers the interactions between pollutants, the energy system, and multiple environmental goals.

Recent studies have made progress towards assessing potential emissions mitigation measures for both climate and public health benefits. A United Nations Environment Programme study identified fourteen emission mitigation measures which, if implemented, will have significant near-term climate and health benefits[11, 17]. The benefits from transitioning away from fossil fuels under a GHG reduction policy are also well documented[18-20].

There has been important progress in combining environmental assessment and cost-benefit analysis. Integrated assessment models simulate the development of the energy system with defined trends of future technologies and global economic conditions, and the resulting global emission scenarios are evaluated for a variety of global climate and environmental endpoints[21-26]. However, previous work has been focused globally and does not include sufficient spatial resolution or technological detail to represent environmental impacts from regional energy system and emission changes in the U.S.

In this paper, we present an energy model-based emission scenario screening tool, GLIMPSE (GEOS-Chem LIDORT Integrated with MARKAL for the Purpose of Scenario Exploration), which integrates U.S. energy system modeling with benefit assessment modeling into a fast, reduced-form modeling framework. The tool captures the variability in possible regional changes in aerosol and GHG emissions and assesses the net health and climate impacts of policies across spatial and temporal scales. GLIMPSE can be used to quickly estimate the broad energy/environmental system response to incremental changes in policies, identifying policy approaches which may later be studied using more detailed modeling.

Specifically, we use GLIMPSE to examine the U.S. energy system under combinations of current air quality and energy-efficiency policies with CO_2-reduction-based climate policies. We evaluate and compare the impacts of the air quality and climate policies independently, as well as their interactions when applied together. First, the change emissions from the energy system due to environmental policies is modeled. Second, we then evaluate the near and long-term radiative forcing and particulate matter related health outcomes of each emission scenario.

2 Materials and Methods

The GLIMPSE decision-model framework, shown in Figure 1, is designed to rapidly provide an estimate of the energy system response to a proposed air quality or climate policy while assessing the health and environmental outcomes with impact factors derived from climate and epidemiological modeling. The framework integrates economic modeling of the energy system with atmospheric modeling of the effects of emissions on climate change and public health. The methodology behind each component of the framework is described in detail below.

2.1 Energy System Emissions Modeling

The first component of the GLIMPSE framework is the MARKet ALlocation (MARKAL) optimization model[27, 28], which is used to model the development of the U.S. energy system over the coming decades. This includes the technologies and fuels used for activities such as energy resource extraction, electricity production, vehicular transportation, space heating and cooling, and electricity and heat produced for industrial use. Defined as such, the emissions from the energy system are a significant contributor to short-lived climate forcers, long-lived GHGs and air pollutants.

MARKAL includes as inputs the energy system demands, such as lumens of lighting required for commercial buildings or vehicle miles traveled for passenger transport. Additionally, MARKAL includes energy production technologies to meet system demands. Technologies range from those specified by fuel type (incorporating mining, processing, conversion to electricity, and final end use) to energy conservation technologies. Each of the end-of-pipe pollution control technologies has a cost and associated emission reduction. MARKAL performs a least-cost optimization to find the set of technologies for a future scenario that meets the energy demands, subject to constraints on emissions. By varying the emission constraints from climate and health-relevant environmental policies, MARKAL may be used to generate possible least-cost energy system technological scenarios which also meet future energy demands.

The EPA MARKAL database is populated with U.S. data that incorporates technology and fuel assumptions from the U.S. Energy Information Administration's 2012 Annual Energy Outlook[29] and availability of renewable energy from Department of Energy's National Energy Modeling System. The EPA MARKAL database has a spatial resolution of 9 U.S. Census Regional Divisions[30] and covers the time period from 2005 – 2055 in 5 year blocks.

2.2 Assessment of Climate and Health Impacts from Energy Sector Emissions

The second component of the GLIMPSE framework is the development of reduced-form climate and health benefit metrics to assess the impacts of energy system emission changes under the alternative policy scenarios.

2.2.1 Climate effects

The short-lived aerosol species – sulfate (resulting from the oxidation of sulfur dioxide (SO_2)) , black carbon (BC), and organic carbon (OC) – have atmospheric lifetimes on the order of one week. In contrast, the greenhouse gases, e.g. methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), have lifetimes that vary from decades to centuries. Short-lived species play a large role in near-term radiative forcing and the rate of climate change, while ultimately the magnitude of long-term climate change is driven by GHG and other long-lived species[11, 31].

Short-lived climate forcing gases and aerosols undergo specific chemical and physical transformations that substantially change their climate impacts. The rates of these transformations and climate impacts of the products vary under different atmospheric conditions depending on factors such as the surface land cover, levels of solar insolation, and prevailing weather patterns[5, 32, 33]. Therefore, the location of sources are included in evaluation of the climate impacts from emissions sources of short-lived species[34]. We use the GEOS-Chem/LIDORT adjoint model[35] to calculate the change in global radiative forcing due to a change in the emission rate in each 2×2.5 degree grid cell, enabling us to evaluate the direct radiative forcing effects of aerosol and precursor emissions by pollutant, emission location and source category at high spatial resolution (see Section 3.2 for more information). Emission effects are aggregated to the nine U.S. census regions to provide direct compatibility with the

MARKAL emission scenarios. A thorough description of the adjoint model and global results from these analyses are presented in other studies[35, 36]. Quantifying the nonlinear aerosol-cloud feedback processes would require climate modeling beyond the scope of the reduced framework presented here. The implications of including these effects in this analysis are qualitatively noted in the discussion section below.

To understand the potential climate outcomes of the future emission scenarios, we develop two climate metrics to analyze both the near- and long-term effects of short-lived aerosol species and long-lived greenhouse gases. The short-term climate metric considered in the GLIMPSE framework is the Time-Integrated Radiative Forcing metric, (TIRF). TIRF represents the sum of radiative forcing over a specific time horizon, from the time of emission to the end of time horizon. For example, TIRF(50) represents the total radiative forcing for a stream of emissions over a 50-year modeling horizon (e.g. period 2005 through 2055). The change in radiative forcing of short-lived aerosols species (BC, OC) and their pre-cursors (SO_2) due to changes in emissions are calculated using the GEOS-Chem/LIDORT, as described above. For radiative forcing from GHGs, the TIRF is calculated using published values[37] integrated from the year of emission to 2055. Radiative effects beyond 2055 are not included. This metric emphasizes the near-term climate effects of aerosols and early greenhouse gas reductions while discounting the long-term climate implications. The derivation of this metric is included in the *Supporting Information, Appendix A.* A number of other plausible metrics have been developed for near-term climate change[37], and as new policy questions arise, alternate metrics could be adopted by GLIMPSE.

Long-term climate change is emphasized by a second climate metric, the 100-year Global Warming Potential, GWP(100). This metric is the standard measure of the climate effects of greenhouse gases [37, 38] and allows comparison of different compounds using a common basis, CO_2 equivalents. Given a 1 kg emission of a compound, the GWP(100) is the equivalent mass of CO_2, emitted as a pulse, that has the same integrated radiative forcing over a 100-year period [37, 38]. Compounds that have large radiative effect or long atmospheric lifetime have larger GWP(100) values. Only emissions within the MARKAL modeling time horizon are included in the 100-year metric calculation.

2.2.2 Health Effects

The potential health effects for the emission scenarios are estimated using national per-ton impact factors that were calculated by Fann et al. [39]. Fann et al. used the Community Multiscale Air Quality (CMAQ) model [40] to simulate the relationship between emissions and atmospheric concentrations, as well as the Environmental Benefits Mapping and Analysis Program, BenMAP [41], to calculate the relationship between atmospheric concentrations and human health based upon fine particulate matter mortality risk estimates [3]. Health costs are calculated as the increase in mortality times the value of a statistical life. Per-ton impact factors are calculated for 12 sector / pollutant combinations. GLIMPSE uses these impact factors to calculate the health impacts due to SO_x, NO_x, and carbonaceous aerosol emissions for three future years: 2015, 2020, and 2030 [42].

3 Results

3.1 Scenarios of the U.S. energy system under alternative air quality and climate policies

MARKAL optimizes the choice of energy sources and technologies under constraints set by emission policies. We evaluate the response of the energy system under four policy scenarios using the MARKAL model:

S1 – Baseline: This scenario represents an estimate of the emission changes, phased in over time, that can be expected under current regulations on the electric sector (e.g., Clean Air Interstate Rule, CAIR, and state-level renewable portfolio standards, RPSs) and on the transportation sector (e.g., the new Corporate Average Fuel Economy (CAFE) standard, which calls for a light duty fleet efficiency of 54.5 miles per gallon by 2025, Tier II light duty emission standards, heavy duty engine emission standards, and diesel sulfur limits). More detail of the specific emission changes modeled in each scenario is shown in the *Supporting Information*, *Appendix B.*

S2 – Rollback: This scenario represents pollutant emission rates approximating what they would have been without the implementation of emission reduction strategies noted under the Baseline scenario (S1).All emission intensities (i.e. emissions per unit production) are held constant at 2005 levels throughout the modeling time horizon. Electric sector constraints on NO_x and SO_2 emissions are removed.

S3 – Baseline with 50% CO_2 cap: A hypothetical climate change mitigation policy is added to the Baseline scenario (S1). The scenario adds a constraint that forces 2050 CO_2 emissions to be 50% below 2005 levels. The constraint is implemented in an incremental fashion, becoming linearly more stringent from its start date in 2015 until full implementation in 2050.

S4 – Rollback with 50% CO_2 cap: The 50% CO_2 emissions reduction target from S3 is implemented onto the relaxed emission constraints of the Rollback scenario (S2).

By isolating the CO_2 and air quality policies between scenarios, we can assess the effects of policies individually and together. The discussion that follows focuses on changes in the energy system, the resulting emissions of greenhouse gases and air pollutants, and the impacts of those emissions on human health and climate change.

The result of the MARKAL optimization is that the mix of energy technologies in scenarios S1 and S2 are similar, while the addition of the CO_2 constraint in S3 and S4 leads to large differences. The details of the technology changes in electricity generation, transportation, industrial and residential energy use are modeled in MARKAL and shown in the *Supporting Information, Appendix B and C*. For S1, the model optimization meets emission limits primarily by using end-of-pipe emission controls as opposed to making large changes in the amount of electricity produced or in the fuels used to produce electricity. Under scenarios without a CO_2 constriant (S1 and S2), coal, nuclear, and renewable electricity production remain at approximately current levels. Additional capacity built over the modeling period primarily uses natural gas. As expected, relaxing the emission constraints from current air quality policy (S2) leads to increased emissions. Notably, CO_2 emissions in S1 remain at or below 2005 levels through 2050, largely because improving vehicle fuel efficiency standards offset growth in demands. By 2055, CO_2 emissions increase by 5% (all emission changes are relative to 2005) in S2. In S1, SO_2, BC, and OC emissions are reduced to 24%, 50% and 65% respectively by 2020 (Figure 2). Since no additional emission constraints are added after 2020, S1 and S2 emissions remain relatively constant, except CO_2, which continues to increase.

In contrast with the relatively stable S1 and S2, major changes in electricity generation fuel sources occur due to the addition of a CO_2 emission reduction target in S3 and S4. In both scenarios, coal use decreases with natural gas-fired plants dominating new fossil fuel based production capacity. Nearly all fossil fuel production capacity has implemented carbon sequestration technologies to remove CO_2 emissions by 2055. Wind and solar electricity production increase depending on regional availability (shown in detail in Figure 3). Given that the emission trend is prescribed by the CO_2 cap, the emission rates of CO_2 for both S3 and S4 are similar. Reductions in SO_2 emissions under the rollback with climate policy scenario (S4) do not approach the level of human health benefits generated by the baseline scenario (S1) until 2040, lagging by 25 years. Beyond 2020, the addition of a CO_2 policy to the baseline scenario in S3 leads to additional emission reductions in SO_2 and OC beyond the reductions which occur in the baseline scenario (S1). Black carbon emissions under the combined policy scenario (S3) are slightly larger than the baseline (S1) due to the residential, commercial, and industrial sectors switching to biomass fuel as a bridge fuel (see *Supporting Information, Appendix C*).

The regional comparison of the adoption of alternative energy production technologies under S1 and S3 are shown in Figure 3. Overall, renewable technologies are adopted in the climate policy scenarios based upon regional resource availability. Biomass becomes a significant fraction of electricity production in New England (Region 1), wind power dominates in the Central Plains and Mountain-west States (Regions 4 and 8), and solar power becomes a major source of electricity in the Western and Southwestern United States (Regions 7 and 9). Natural gas dominates in areas without significant sources of renewable or non-carbon energy, such as the South Atlantic States (Region 5) and Midwestern states (Region 3). In other regions such as the Mid-atlantic and south-central states (Regions 2 and 6), the projected generation capacity is reduced and power is imported from other regions. In nearly all cases, the use of coal for electricity production decreases. In some regions, the total electricity generation is different for 2055 which reflects different levels of electrification of the transportation sector. These are just two of many possible technology pathways for meeting the CO_2 constraint. With such a high reliance on intermittent power production – wind and solar – the realization of these scenarios may also require advances and cost reductions in energy storage technologies, which could shift electricity production times to match demands [43]. MARKAL does not include sufficient temporal detail to capture some of the details of daily load shifting and its implications.

3.2 Climate and health impacts of scenarios

Given the projected trends in regional emissions, we assess the future climate forcing and health effects of the policies modeled in our scenarios. For each U.S. census region, the change in radiative forcing due to an additional mass emitted of each aerosol species (i.e. the radiative forcing efficiency) is calculated using the GEOS-Chem/LIDORT adjoint model (Figure 4a). The efficiency of aerosols to affect global radiative forcing varies based upon the surrounding land cover and atmospheric composition. For example, black carbon emissions from Region 4, the central plains states, have the largest impact on global radiative forcing. This is in part because the highly light absorbing black carbon aerosols have a larger impact when emitted over high albedo snow surface cover in winter. Conversely, black carbon efficiencies in the southern east-coast states (Region 5) are small, since prevailing winds transport black carbon aerosols over the comparatively low albedo ocean.

While the radiative forcing efficiencies are highly variable by region, the total amount of aerosol emissions plays a large role in determining the effect of a region's emissions on global radiative forcing. The radiative forcing for each region is shown in Figure 4b, and the total radiative forcing efficiency for each state in 2005 are shown in Figure 4c-e. Returning to the black carbon example, while Region 4 has the largest black carbon radiative forcing efficiency, it does not have the most emissions. Region 3, the western Great Lakes states, has the largest black carbon emissions in addition to the second highest radiative forcing efficiency. This combination leads to the largest total impact on radiative forcing from black carbon emissions of any U.S. region.

In the case of organic carbon and SO_2, regional differences in radiative forcing efficiency are not as great as those for black carbon. Regional differences arise from vastly differing emission rates across the regions. Regions 3, 5 and 6 have the largest SO_2 emissions. Overall, at current emission rates, the U.S. net radiative forcing of the three aerosol species considered here is dominated by the cooling radiative forcing from sulfate aerosols and organic carbon.

Going forward, in the rollback scenario (S2) where emissions are not reduced, the cooling effect of sulfate aerosols is maintained, leading to the lowest values of the near-term climate metric, TIRF(50) (Figure 5a), even though BC emissions increase. The baseline scenario (S1), with significant decreases in emissions, leads to an increase in the TIRF(50) metric. The difference could be seen as a climate disbenefit of the regulations in the baseline scenario. However, the CO_2 emission reductions in S3 and S4 offset this increase in TIRF(50) from the SO_2 reductions. Since the CO_2 emission reductions are gradually phased in, the largest emission changes occur later in the scenario, and the change in the TIRF(50) is somewhat muted. The CO_2 emissions reductions early in the scenario impact radiative forcing during a longer integration time, where as emission reductions later in the scenario have an effect over a shorter integration time.

The climate warming disbenefit between scenarios S1 and S2 is less evident when considering the 100 year global warming potential metric (Figure 5b). However, in both cases, the CO_2 reductions in S3 and S4 cause a large reduction in GWP(100) from the S1 and S2 scenarios. The air quality and energy efficiency regulations in S3 additionally reduces long-term climate warming equivalent to a reduction of 1.6 gigatons of CO_2 emissions over the rollback scenario with the same climate policy. The GWP(100) from N_2O and CH_4 increase in the rollback scenarios relative to the baseline scenario. Implementing a CO_2 policy does not lead to significant reductions to CH_4 and N_2O emissions, and in the absence of new policies, emissions of these species are expected to increase.

Expected reductions in emissions of particulate matter and precursors under the emission regulations in S1 have significant health benefits in 2015, 2020 and 2030 when compared to S2 (Figure 5c-e). While there are some near-term climate drawbacks, the health benefits from reducing SO_2 emissions are clear. Relative to the health impacts in each year under S1, the rollback of emission constraints in S2 increases health impacts by 130%, 148%, and 165% in 2015, 2020, and 2030 respectively. Under S3, in 2020, increased NO_x and BC emissions from the industrial sector lead to a 1% increase in health impacts over S1. By 2030, additional reductions of SO_2 and OC cause health benefits effects to decrease to 80% relative to the health impacts in the same year under S1. Because of the late requirements for emission reductions under the CO_2 policy in S4, co-reductions in emissions of other health relevant pollutants occur much later than under S1 or S3, leading to increased health impacts of 117%, 121%, and 80% for 2015, 2020 and 2030. Though these health impacts are improved over S2 particularly in later years, they are still significantly higher than S1 or S3.

In S3, there is little effect on health benefits or TIRF from the addition of a CO_2 emission cap to the baseline emission scenario primarily because the CO_2 emission limits do not become stringent until later years. In contrast to recent global studies which show large human health co-benefits for adopting a CO_2 emission limit[24, 26], the U.S. already has substantial SO_2 end-of-pipe controls on power plants. Along with the gradual implementation of the CO_2 limit, this delays the health benefits until later in the scenario. Since the GLIMPSE framework allows for the rapid testing of alternative policy approaches, the effect of setting an earlier date to meet the CO_2 reduction target can be readily assessed. Setting an earlier date could offset climate warming from reductions in sulfate and other cooling aerosols in the baseline scenarios and lead to earlier realization of the increased health benefits seen in 2030 under S3. We create an additional set of 4 scenarios repeating the emission caps from S3 with the exception of achieving the CO_2 cap in the year 2030, 2035, 2040, and 2045. Setting an earlier date for the CO_2 cap, without altering the assumptions over the alternative sources of non-carbon electricity production, leads to a similar distribution of energy technologies (*Supporting Information*, *Appendix D*); however, the adoption of these technologies is achieved earlier with each progressively earlier target year. The near- and long-term climate metrics and the health impact metrics are all reduced relative to the baseline scenario. When the 50% reduction in CO_2 is achieved in 2030, the climate disbenefits from the removal of cooling aerosols are fully offset. Moreover, the long-term radiative forcing is decreased by 28% relative to S1 – an improvement of 8% over a 2050 reduction target date. Furthermore, setting the CO_2 reduction target date to 2030 reduces health impacts by 15% in 2020 and 29% in 2030 relative to S1. These health costs are significantly lower than either S1 or S4.

4 Discussion

Policymakers and other stakeholders propose energy policies to promote various causes, from domestic energy independence to protecting public health and mitigating climate change. The framework developed here aims to provide a common platform to demonstrate multiple environmental outcomes of potential energy policies. The scenarios presented here are not indicators of current or future U.S. EPA policy, only representations of policies that can be assessed using this framework.

Our analysis re-confirms that emission reductions of aerosols and their precursors under expected U.S. air quality regulations will lead to significant benefits to human health, yet they will, on net, increase the rate of near-term climate change because reductions US emissions of cooling sulfate aerosols will more than offset reductions in warming black carbon aerosols. We demonstrate that the addition of a CO_2 emission cap may be able to offset these effects, particularly if the cap is set to an aggressive, early-century date.

While these scenarios benefit human health and achieve long-term climate change mitigation, no scenario achieves substantial reduction in radiative forcing between now and 2055. At best, due to the significant reductions in sulfate aerosols, the combined climate and air quality scenario achieves parity with the rollback of current air quality and energy efficiency policies. The contribution of aerosols to radiative forcing would likely change if our calculation also included the effects of aerosols on clouds. This would likely increase the cooling effects of aerosols [32, 44, 45], exacerbate the increase in near-term radiative forcing in these scenarios, possibly requiring even larger reductions in greenhouse gases to offset the aerosol impacts. Future work should examine additional contributors to near-term radiative forcing, such as methane, tropospheric ozone, or light absorbing brown carbon to discover additional options for mitigating near-term climate forcing.

Although air quality and climate policies have large interactions within the energy system, our analysis of these scenarios demonstrates that neither policy is a true replacement for the other when the timing of emission reductions is taken into account. The air quality policies are designed to produce immediate reductions from existing sources, while the long-term cap on

CO_2 emissions leads to a broad transition to new energy production technologies by mid-century. In the combined scenario where both near-term emission limits were put into place alongside a long-term CO_2 reduction goal, we find opportunities to improve both human health and climate outcomes beyond the outcomes from a single policy. The modeling framework outlined here allows U.S. policymakers to coordinate air quality regulation across timescales, bridging the gap between setting short-term and long-term emission reductions.

Figures

Figure 1. The GLIMPSE modeling system. Scenario policy constraints are within the MARKAL energy system model. Using high resolution information regarding the effects of emissions from each US region, changes to emissions within each region are evaluated.

Figure 2. Scenario Emission Rates Relative to 2005. Emission rates for CO_2 (Panel A), SO_2 (Panel B), black carbon (Panel C), and organic carbon (Panel D) are shown for each scenario. Baseline scenarios (solid lines) lead to significant reductions in particulate matter concentrations and keep CO_2 concentrations below 2005 levels through 2035. Rolling back baseline air quality and energy efficiency regulations and implementing CO_2 emission reductions (dashed red line) leads to significant decreases in SO_2 emissions, though at a significant time delay, and small to no emission reductions in black and organic carbon emissions. Overall the combined approach of both air quality and CO_2 reduction policies (red dashed lines) lead to the largest reductions in emissions in SO2 and OC, but lead to small increases in emissions of BC from 2020 to 2040 (see text). Additional emissions information for other species are shown in the *Supporting Information, Appendix B.*

Figure 3. Scenario electricity production by region. The final electricity generation technology mixes for S1 and S3 in 2050 are compared with 2005 levels. The adoption of specific electricity generation technologies vary based upon the availability of low-carbon technologies and the relative cost of these alternative technologies against either the import of electricity from neighboring regions or the adoption of carbon sequestration technology.

Figure 4. Regional Global Radiative Forcing Efficiency. The effect of each region's emissions on the global radiative forcing burden from aerosols is calculated using the GEOS-Chem/LIDORT adjoint model. Panel A is the annual, direct radiative forcing (ADRF) efficiency and Panel B is the radiative forcing, calculated as the product of the ADRF efficiency with the annual emissions. Panels C-E show the spatial variability in radiative forcing sensitivity to emissions of black carbon aerosol, organic carbon aerosol, and sulfur dioxide emissions, respectively.

Figure 5. Scenario Climate and Health Impact Metrics. The near-term warming effect of scenario emissions varies primarily with the changes in emissions of aerosols and early reductions in CO_2 emissions (Panel A). The increase in warming from the loss of sulfate aerosols is compensated in the near-term by implementing a CO_2 policy. The long-term forcing after 100 years is dominated by the changes in CO_2 emissions with shorter-lived species playing a reduced role (Panel B). The reduction in health effects from reducing emissions of aerosols and their precursors under the baseline scenarios is clearly evident (Panel C-E). Additional health benefits are seen in S4 in 2030 as co-reductions of aerosol occur with reductions of CO_2.

Supporting Information

The supporting information contains: (A) the derivation of the radiative forcing metrics, time-integrated radiative forcing and 100-year global warming potential; (B) regional electricity generation and energy production technology scenario results; (C) scenario emissions by energy sector; (D) electricity generation and energy production technology scenario results for alternative climate policy scenarios. This material is available free of charge via the Internet at http://pubs.acs.org

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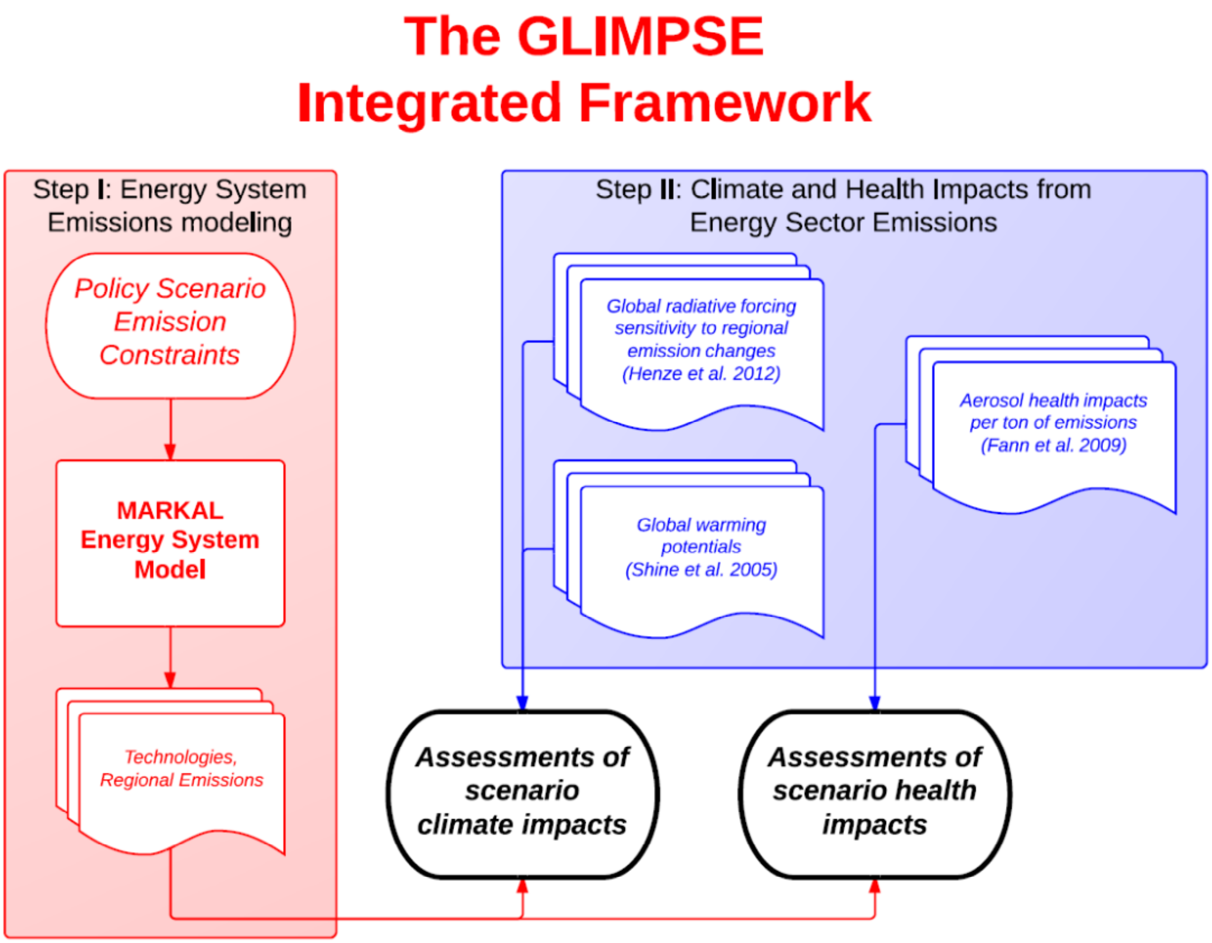

Figure 1. The GLIMPSE modeling system. Scenario policy constraints are within the MARKAL energy system model. Using high resolution information regarding the effects of emissions from each US region, changes to emissions within each region are evaluated.

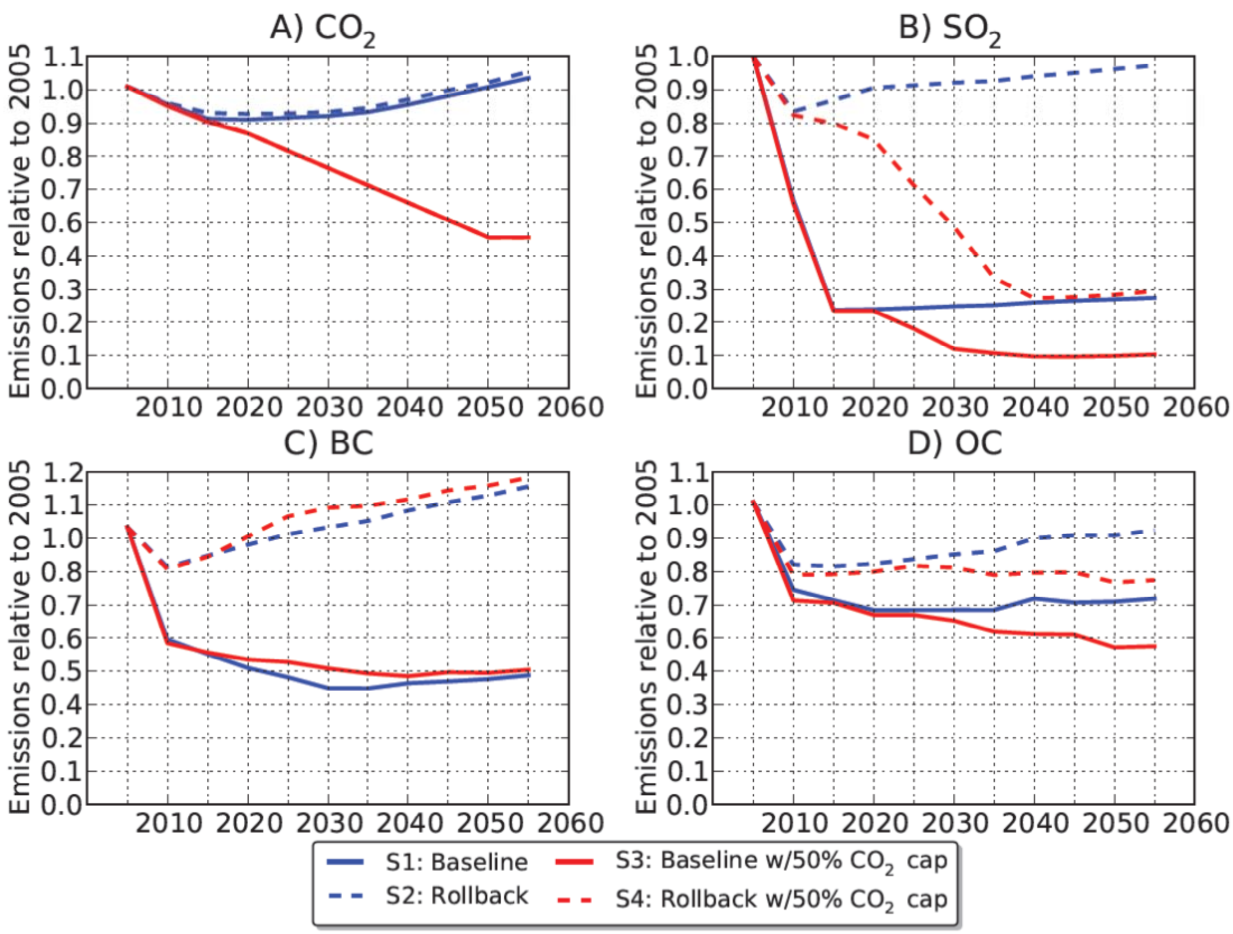

Figure 2. Scenario total U.S. Emission Rates Relative to 2005. Emission rates for CO_2 (Panel A), SO_2 (Panel B), black carbon (Panel C), and organic carbon (Panel D) are shown for each scenario. Baseline scenarios (solid lines) lead to significant reductions in particulate matter concentrations and keep CO_2 concentrations below 2005 levels through 2035. Rolling back baseline air quality and energy efficiency regulations and implementing CO_2 emission reductions (dashed red line) leads to significant decreases in SO_2 emissions, though at a significant time delay, and small to no emission reductions in black and organic carbon emissions. Overall the combined approach of both air quality and CO_2 reduction policies (red dashed lines) lead to the largest reductions in emissions in SO_2 and OC, but lead to small increases in emissions of BC from 2020 to 2040 (see text). Additional emissions information for other species are shown in the *Supporting Information*, *Appendix B.*

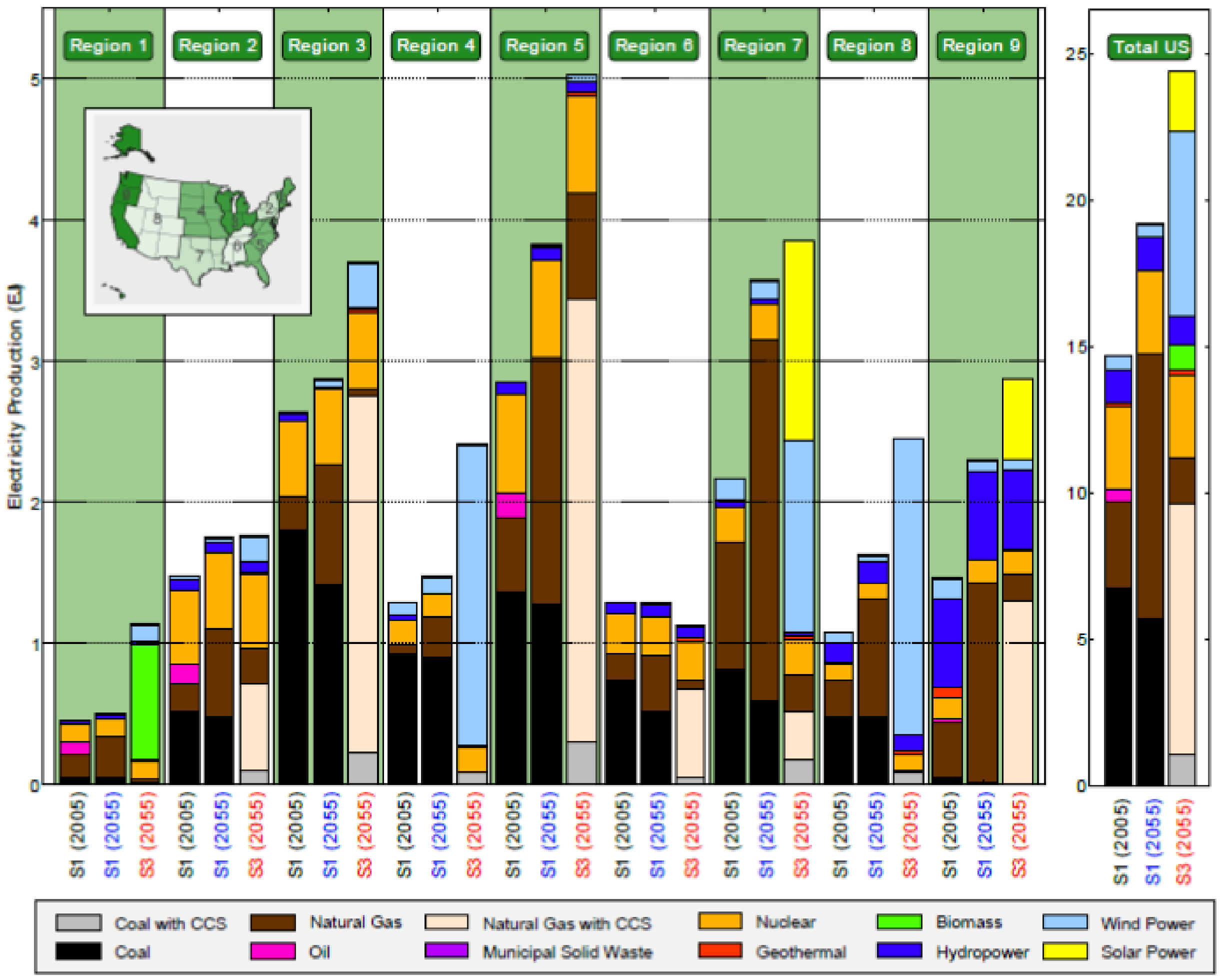

Figure 3. Scenario electricity production by region. The final electricity generation technology mixes for S1 and S3 in 2050 are compared with 2005 levels. The adoption of specific electricity generation technologies vary based upon the availability of low-carbon technologies and the relative cost of these alternative technologies against either the import of electricity from neighboring regions or the adoption of carbon sequestration technology.

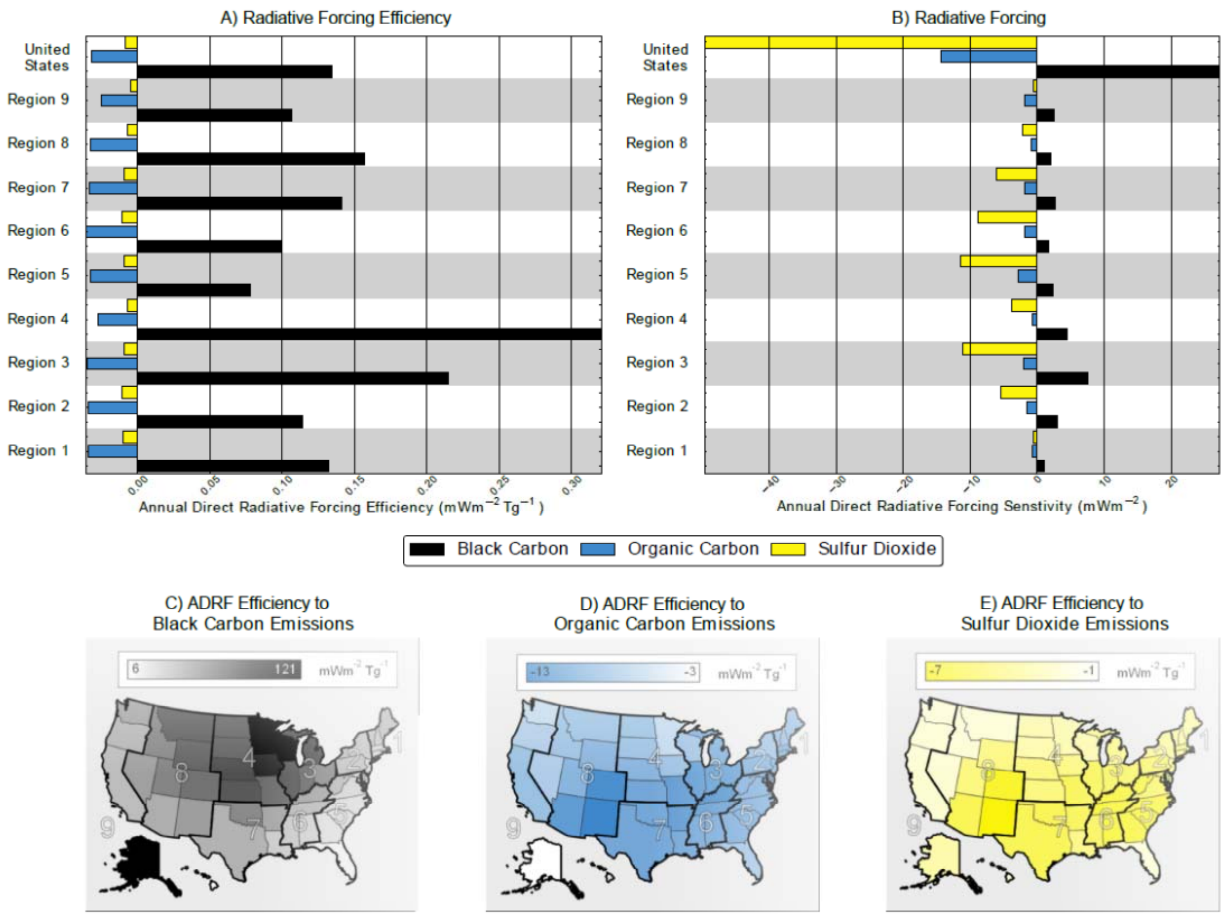

Figure 4. Regional Global Radiative Forcing Efficiency. The effect of each region's emissions on the global radiative forcing burden from aerosols is calculated using the GEOS-Chem/LIDORT adjoint model for 2005 U.S. emissions. Panel A is the annual, direct radiative forcing (ADRF) efficiency and Panel B is the radiative forcing, calculated as the product of the ADRF efficiency with the annual emissions. Panels C-E show the spatial variability in radiative forcing sensitivity to emissions of black carbon aerosol, organic carbon aerosol, and sulfur dioxide emissions, respectively.

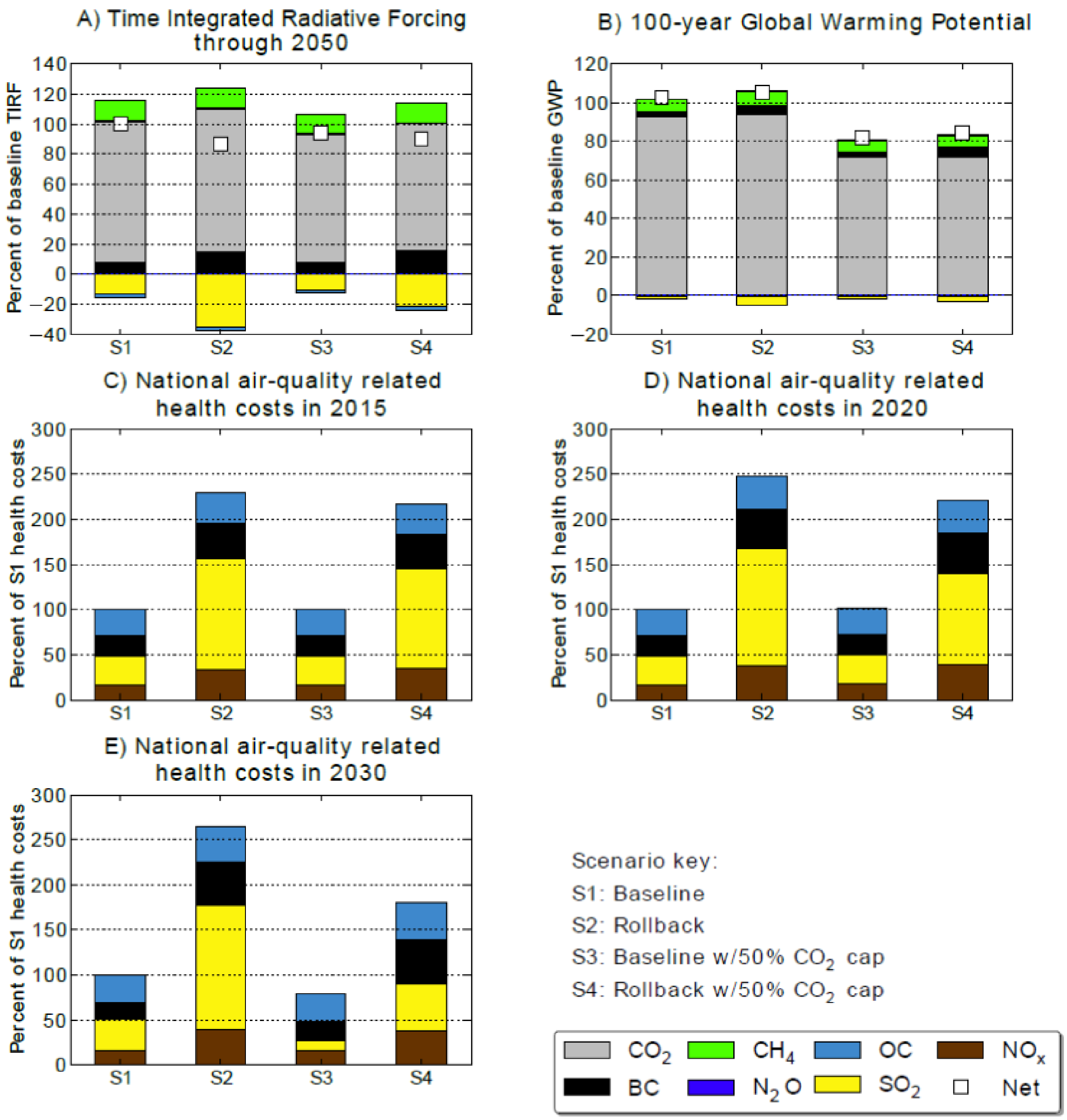

Figure 5. Scenario Climate and Health Impact Metrics. The near-term warming effect of scenario emissions varies primarily with the changes in emissions of aerosols and early reductions in CO_2 emissions (Panel A). The increase in warming from the loss of sulfate aerosols is compensated in the near-term by implementing a CO_2 policy. The long-term forcing after 100 years is dominated by the changes in CO_2 emissions with shorter-lived species playing a reduced role (Panel B). The reduction in health effects from reducing emissions of aerosols and their precursors under the baseline scenarios is clearly evident (Panel C-E). Additional health benefits are seen in S3 in 2030 as co-reductions of aerosol occur with reductions of CO_2.

Supporting Information
Appendix A
Definition of radiative forcing metrics

The purpose of GLIMPSE is to have a common framework for finding scenarios that simultaneously reduce short-lived climate forcers (SLCFs) and greenhouse gases (GHGs). Accordingly, it is important to have a common framework for comparing the impacts of species. The challenge is that these compounds have very different radiative effects and atmospheric lifetimes. For the SLCFs we consider – sulfate, black carbon, and organic carbon particles – all of atmospheric lifetimes are on the order of 1 week. The GHGs methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) have lifetimes of decades to centuries. What is an appropriate metric for considering the radiative forcing impacts of these compounds?

We begin with metrics as previously developed by Shine et al. [2005] and Fuglestvedt et al. [2010]. One such metric is the absolute global warming potential, AGWP(t) (W m^{-2} kg^{-1} year), or the integrated radiative forcing over t years. For the short-lived species, the lifetime in the atmosphere is short, so the AGWP is equal to the instantaneous radiative forcing, and the AGWP does not depend on the integration time, t. For the GHGs, the lifetime of the compound and time of integration t are important. Because the GHGs persist in the atmosphere, the AGWP increases with t.

For a specific compound, x, the AGWP is calculated as

$$\texttt{AGWP}(t) = \int_0^t A_x e^{-\frac{t}{\alpha_x}} \, dt = A_x \alpha_x [1 - e^{-\frac{t}{\alpha_x}}] \tag{1}$$

where A_x is the instantaneous radiative forcing (W m^{-2} kg^{-1}) and α_x is the atmospheric lifetime [Shine et al., 2005, Fuglestvedt et al., 2010]. Because the atmospheric lifetime of CO_2 depends on the absolute concentration and the relative magnitude of terrestrial and oceanic sinks, the formulation for CO_2 is derived using a carbon cycle model.

$$\texttt{AGWP}_{\texttt{CO2}}(t) = \int_0^t A_{\texttt{CO2}} [a_0 + \sum_i^{i=3} a_i e^{-\frac{t}{\alpha_i}}] dt \tag{2}$$

$$\mathtt{AGWP}_{\mathtt{CO2}}(t) = A_{\mathtt{CO2}}[a_0 t + \sum_{i}^{i=3} a_i \alpha_i (1 - e^{-\frac{t}{\alpha_i}})] \quad (3)$$

The parameters a_i and α_i are based on the revised version of the Bern Carbon cycle model as reported in the IPCC 4th Assessment Report [Forster et al., 2007].

To compare compounds, the global warming potential (GWP) is defined as the ratio of the AGWP of 1 kg of an emitted compound to the AGWP of 1 kg of CO_2. Like AGWP, the GWP is also calculated for specified integration time t. For example, while CH_4 has a GWP($t = 20$ years) of 72 CO_2 equivalents, the GWP($t = 100$ years) is only 25 CO_2 equivalents because the radiative effects of CH_4 relative to CO_2 diminish over time. Short-lived climate forcers have a large GWP(20), but much lower GWP(100).

Depending on the policy goal of interest, there are multiple ways to use these metrics to express constraints on the radiative impacts of emissions. We propose two methods.

The first is to calculate the time-integrated radiative forcing, TIRF(50), defined as the sum of the radiative effects of a stream of emissions from 2005 to 2055. Constraining this metric will reduce the total radiative forcing over the 50 year period. This metric is for asking questions of the form "how do we reduce the total amount of radiative forcing over the next 50 years?"

We define the time-integrated radiative forcing (TIRF) as the sum of radiative impacts due to a stream of emissions over the 50 year period from 2005 to 2055, as defined by Equation 4:

$$\mathtt{TIRF} = \sum_{t}^{2005,\ldots,2055} E_t \times \mathtt{AGWP}(t) \quad (4)$$

where t is the year, E_t is the emissions in year t. For the greenhouse gases, the emissions are multiplied by the AGWP shown in Table A1. For 2005, the AGWP(50) is used, since emissions in 2005 can impact the entire 50 year period. For 2050, the AGWP(5) is used, since emissions in 2050 can only impact the last 5 years of the 50 year period. For the SLCFs, the AGWP is calculated using the instantaneous radiative forcing calculated by GEOS-Chem adjoint and is shown in Table A2.

For long-lived species, this metric emphasizes reducing emissions early since later emissions have less of an effect on the entire period. For a given short-lived species, emission reductions in any time period have equal effect.

The second type of metric is to use CO_2 equivalence calculated using GWP(100). Over long integration time periods, the effects of the long-lived greenhouse gases control the ultimate magnitude of climate change. This metric is for asking questions of the form "how do we reduce the overall magnitude of climate change?" We refer to this metric as GWP:

$$\texttt{GWP}_{100} = \sum_{t}^{2005,\ldots,2055} E_t \times \texttt{GWP}_{100} \qquad (5)$$

The GWP(100) values derived from a literature survey are listed in Table A3.

The differences between these two metrics can be illustrated by applying them to a test scenario where CO_2 and SO_2 emissions are held constant from 2005 – 2055. Figure A1 shows the resulting TIRF and GWP(100) for each compound calculated for emissions occurring in each year. For the TIRF metric, emissions of CO_2 in early years have a larger impact, because those emissions persist in the atmosphere and impact the entire 50 year period. Emissions of CO_2 in the later years have less impact, because the emissions in those later years can only impact the radiative forcing in those later years (Figure A1(a)). Emissions of SO_2 impact the radiative forcing equally in all periods, because these compounds have a short lifetime and do not persist for long enough to impact the radiative forcing in other periods. While TIRF considers the radiative impacts from the time of emission to the end of the scenario period, GWP(100) considers the radiative impact from the time of emission to 100 years from the time of emission. Consequently, for GWP(100), CO_2 has an equal impact in all periods, because the integration time is always 100 years.

The TIRF metric puts more emphasis on SLCFs and early reductions on GHGs. The result is the TIRF has less integrated radiative forcing from CO_2 which means the SLCFs have relatively more weight. This is shown in Figure A1(c) where the relative importance of SO_2 is greatest in the TIRF calculation. The form of the metric influences both the relative importance of SLCF and GHGs, as well as the relative importance of the timing of GHG emissions.

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Table A1: For each GHG, the AGWP (W m^{-2} Gg^{-1} year) for different integrating times. These values are used in Equation 4 as `AGWP`(t).

year	CO_2	N_2O	CH_4
50	5.124×10^{-8}	1.603×10^{-5}	1.997×10^{-6}
45	4.724×10^{-8}	1.472×10^{-5}	1.980×10^{-6}
40	4.311×10^{-8}	1.336×10^{-5}	1.956×10^{-6}
35	3.883×10^{-8}	1.193×10^{-5}	1.918×10^{-6}
30	3.437×10^{-8}	1.045×10^{-5}	1.862×10^{-6}
25	2.968×10^{-8}	8.890×10^{-6}	1.775×10^{-6}
20	2.472×10^{-8}	7.264×10^{-6}	1.645×10^{-6}
15	1.942×10^{-8}	5.566×10^{-6}	1.447×10^{-6}
10	1.368×10^{-8}	3.791×10^{-6}	1.147×10^{-6}
5	7.389×10^{-9}	1.937×10^{-6}	6.911×10^{-7}

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Table A2: The AGWP (W m^{-2} Gg^{-1}) for the direct radiative effects of short-lived climate forcers, by sector by US region, calculated using GEOS-Chem Adjoint. These values are used in Equation 4 as $\mathtt{AGWP}_t$. Since they have a short lifetime, these AGWP values are constant with respect to integration time.

	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8	Region 9	US	World
Black carbon											
Anthropogenic	3.63×10^{-5}	3.68×10^{-5}	8.10×10^{-5}	9.25×10^{-5}	2.58×10^{-5}	3.66×10^{-5}	4.32×10^{-5}	5.86×10^{-5}	3.99×10^{-5}	5.05×10^{-5}	4.07×10^{-5}
Biofuel	4.07×10^{-5}	4.15×10^{-5}	8.14×10^{-5}	1.00×10^{-4}	2.42×10^{-5}	3.18×10^{-5}	4.33×10^{-5}	6.22×10^{-5}	4.27×10^{-5}	4.69×10^{-5}	3.23×10^{-5}
Biomass	5.49×10^{-5}	3.58×10^{-5}	5.22×10^{-5}	1.28×10^{-4}	2.82×10^{-5}	3.18×10^{-5}	5.48×10^{-5}	3.63×10^{-5}	2.42×10^{-5}	3.74×10^{-5}	3.24×10^{-5}
Organic carbon											
Anthropogenic	-1.03×10^{-5}	-9.81×10^{-6}	-1.05×10^{-5}	-8.77×10^{-6}	-9.80×10^{-6}	-1.09×10^{-5}	-1.00×10^{-5}	-1.03×10^{-5}	-7.19×10^{-6}	-9.72×10^{-6}	-9.90×10^{-6}
Biofuel	-1.06×10^{-5}	-9.81×10^{-6}	-1.06×10^{-5}	-8.52×10^{-6}	-1.02×10^{-5}	-1.12×10^{-5}	-1.11×10^{-5}	-8.95×10^{-6}	-7.03×10^{-6}	-1.01×10^{-5}	-9.29×10^{-6}
Biomass	-1.28×10^{-5}	-1.41×10^{-5}	-1.33×10^{-5}	-9.99×10^{-6}	-1.24×10^{-5}	-1.35×10^{-5}	-1.18×10^{-5}	-1.28×10^{-5}	-1.08×10^{-5}	-1.19×10^{-5}	-1.05×10^{-5}
SO_2											
Anthropogenic	-4.30×10^{-6}	-4.78×10^{-6}	-4.64×10^{-6}	-3.79×10^{-6}	-5.03×10^{-6}	-5.77×10^{-6}	-4.78×10^{-6}	-4.73×10^{-6}	-2.21×10^{-6}	-4.80×10^{-6}	-3.69×10^{-6}
Biofuel	-2.36×10^{-6}	-1.53×10^{-6}	-1.83×10^{-6}	-1.41×10^{-6}	NA	NA	-2.19×10^{-6}	-2.64×10^{-6}	-1.50×10^{-6}	-2.06×10^{-6}	-1.37×10^{-6}
Biomass	-3.12×10^{-6}	-3.84×10^{-6}	-2.71×10^{-6}	-2.17×10^{-6}	-2.98×10^{-6}	-2.89×10^{-6}	-2.54×10^{-6}	-9.48×10^{-7}	-9.94×10^{-7}	-1.91×10^{-6}	-2.05×10^{-6}
Shipping	-2.14×10^{-6}	-2.08×10^{-6}	-1.72×10^{-6}	-1.19×10^{-6}	-1.34×10^{-6}	-1.65×10^{-6}	-1.83×10^{-6}	-1.55×10^{-6}	-1.21×10^{-6}	-1.44×10^{-6}	-2.01×10^{-6}
NH_3											
Anthropogenic	-8.79×10^{-6}	-7.28×10^{-6}	-1.34×10^{-5}	-1.09×10^{-5}	-4.54×10^{-6}	-5.64×10^{-6}	-8.16×10^{-6}	-1.21×10^{-5}	-6.56×10^{-6}	-9.22×10^{-6}	-5.79×10^{-6}
Natural	-9.27×10^{-6}	-8.39×10^{-6}	-1.66×10^{-5}	-1.20×10^{-5}	-4.43×10^{-6}	-6.72×10^{-6}	-8.60×10^{-6}	-1.20×10^{-5}	-4.92×10^{-6}	-1.01×10^{-5}	-3.27×10^{-6}
Biomass	-7.43×10^{-6}	-7.03×10^{-6}	-1.04×10^{-5}	-1.32×10^{-5}	-5.14×10^{-6}	-5.96×10^{-6}	-8.52×10^{-6}	-1.33×10^{-5}	-7.34×10^{-6}	-7.99×10^{-6}	-4.42×10^{-6}
Biofuel	-1.08×10^{-5}	-1.01×10^{-5}	-1.73×10^{-5}	-1.27×10^{-5}	-4.77×10^{-6}	-6.03×10^{-6}	-7.94×10^{-6}	-9.38×10^{-6}	-5.29×10^{-6}	-8.98×10^{-6}	-3.95×10^{-6}

Table A3: Global warming potential for 20 and 100 years. The source of each value is shown in brackets.

species	**GWP(20)**	**GWP(100)**
SO_2	-100 [Rypdal et al., 2009]	-25 [Rypdal et al., 2009]
CO	10.5 [Berntsen et al., 2005]	3.8 [Berntsen et al., 2005]
NO_x	14.8 [Berntsen et al., 2005]	-1.45 [Berntsen et al., 2005]
non-methane VOC	4.5 [Rypdal et al., 2009]	4.5 [Rypdal et al., 2009]
CH_4	72 [Forster et al., 2007]	25 [Forster et al., 2007]
N_2O	289 [Forster et al., 2007]	298 [Forster et al., 2007]
Black Carbon	2400 [Bond et al., 2011]	690 [Bond et al., 2011]
Organic Carbon	-110 [Bond et al., 2011]	-30 [Bond et al., 2011]

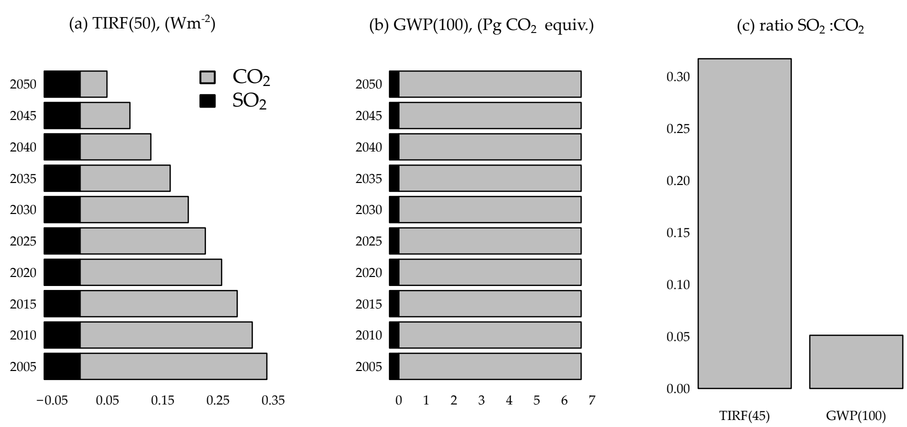
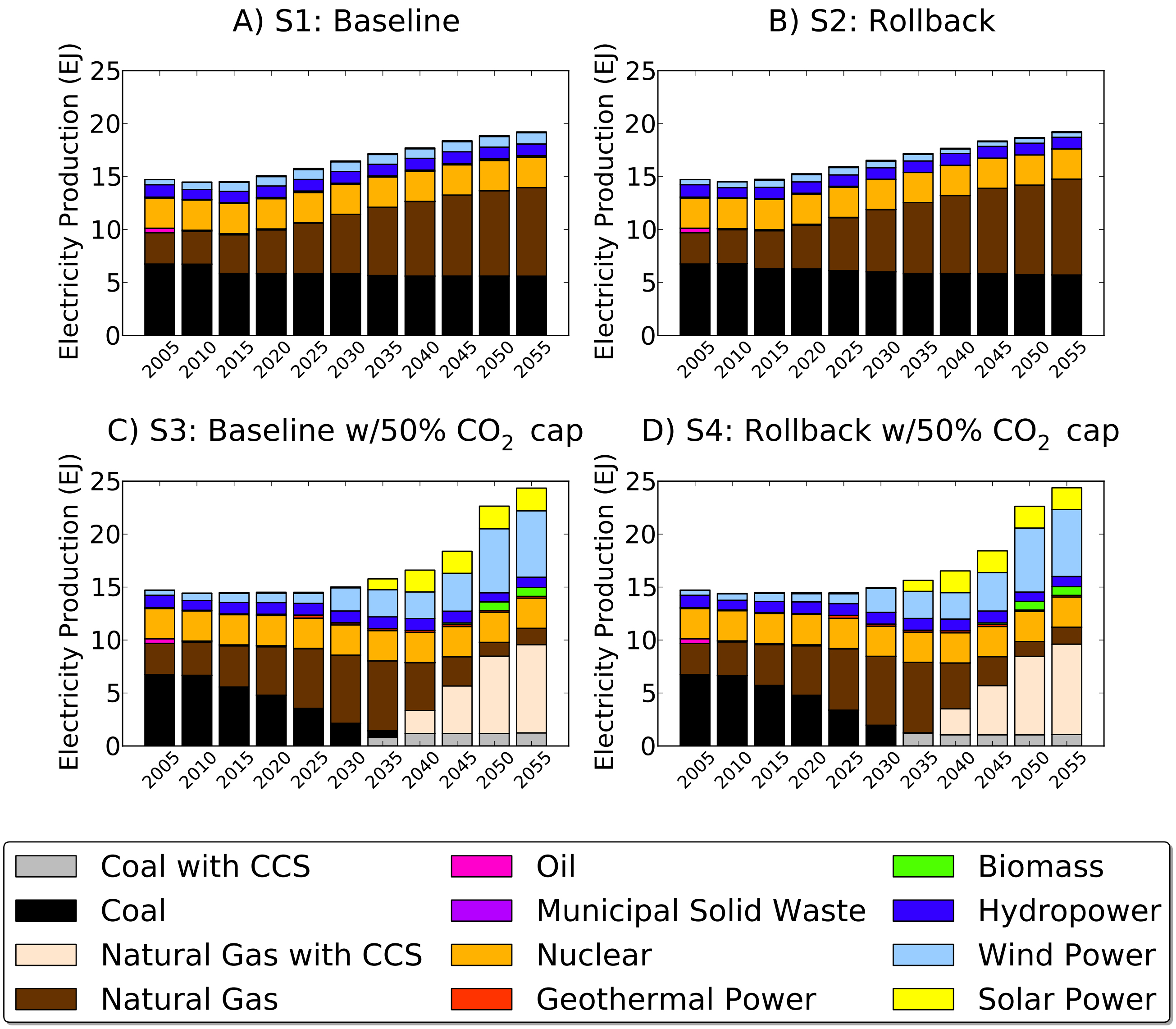


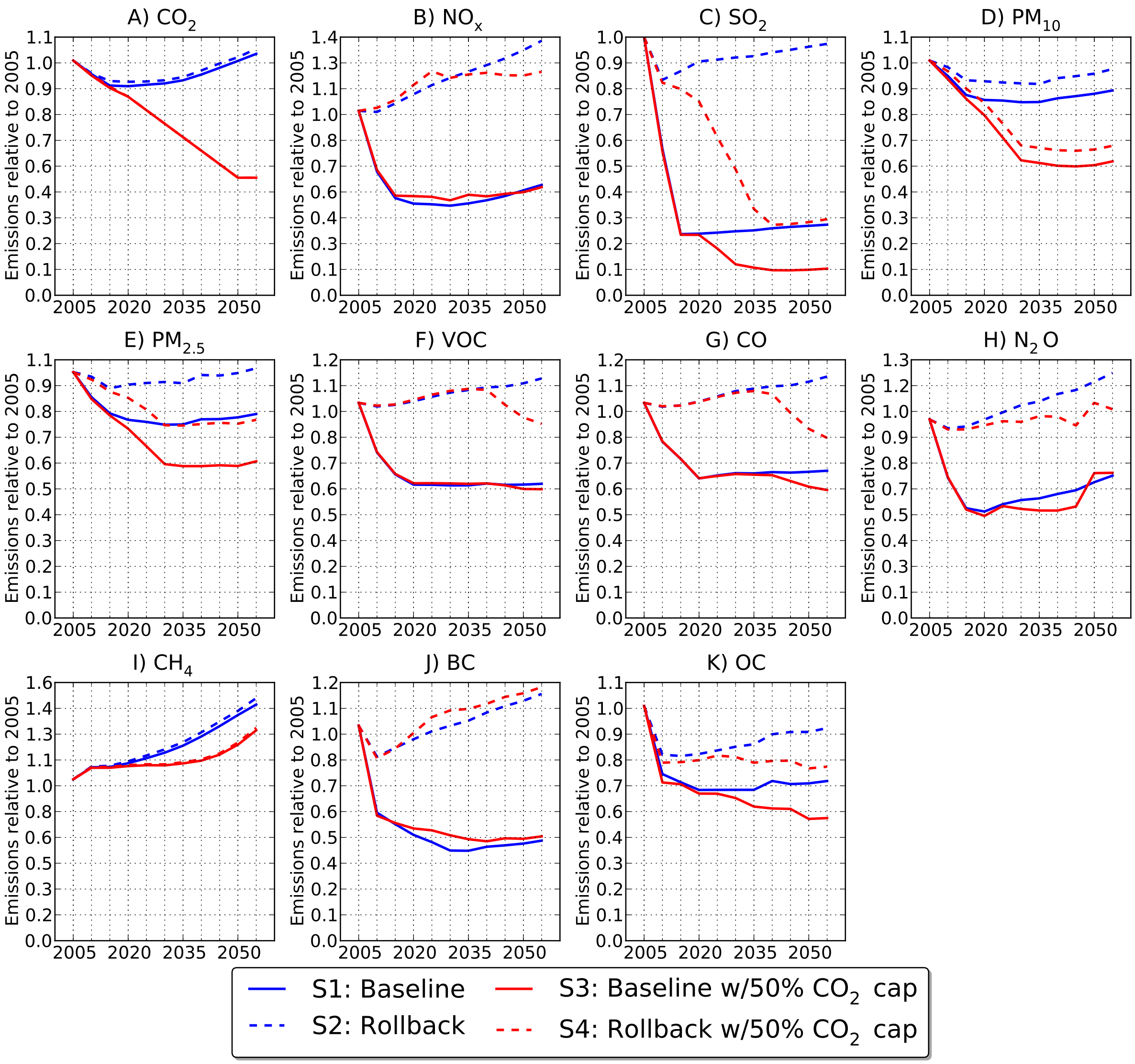
Figure A1: The contribution of each year's emissions to the TIRF(50), GWP(100) for a scenario with constant emissions of CO_2 and SO_2 (a, b). Figure (c) shows the ratio of the contribution of SO_2 to CO_2 for the two metrics. Note that SO_2 is relatively larger impact on the TIRF(50) metric.

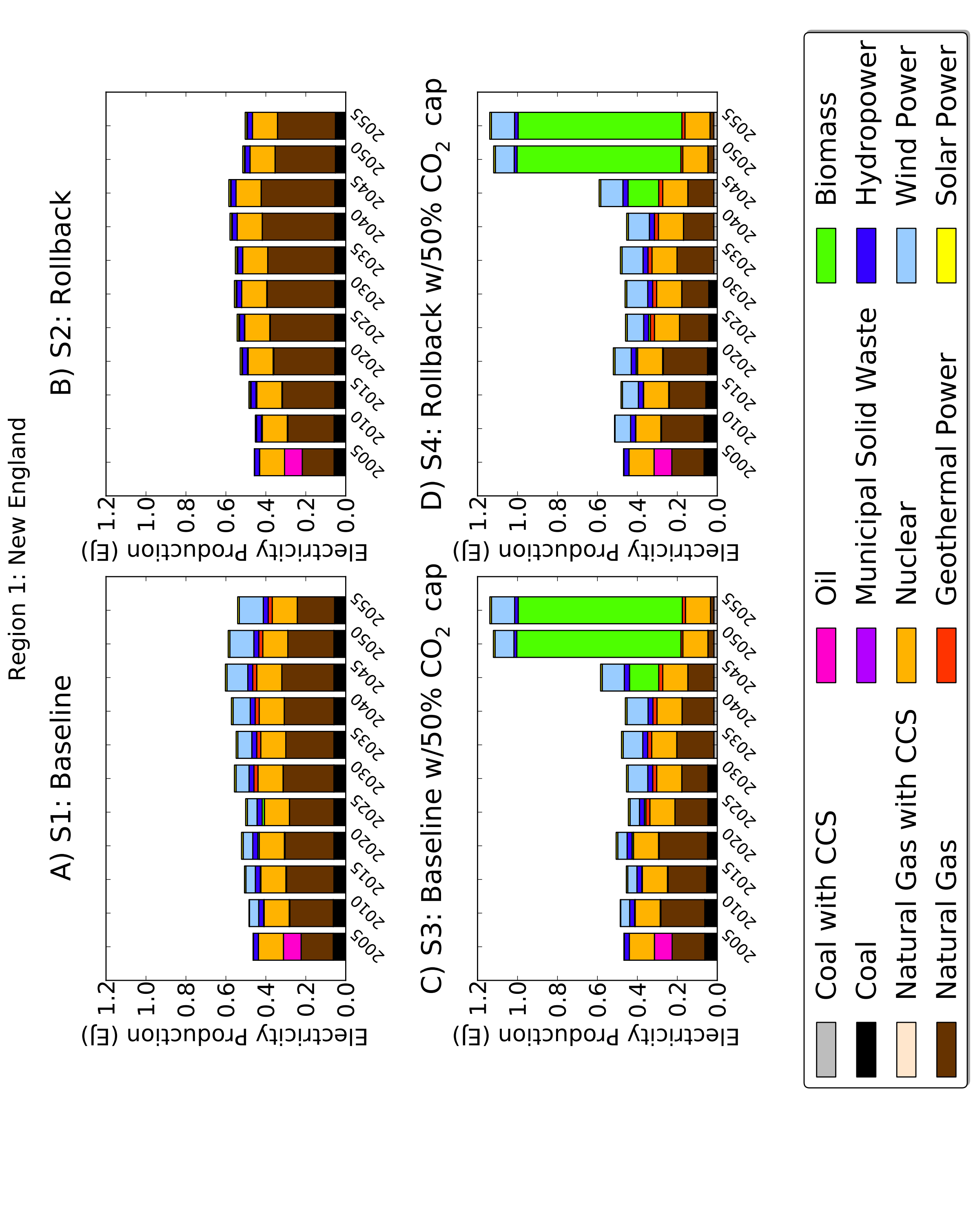
Supporting Information
Appendix B
Regional Electricity Generation and Energy Results

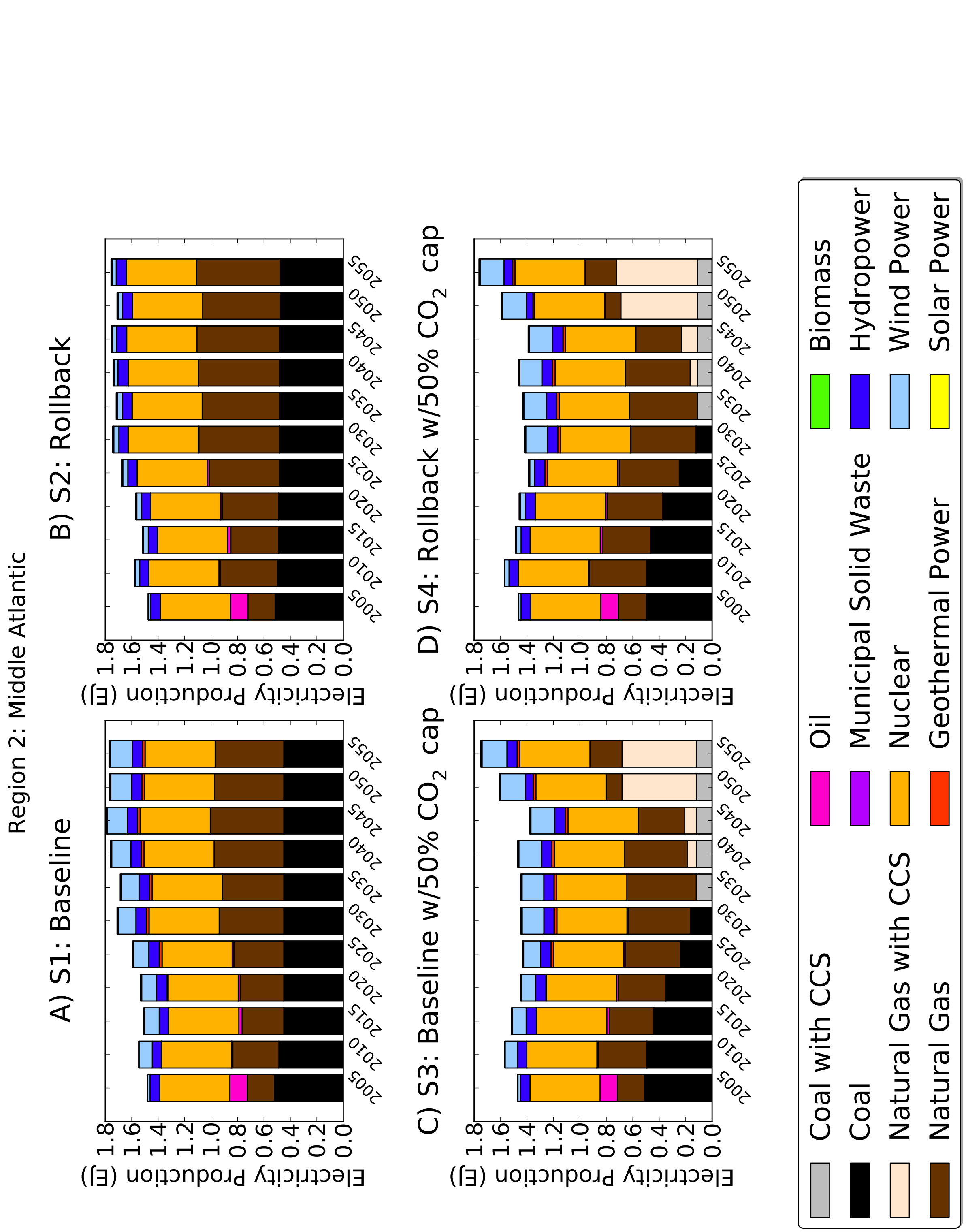
The first figure shows the fuels used for electricity generation for each scenario. The adoption of current air quality regulations does not lead to a significant change in the mix of fuels used in the electricity generation sector (Panel B), but the adoption of a CO_2 emission reduction target (Panels C and D), however, leads to significant changes in generation technology, including the removal of coal fuels, more widespread use of carbon capture and sequestration (CCS), and the adoption of solar and wind power. Other sectors including industrial, residential and transportation energy use are shown in the Appendix C. The second figure shows the US emission changes for each pollutant for each of the four scenarios. In the next 9 figures, each show the relative contribution of different technologies to electricity production. Each of the nine regions is labeled. The next nine figures are for the emissions in each region. These emissions are for the entire energy system modeled by MARKAL.

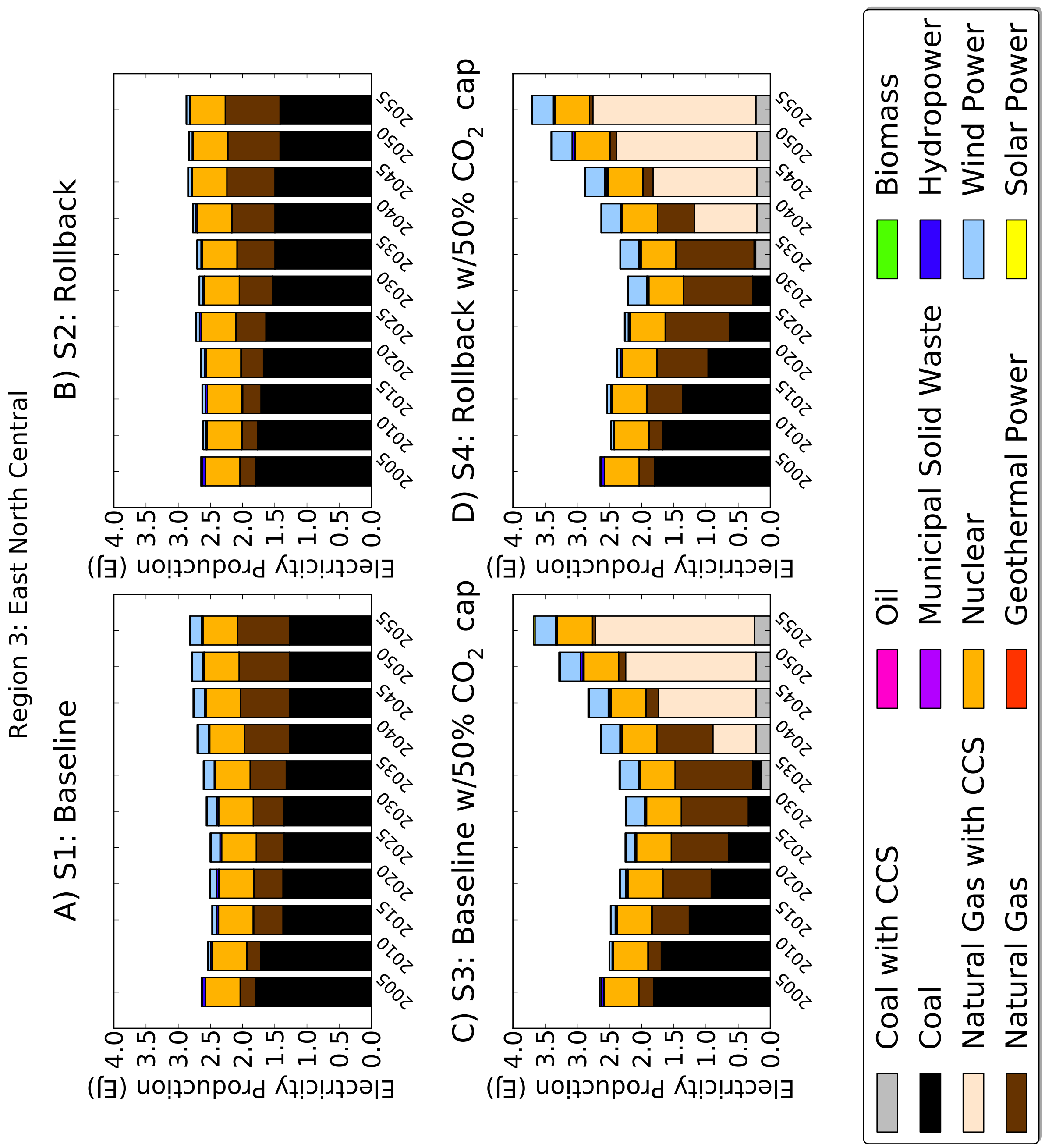


A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0
5
10
15
20
25
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

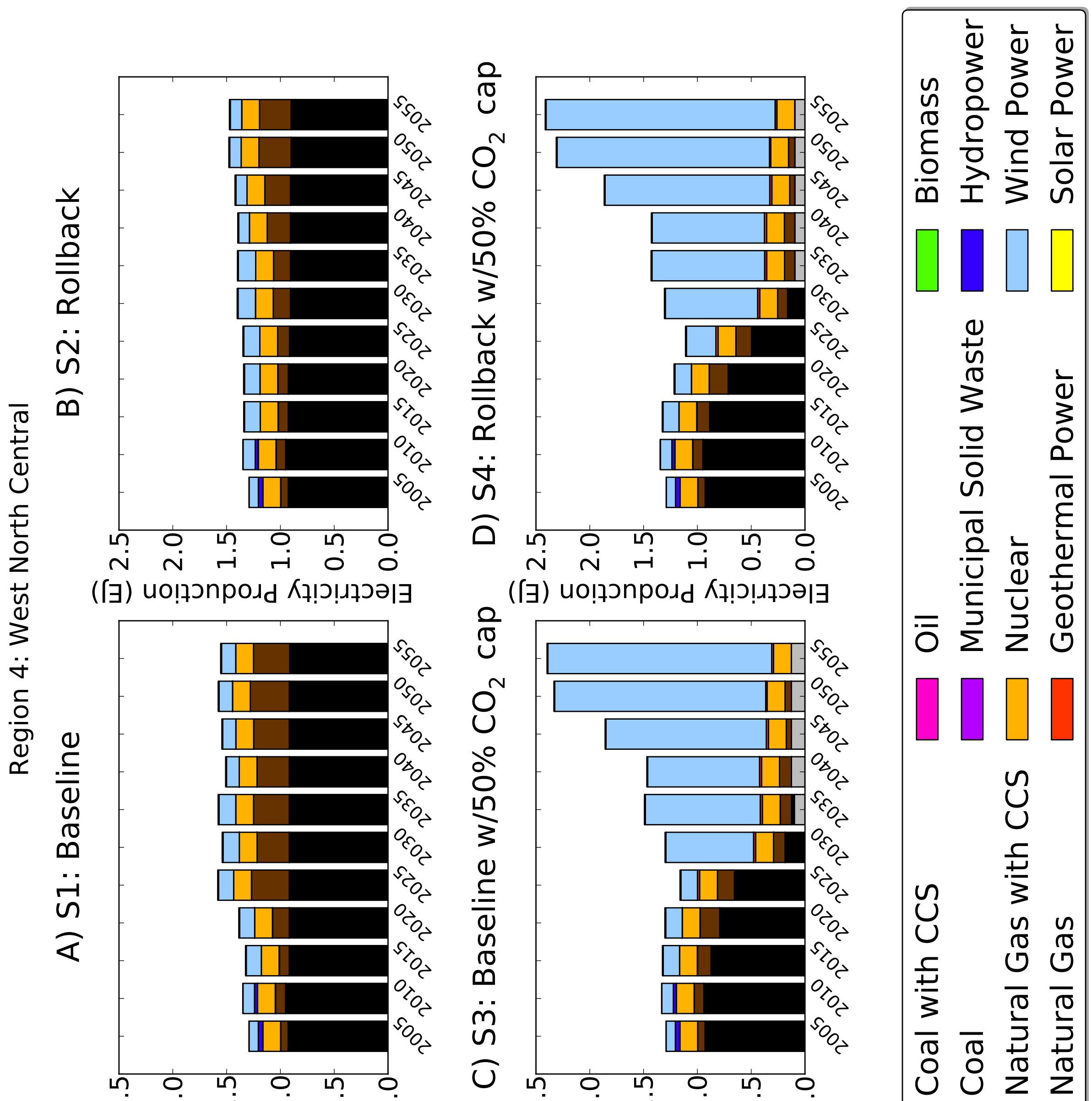

A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

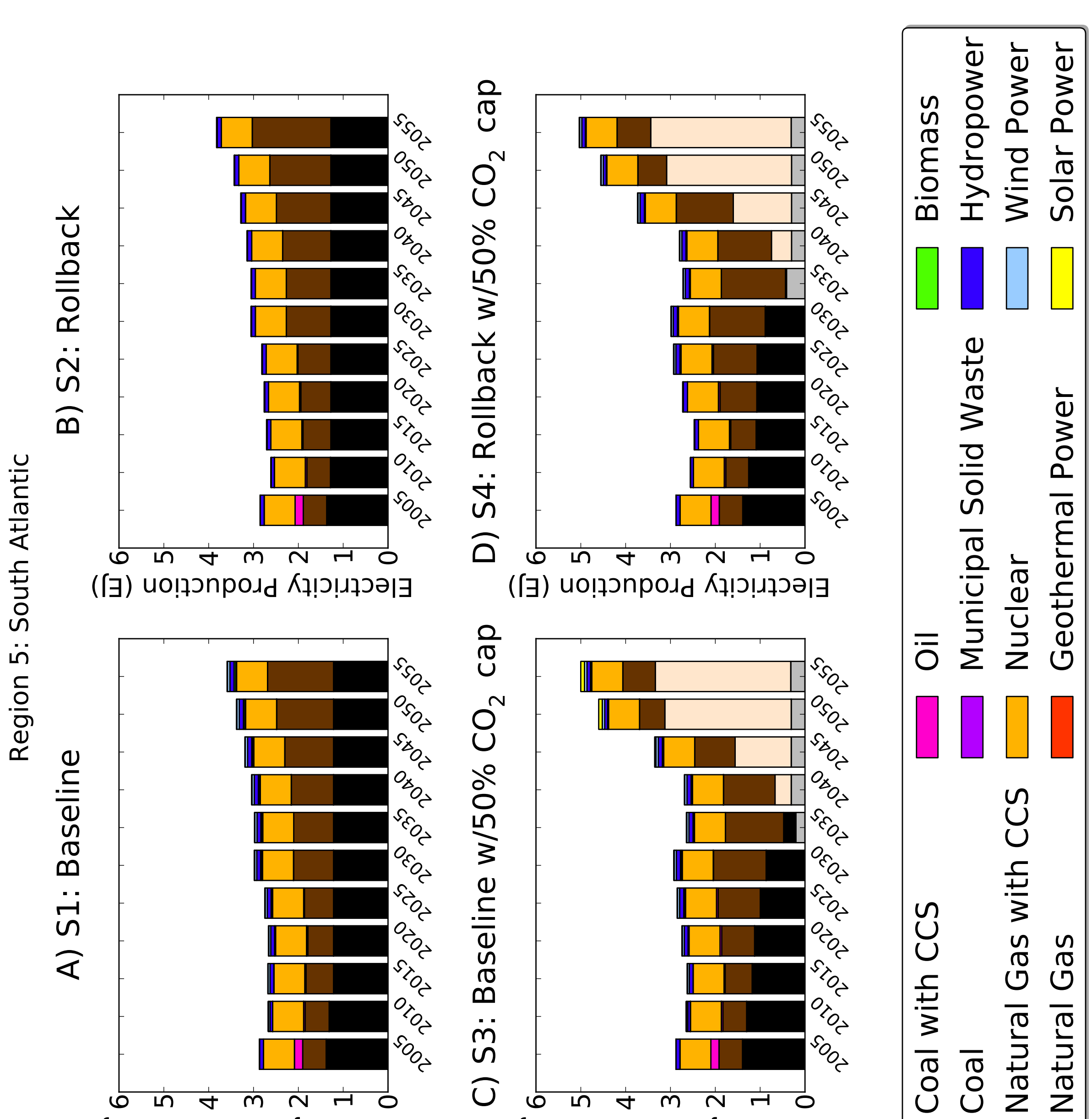

Region 1: New England
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO2 cap
D) S4: Rollback w/50% CO2 cap
Electricity Production (EJ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

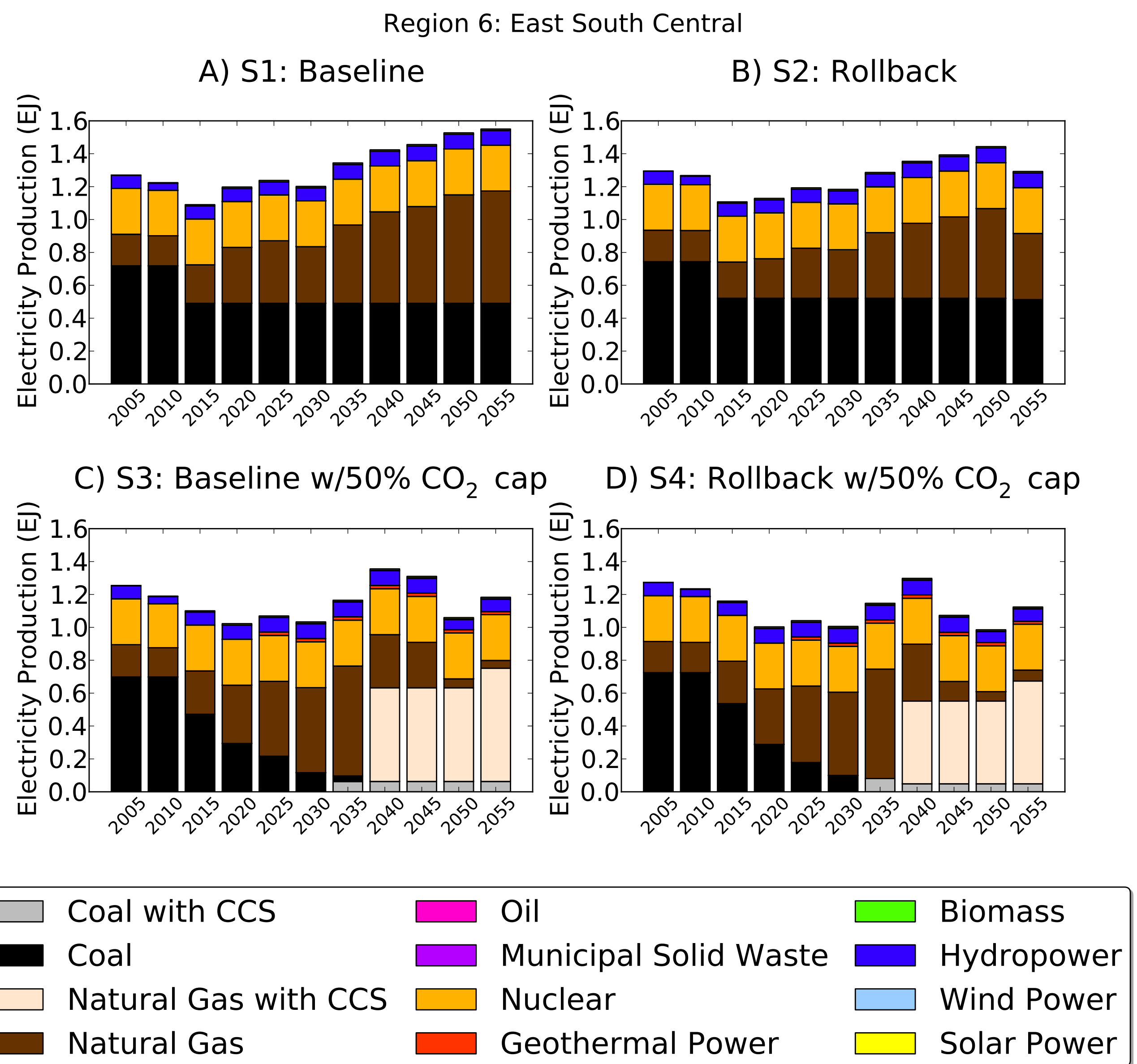

Region 2: Middle Atlantic
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

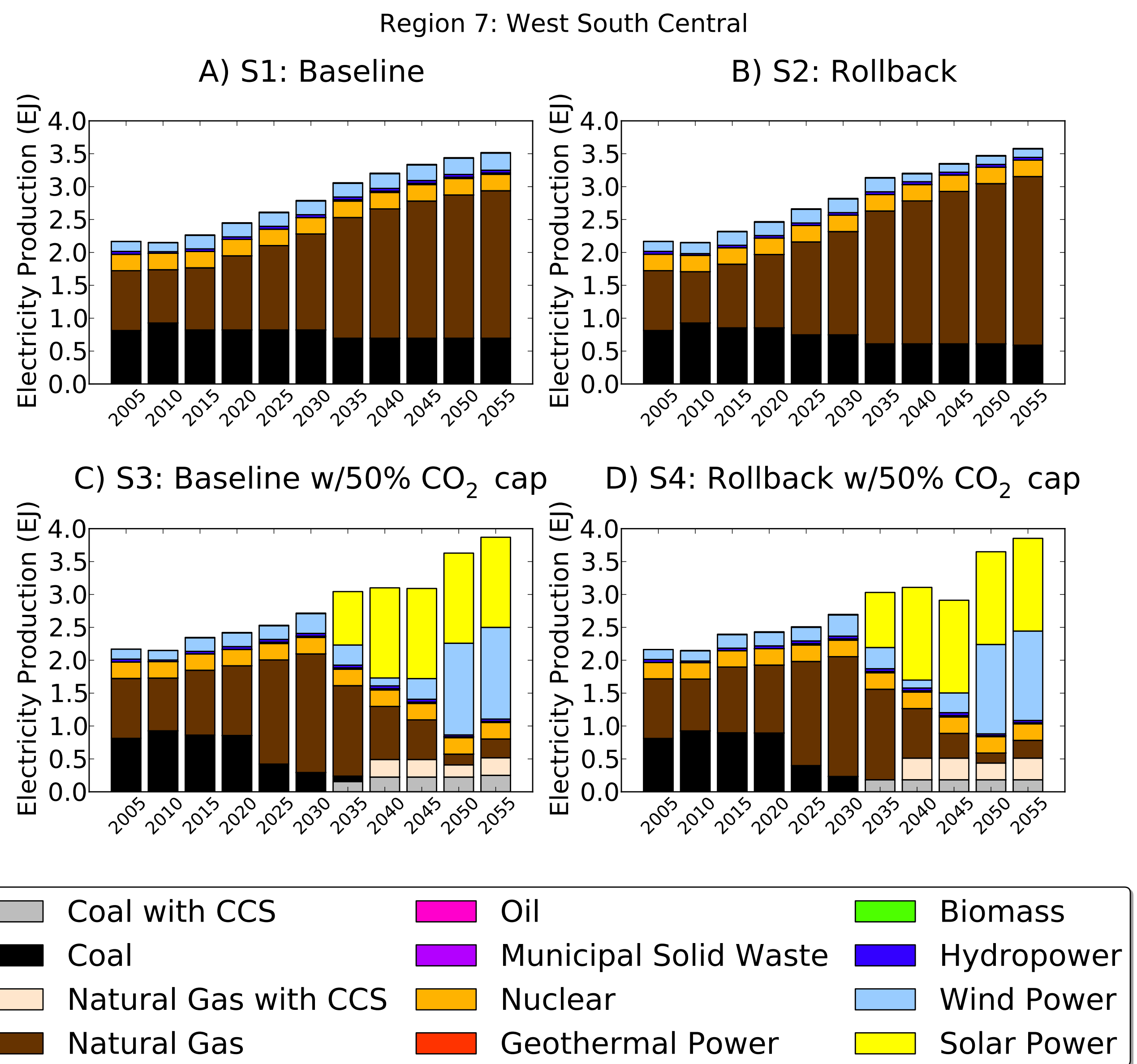


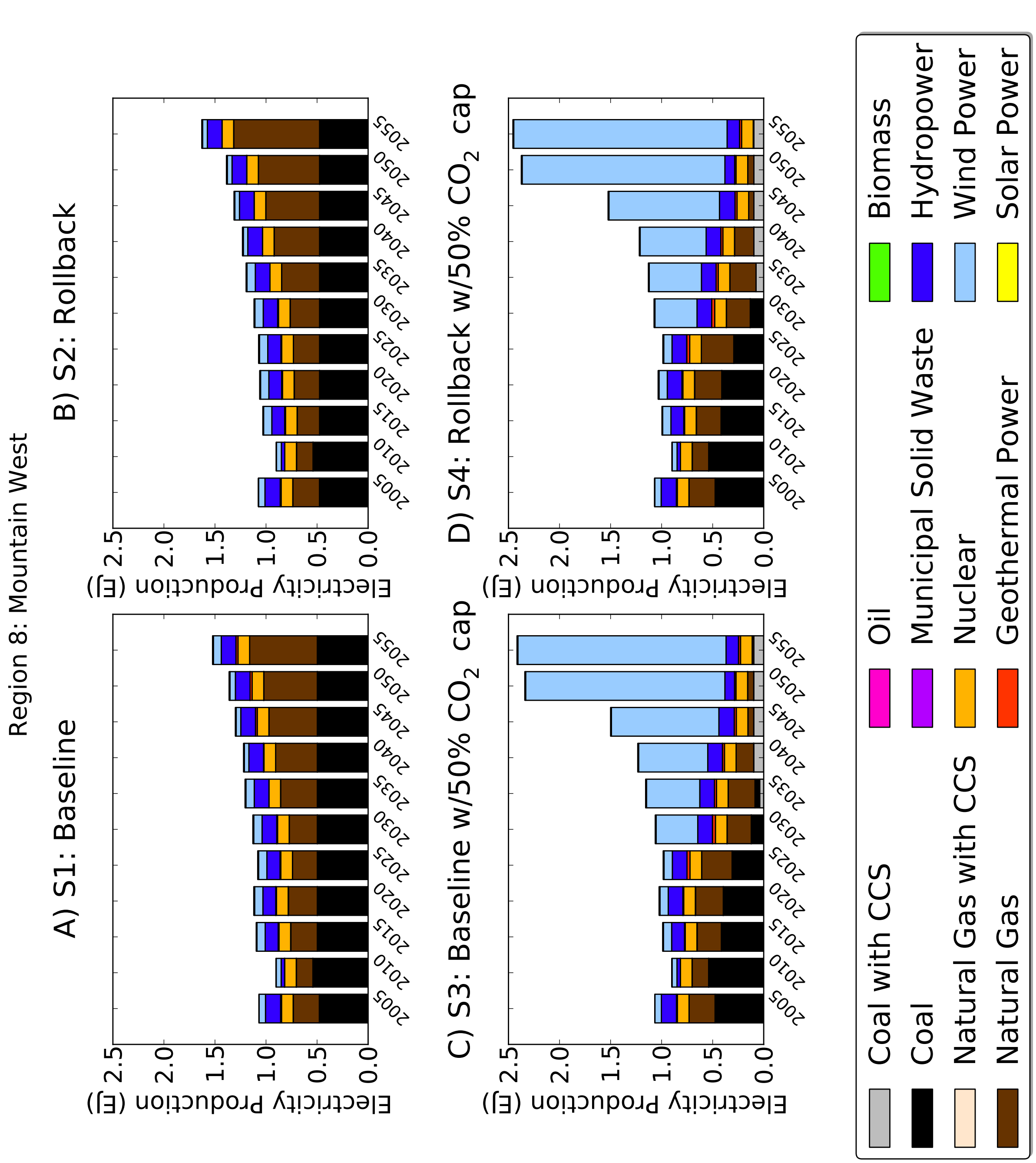
Region 3: East North Central
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

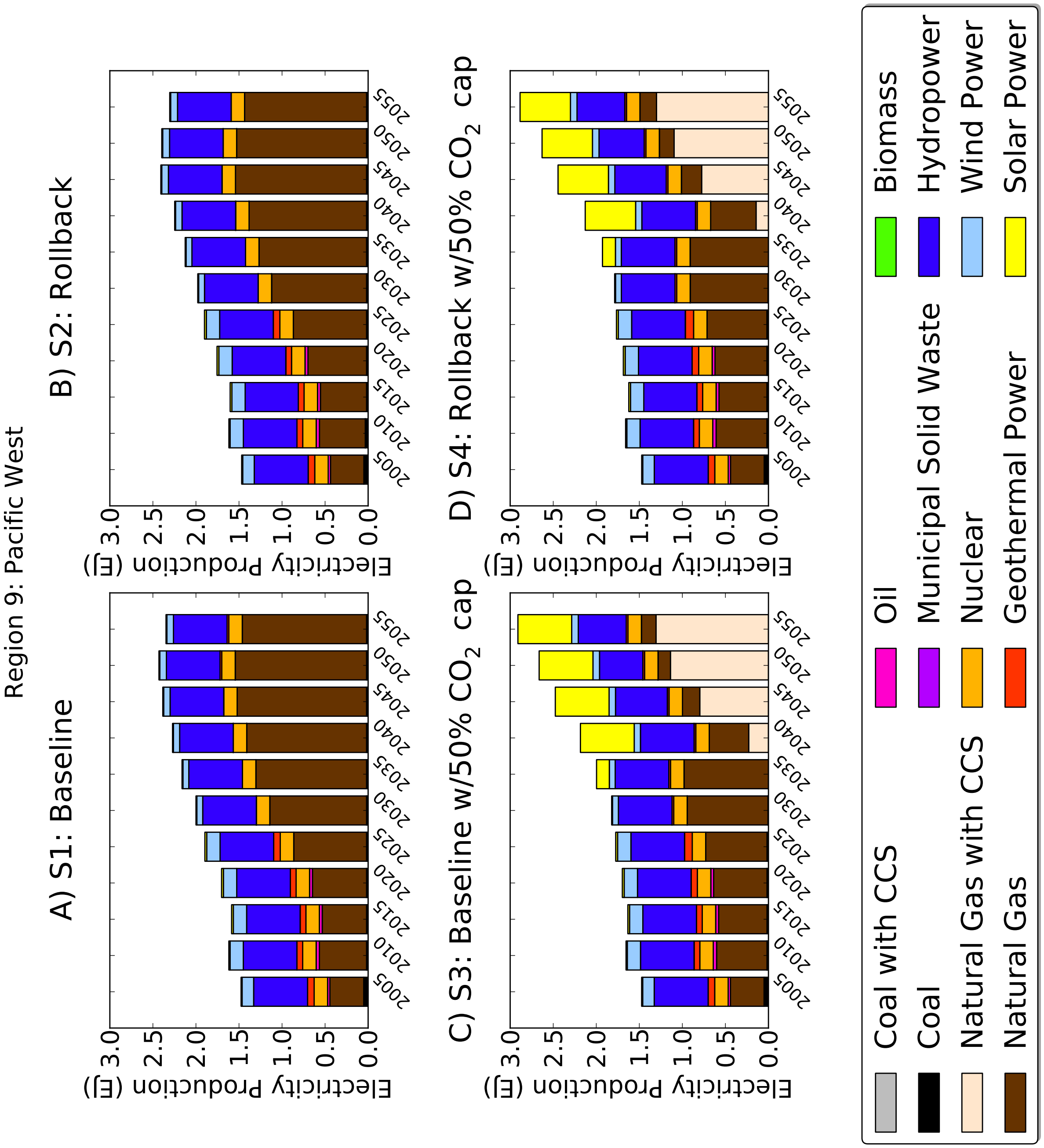

Region 4: West North Central
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.5
1.0
1.5
2.0
2.5
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power


Region 5: South Atlantic
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0
1
2
3
4
5
6
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power


Region 6: East South Central
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

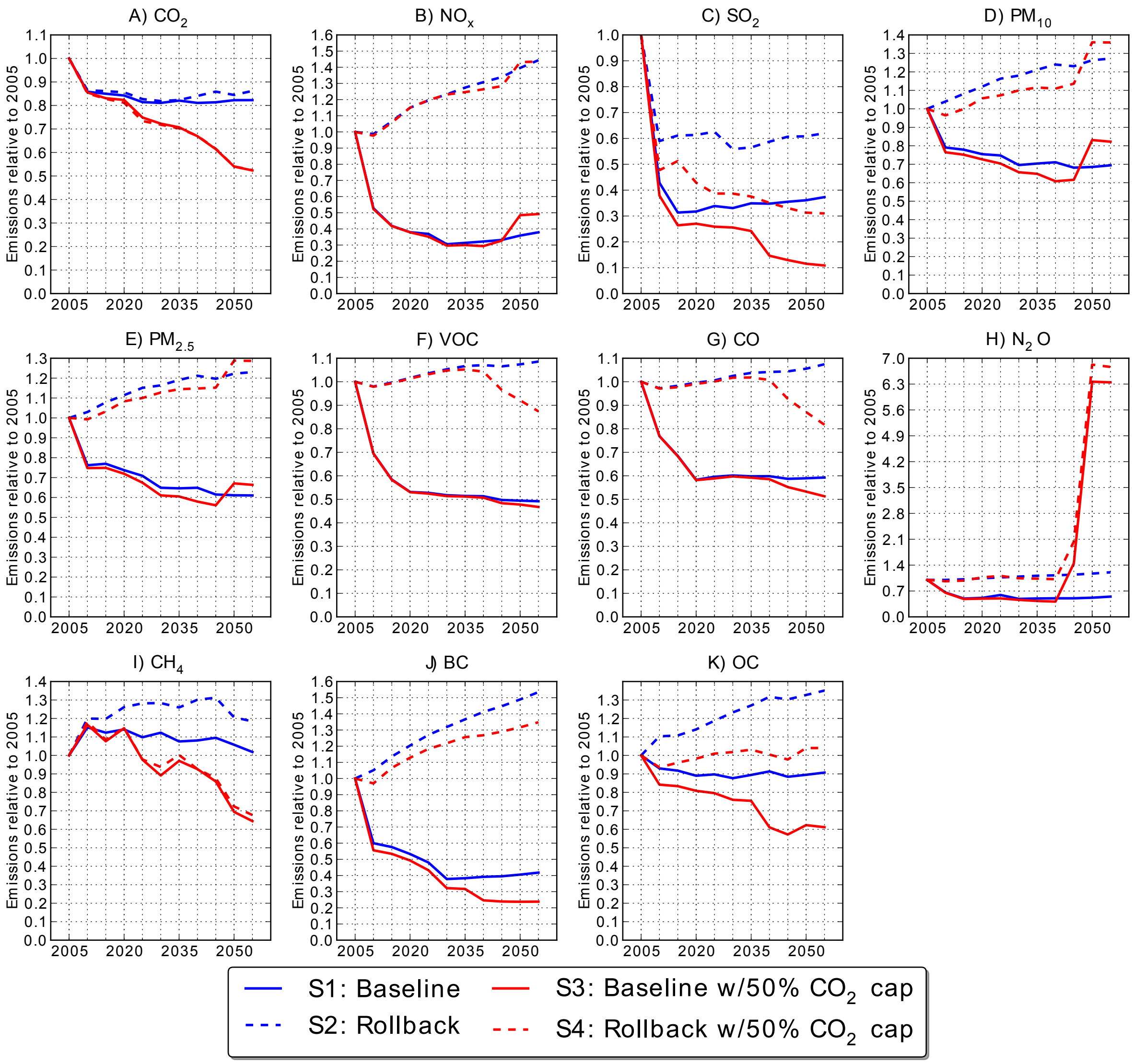

Region 7: West South Central
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power


Region 8: Mountain West
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.5
1.0
1.5
2.0
2.5
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

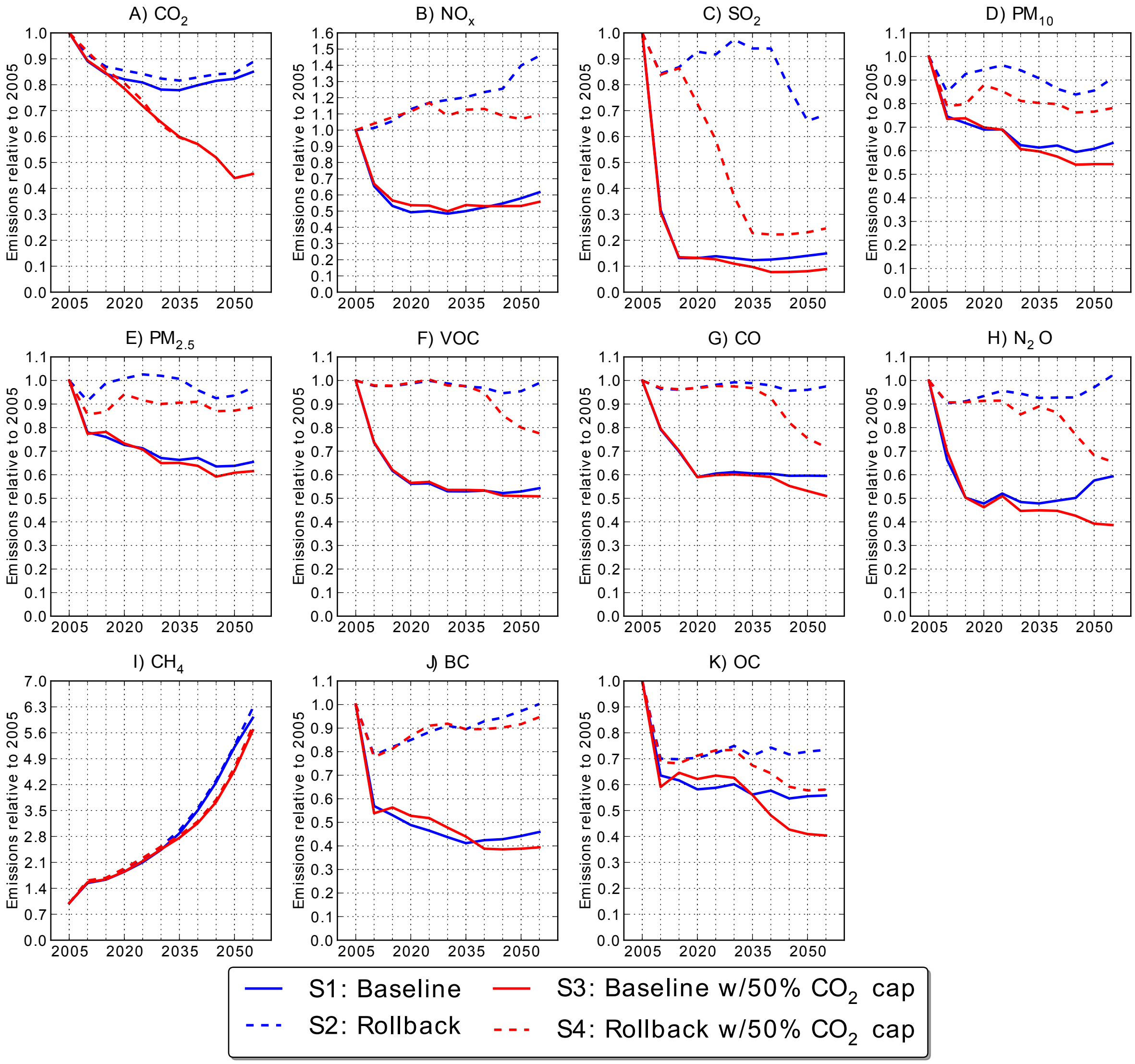


Region 9: Pacific West
A) S1: Baseline
B) S2: Rollback
C) S3: Baseline w/50% CO_2 cap
D) S4: Rollback w/50% CO_2 cap
Electricity Production (EJ)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power

Region 1

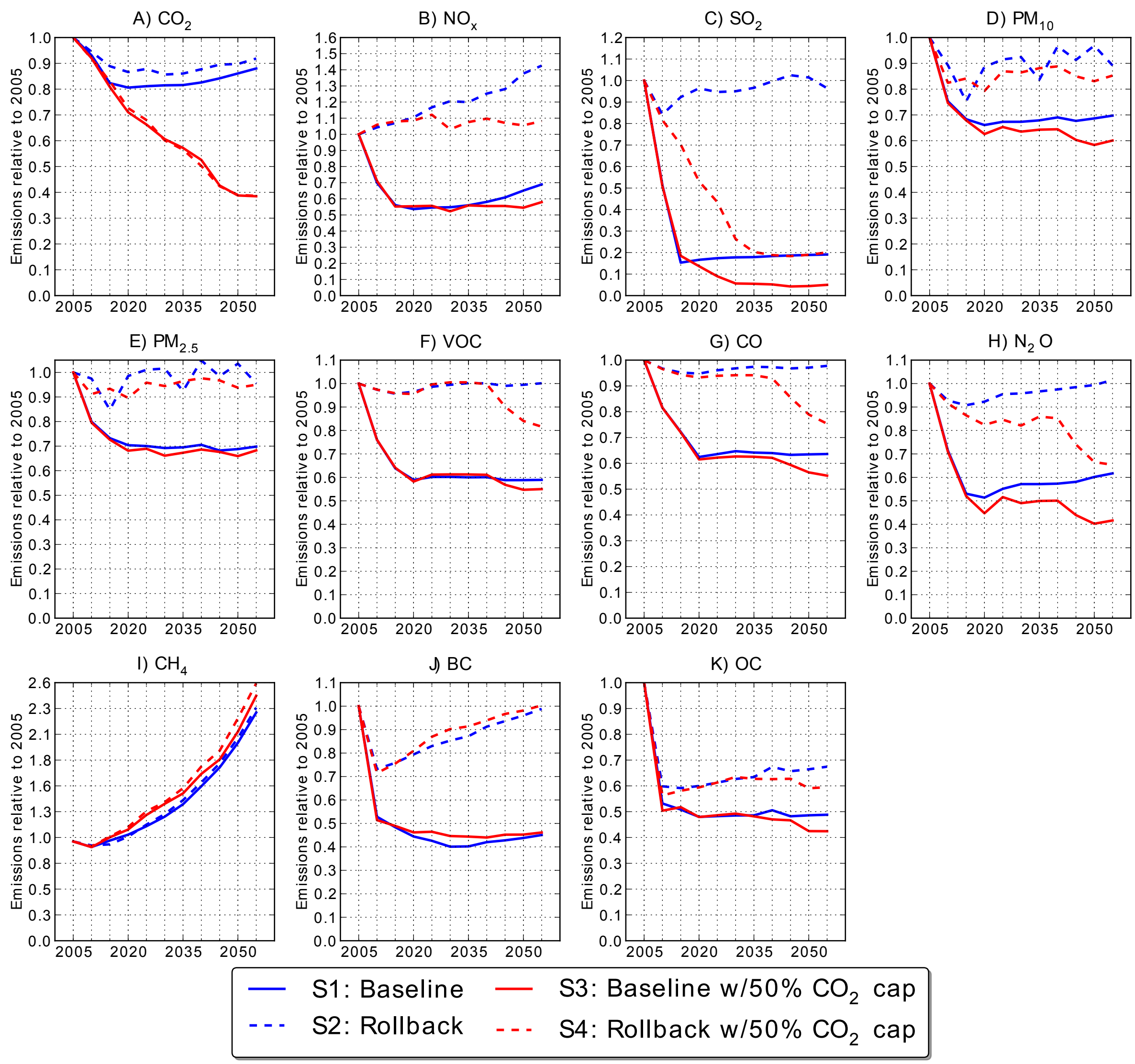

A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005
2020
2035
2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

Region 2

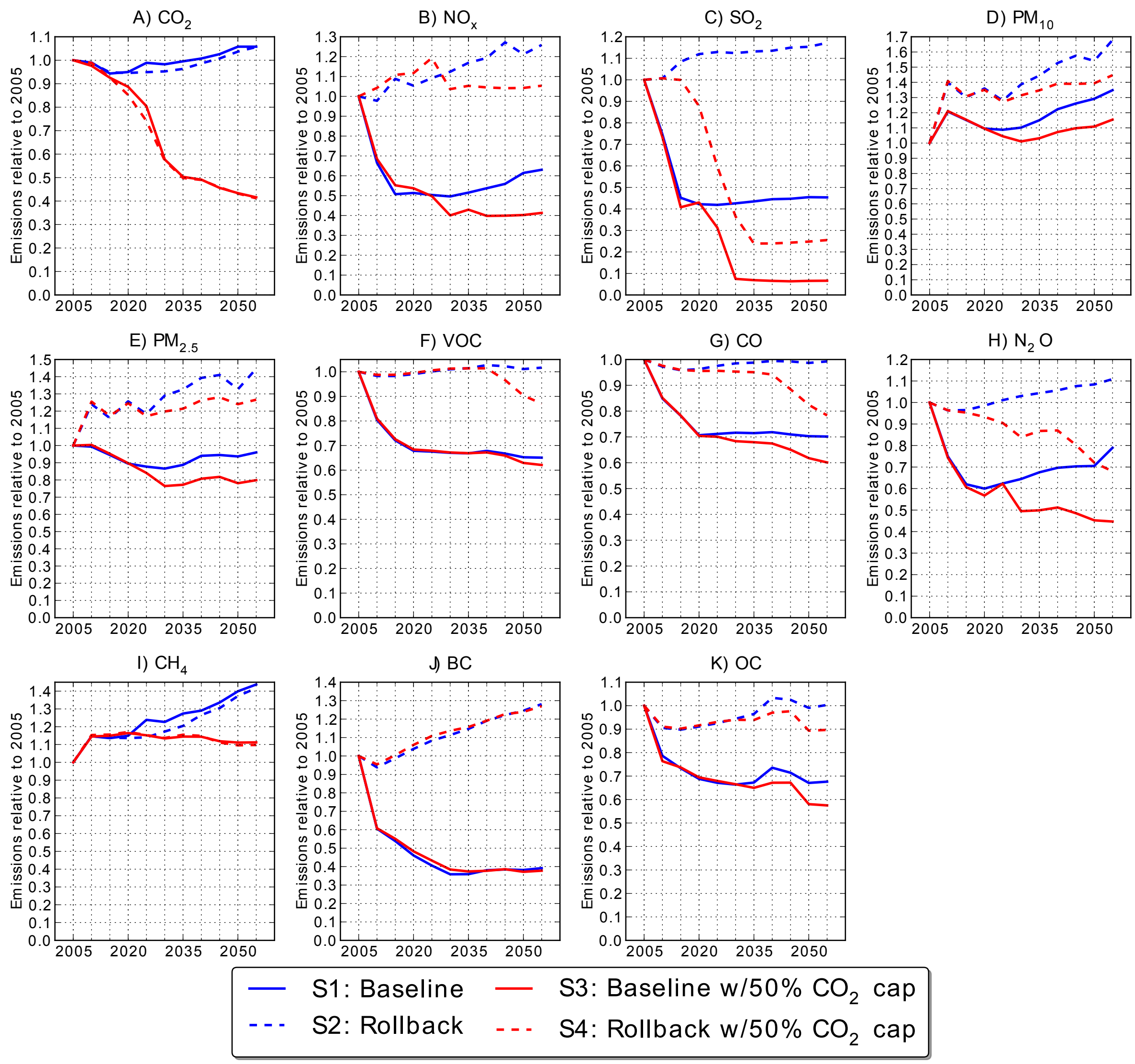


A) CO2
B) NOx
C) SO2
D) PM10
E) PM2.5
F) VOC
G) CO
H) N2 O
I) CH4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO2 cap
S4: Rollback w/50% CO2 cap

Region 3

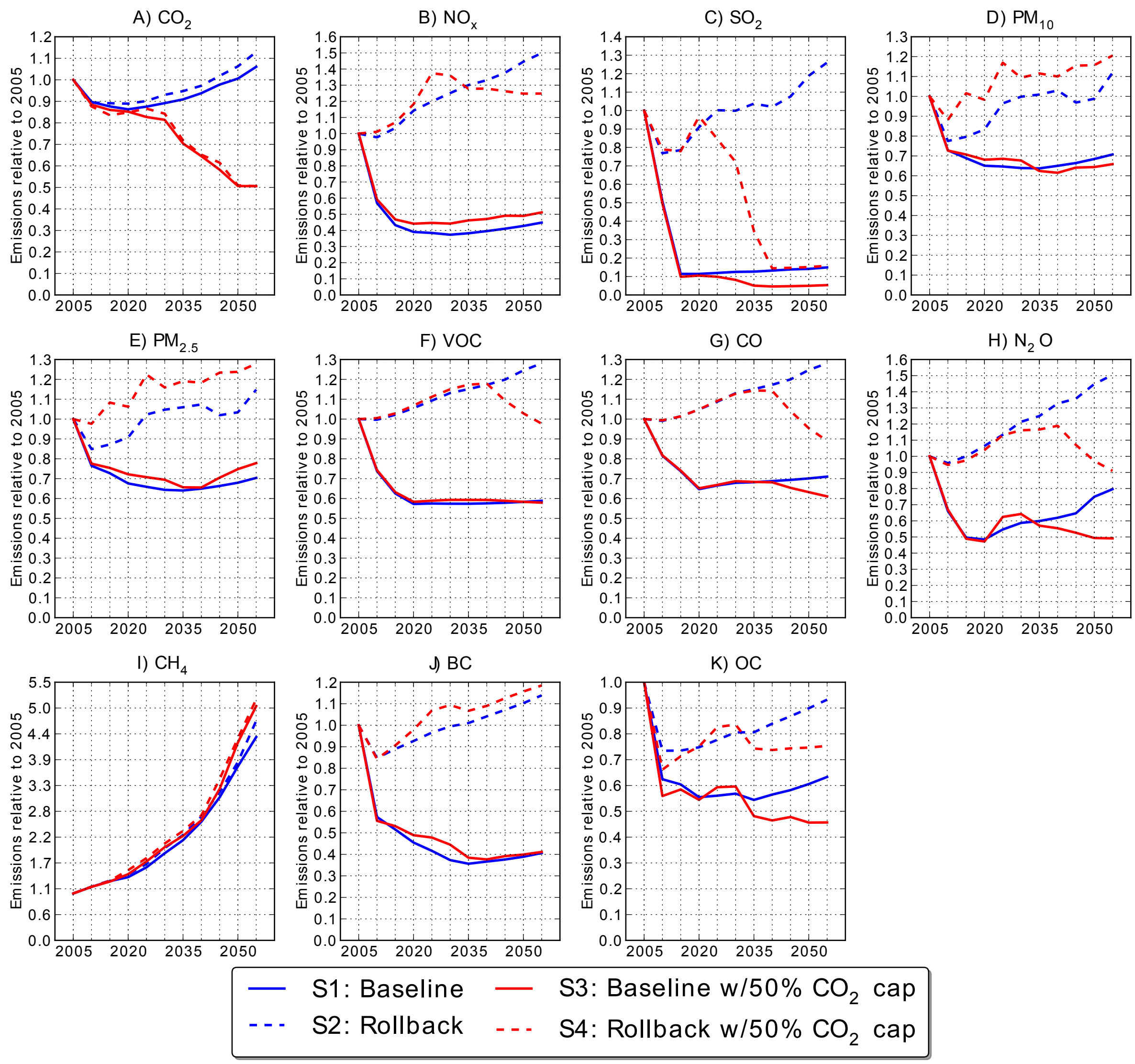

A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005
2020
2035
2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

Region 4

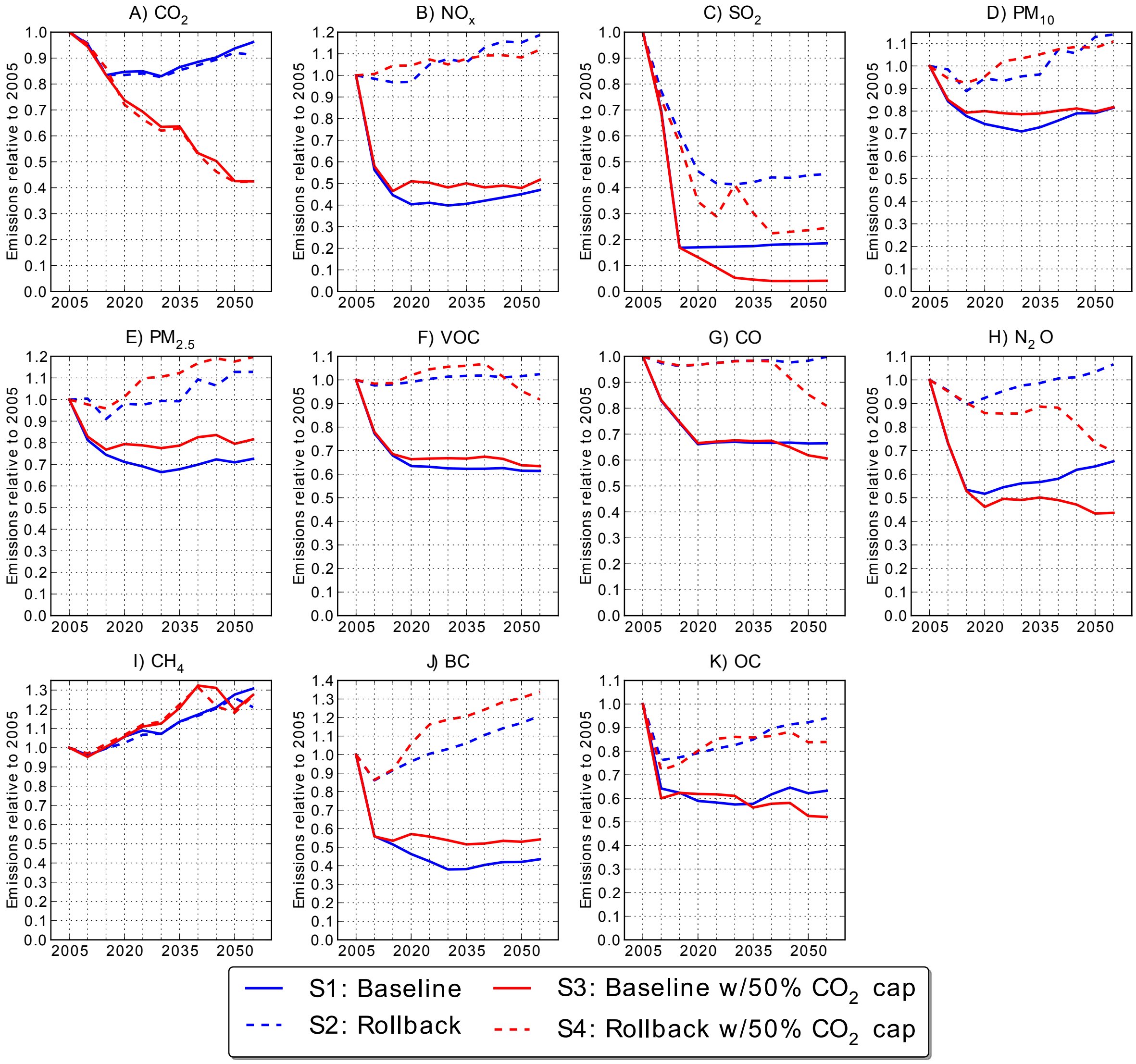


A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

Region 5

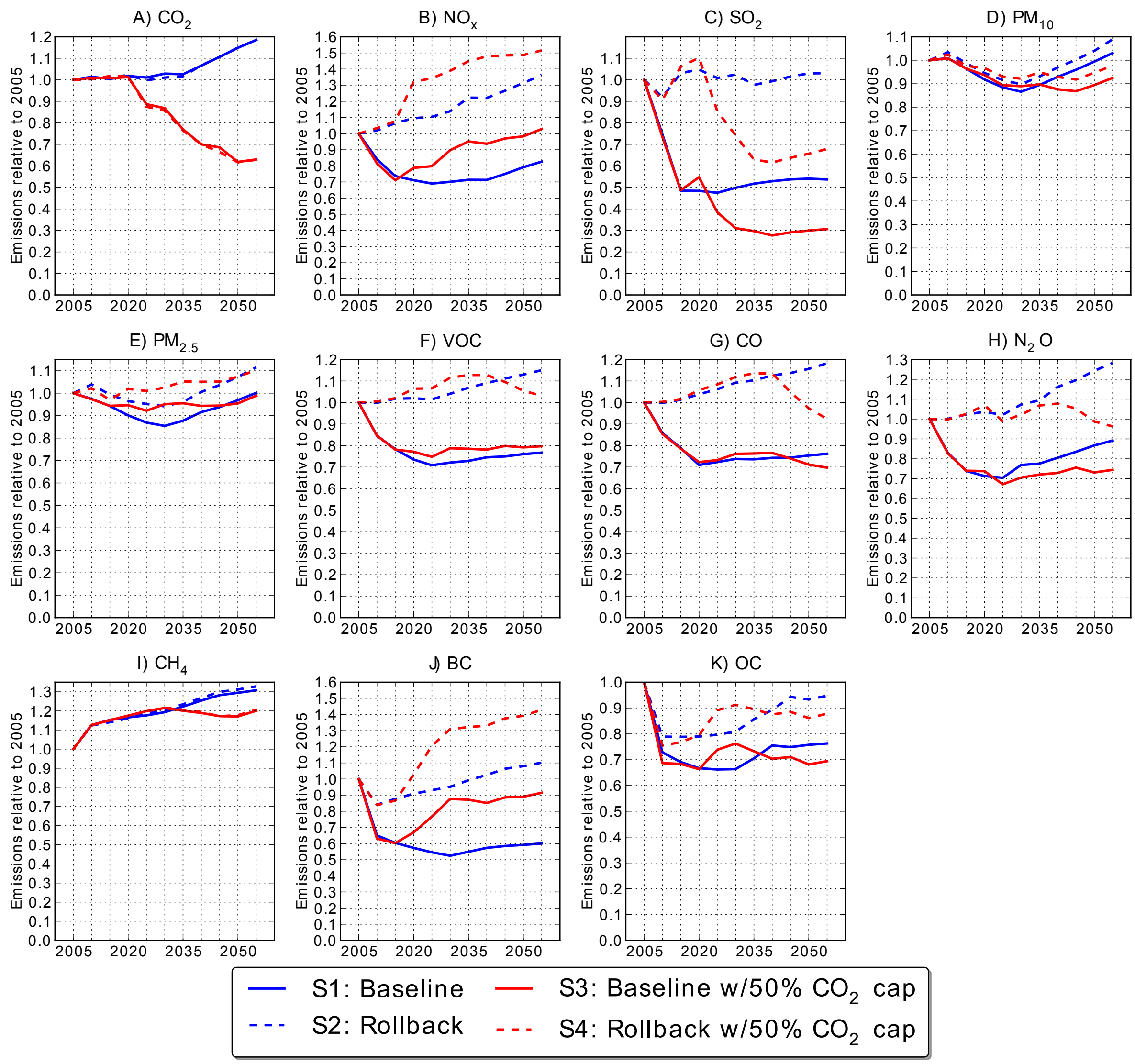

A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

Region 6

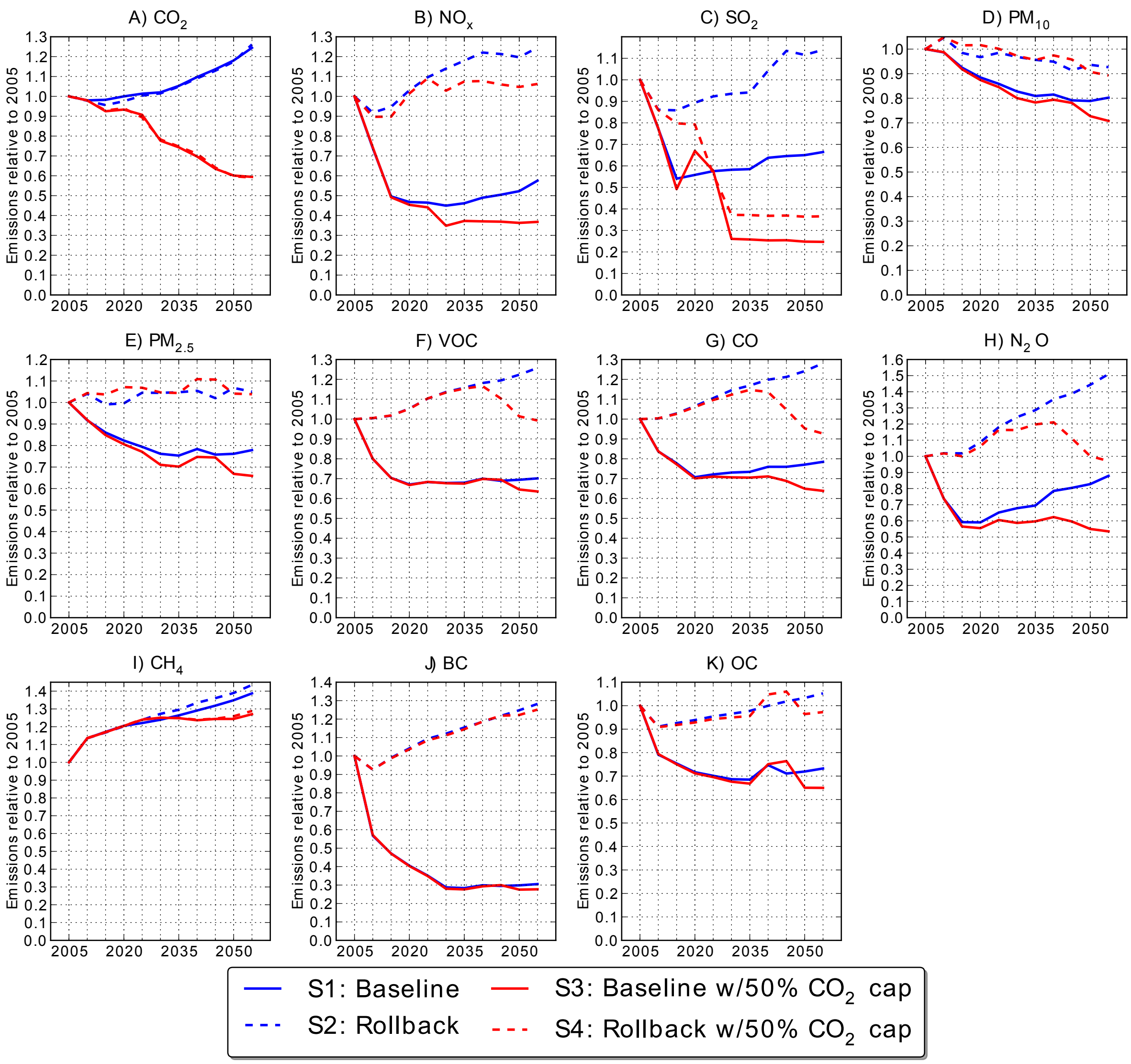


A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

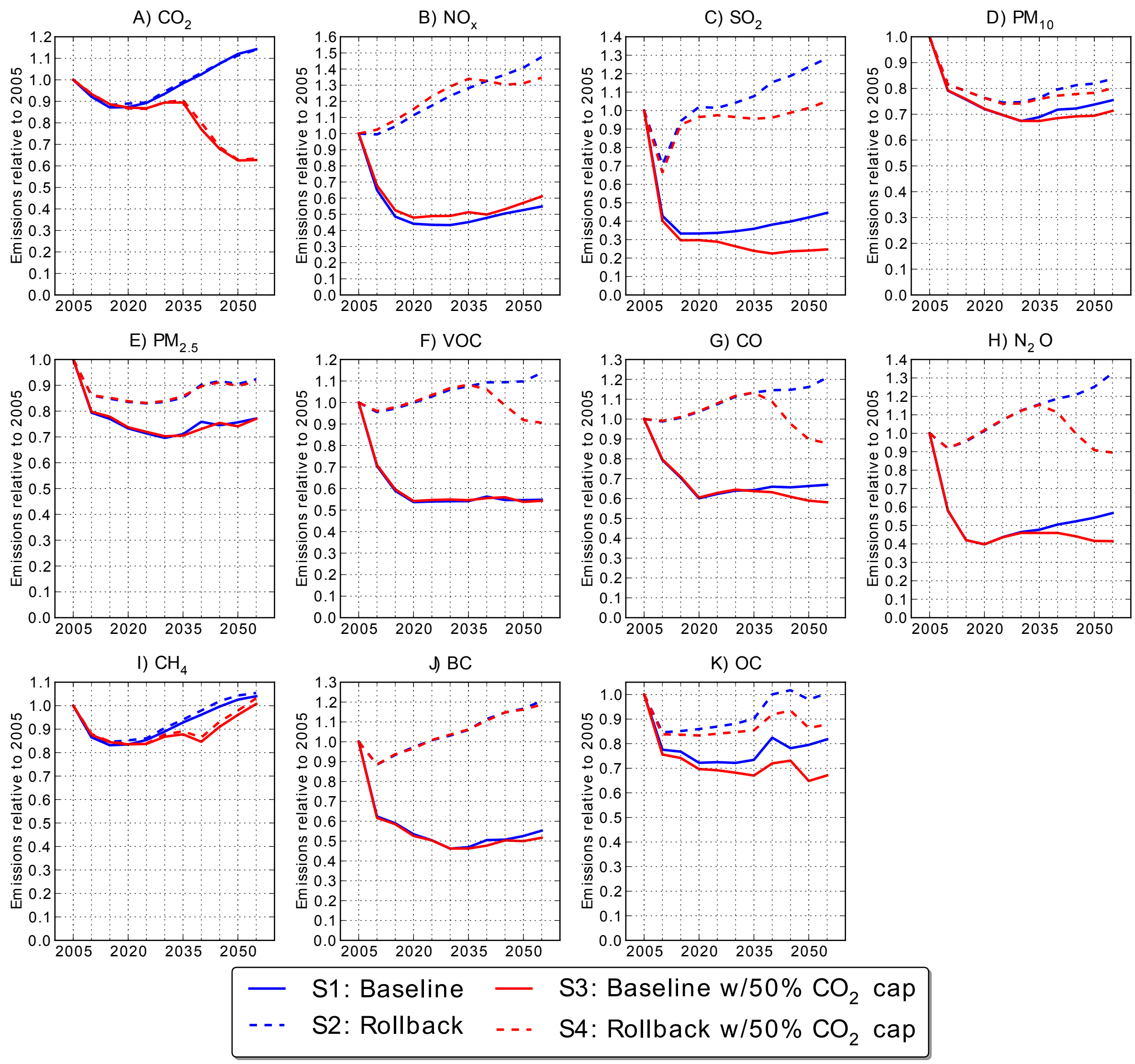
Region 7


A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

Region 8


A) CO2
B) NOx
C) SO2
D) PM10
E) PM2.5
F) VOC
G) CO
H) N2 O
I) CH4
J) BC
K) OC
Emissions relative to 2005
2005
2020
2035
2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO2 cap
S4: Rollback w/50% CO2 cap

Region 9

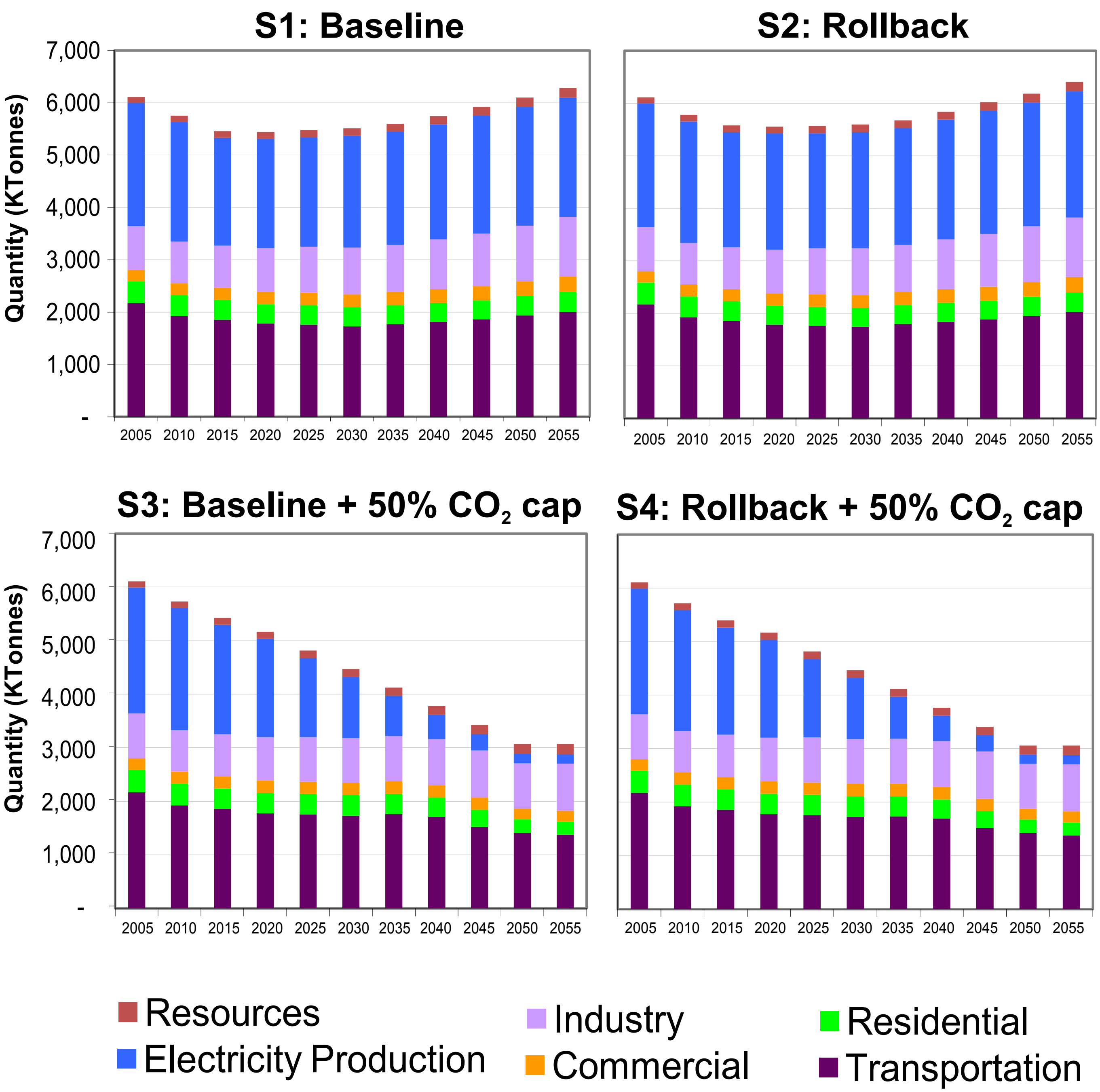


A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005 2020 2035 2050
S1: Baseline
S2: Rollback
S3: Baseline w/50% CO_2 cap
S4: Rollback w/50% CO_2 cap

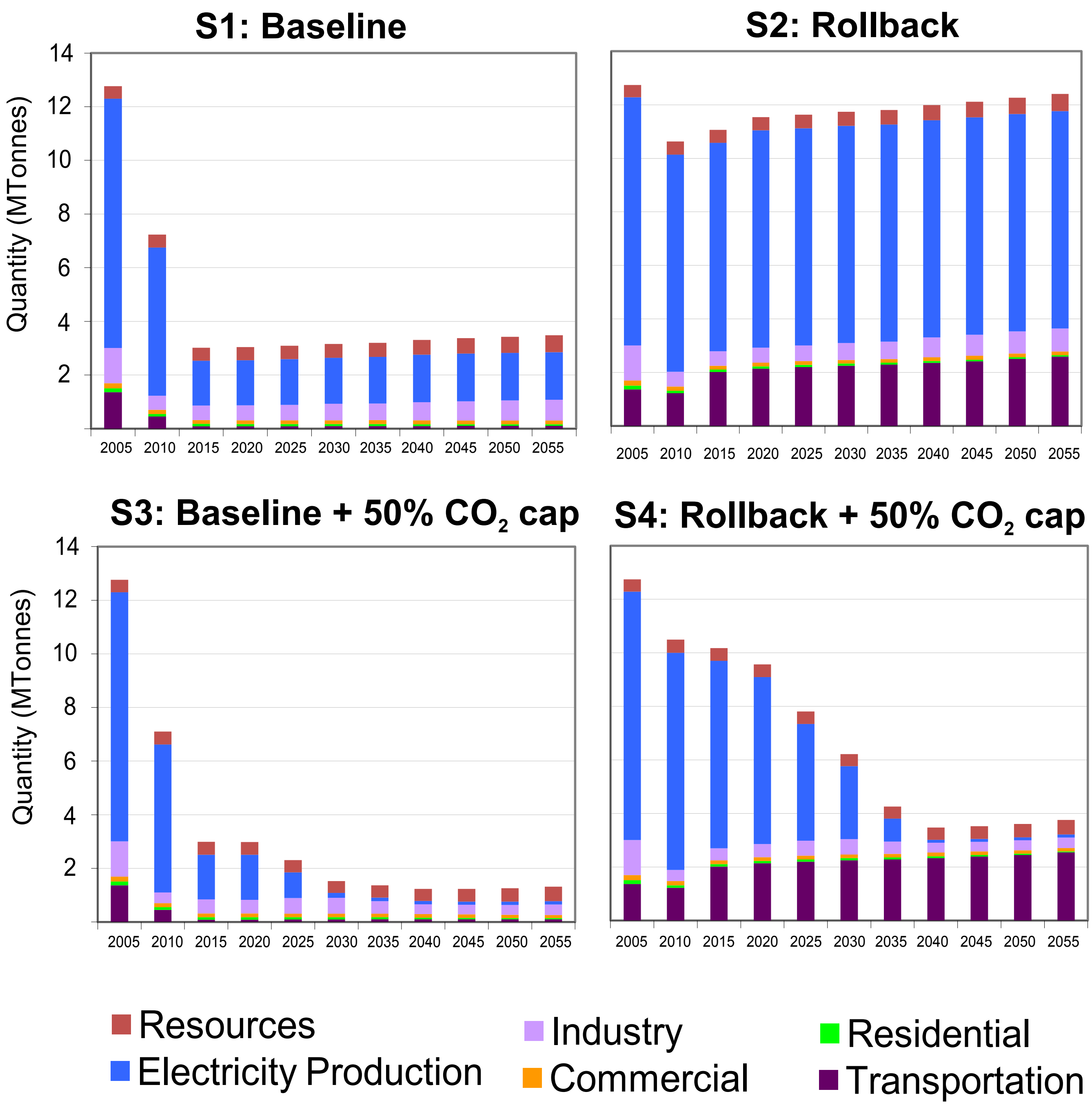
Supporting Information
Appendix C
Scenario emissions by energy sector

The presentation of results in the manuscript focuses primarily on electricty generation, yet emissions are also calculated for other energy system sectors, including transportation, residential, industrial, commercial, and resource extraction. These figures show the emission changes for these sectors for the four scenarios for CO_2, SO_2, black carbon, and organic carbon.

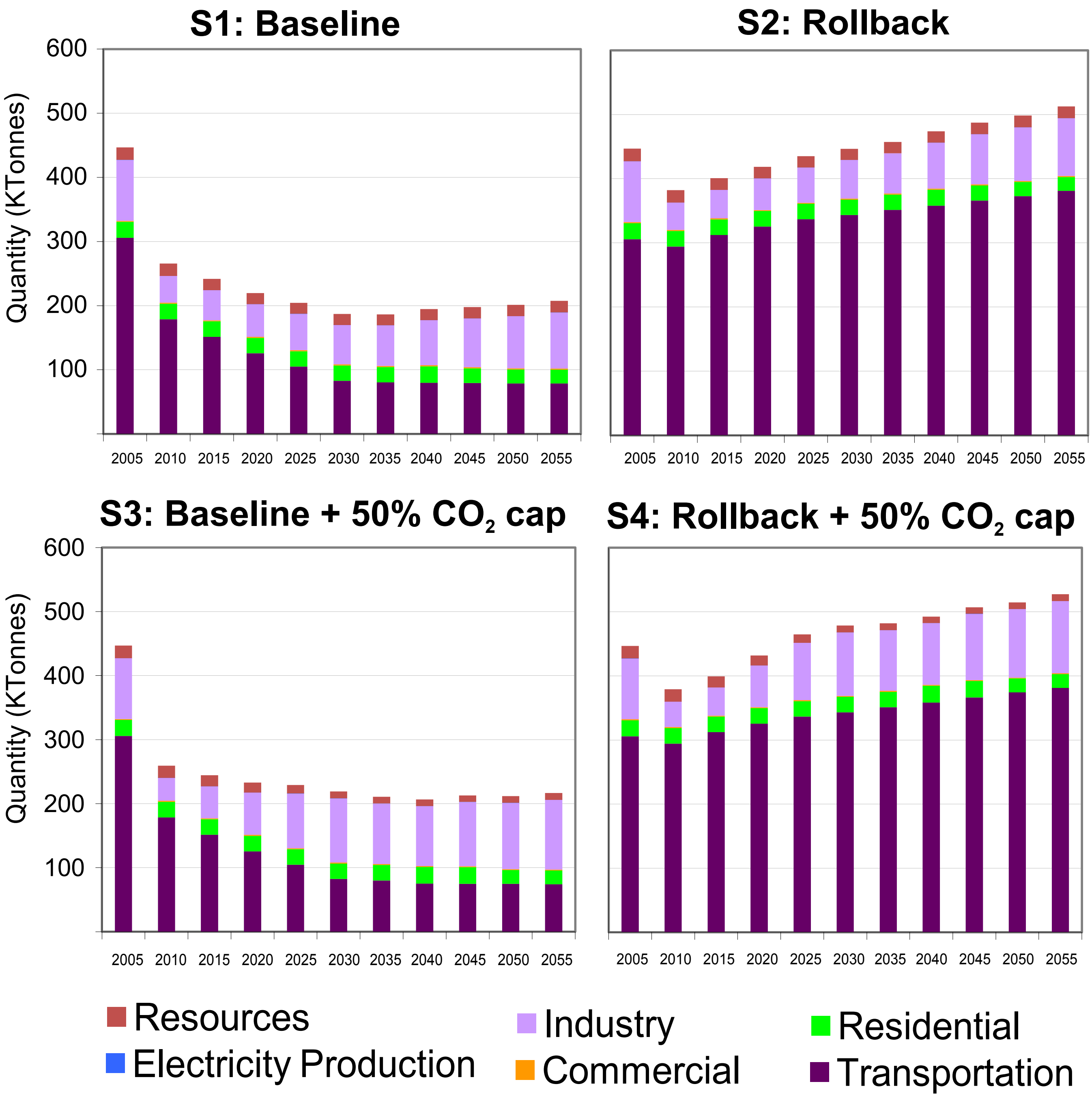
CO_2 emissions from the energy sector



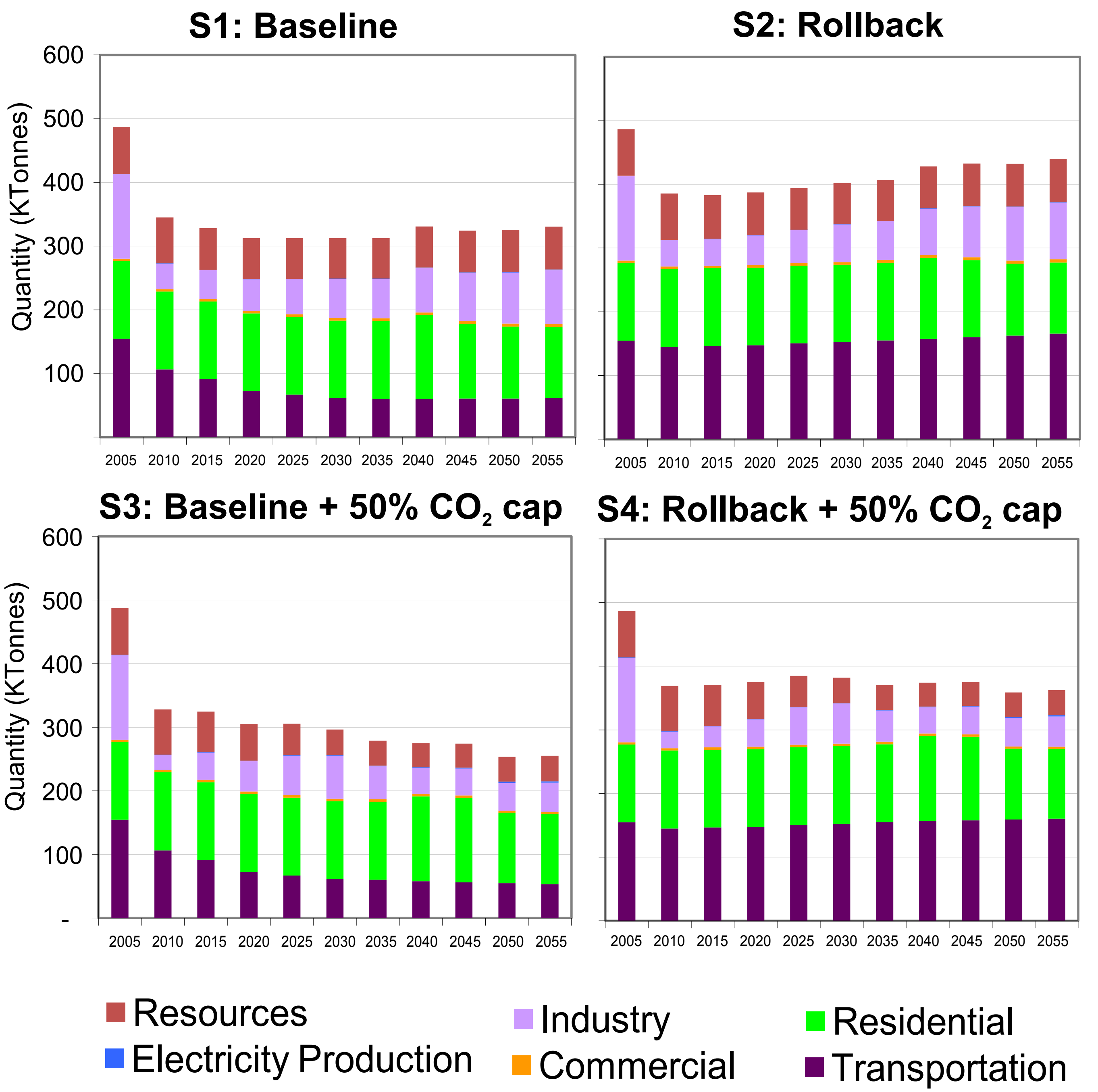
SO_2 emissions from the energy sector



Black Carbon emissions from the energy sector

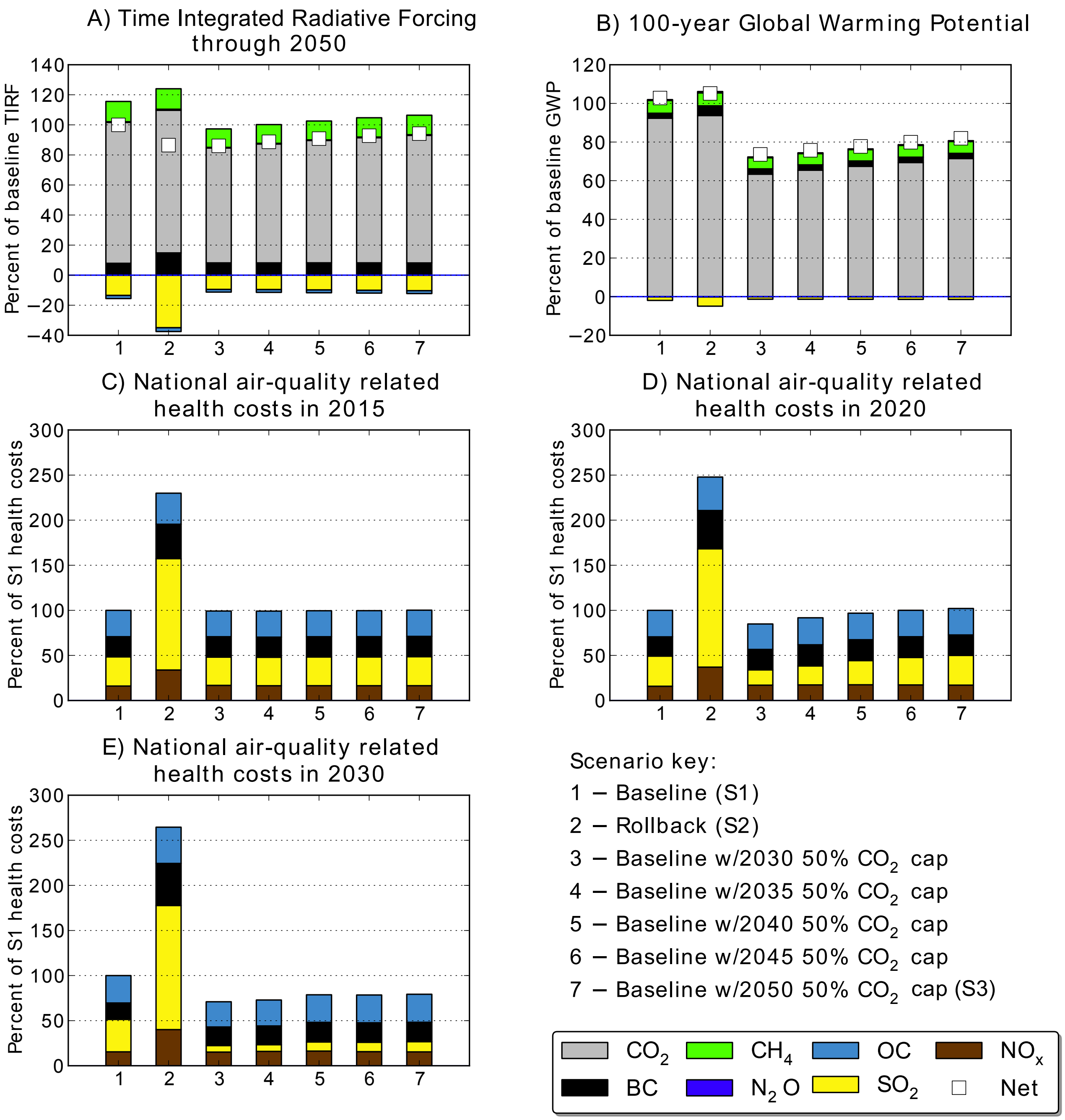


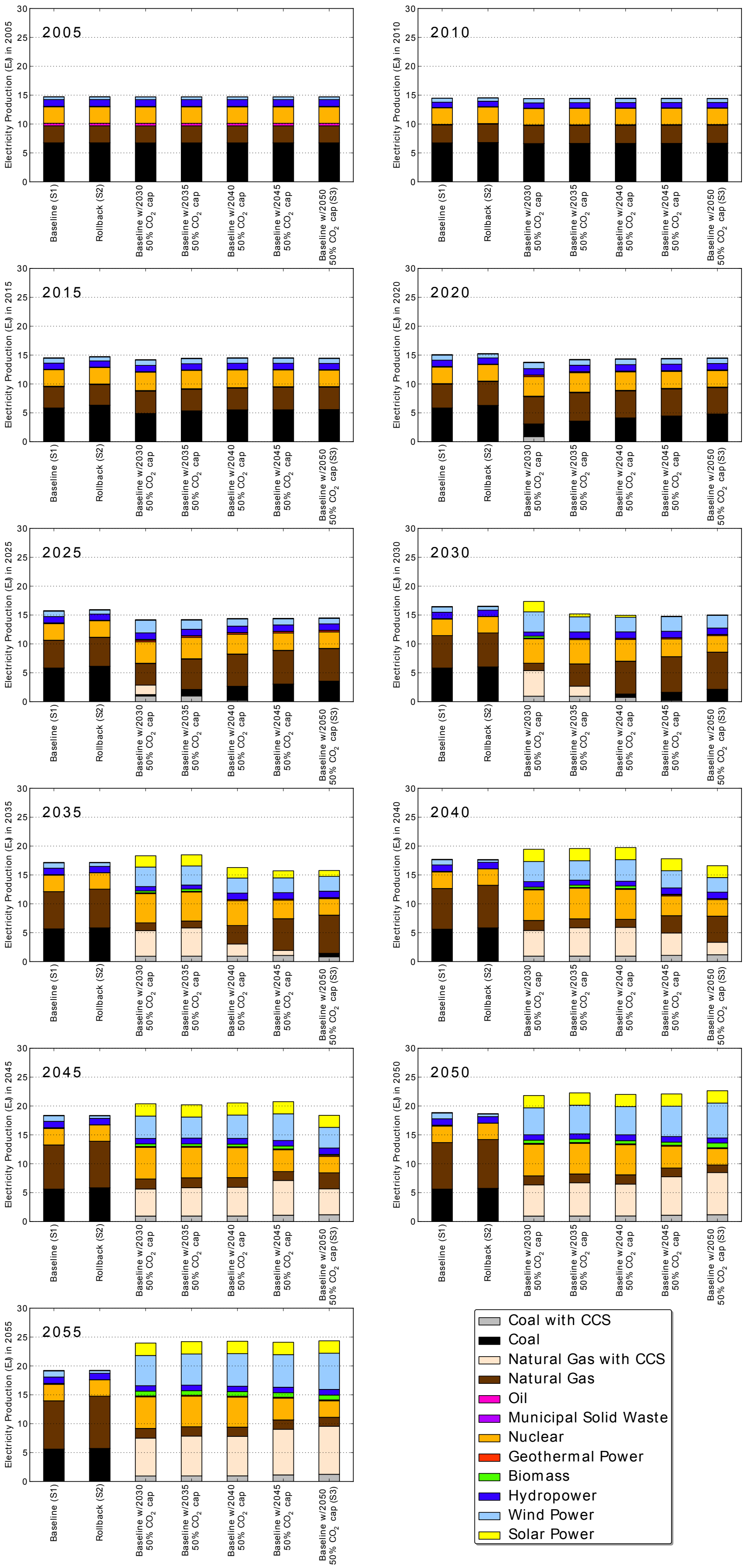
Organic Carbon emissions from the energy sector



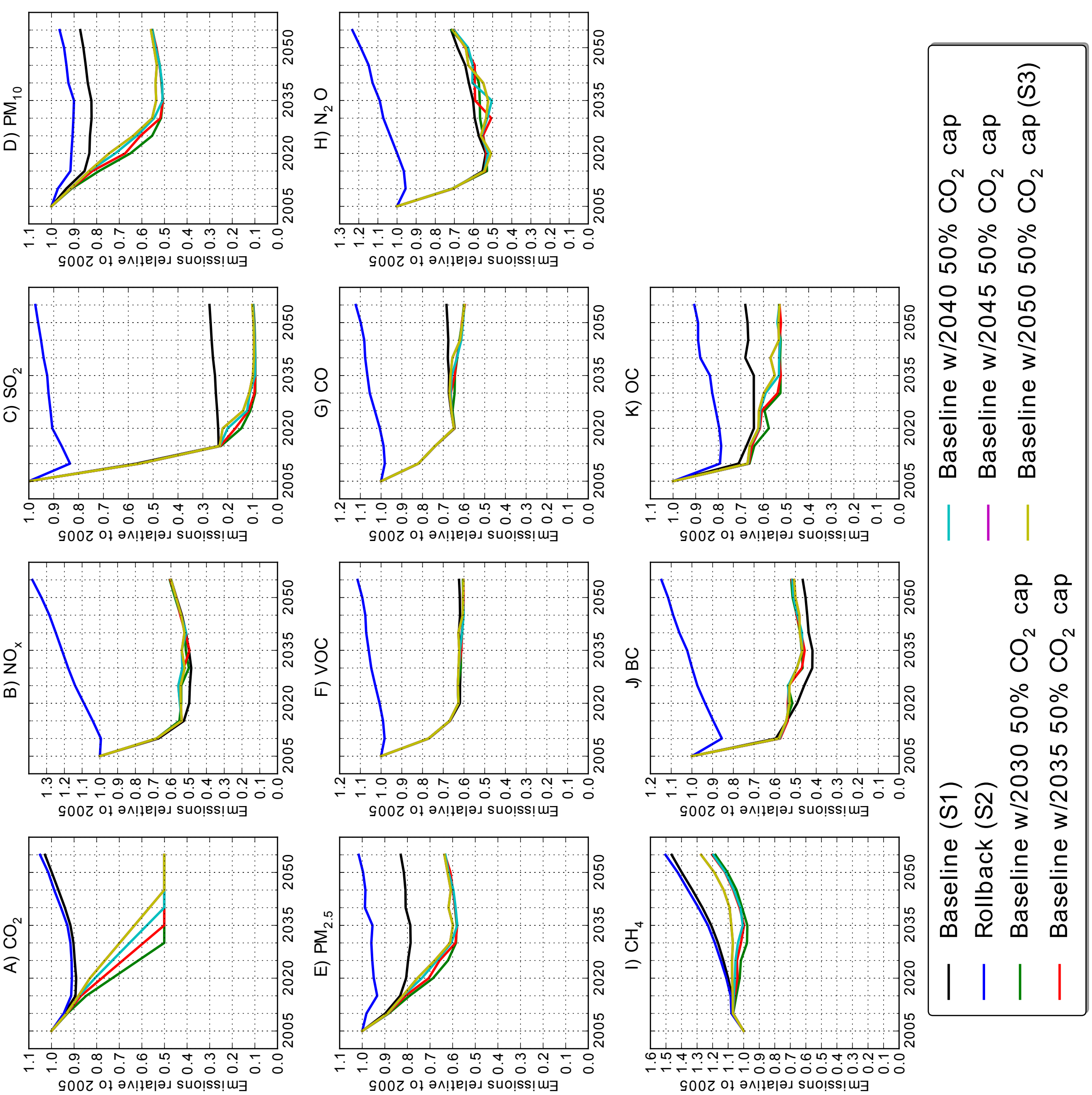
Supporting Information
Appendix D
Electricity Generation and Energy Production Technology Scenario Results for Alternative CO_2 Scenarios

This appendix presents three figures for understanding the alternative CO_2 scenarios. These scenarios represent current regulated emission reductions that are phased in over the next 20 years, as well as a 50% CO_2 emission reduction requirement. These scenarios require that the 50% CO_2 emission reduction must be achieved by an earlier year, ranging from 2030 to 2050. The first figure is parallel to Figure 5 in the manuscript, and it is a comparison of climate and health impact metrics for alternative CO_2 scenarios. In each scenario, the emission constraints include both a 50% reduction of 2005 CO_2 emissions as well as current air pollution and energy efficiency policies in place. Achieving earlier CO_2 reductions reduce near- and long-term radiative forcing and lead to decreases in health impacts from air pollution relative to current policy. The second figure compares the composition of the electricity generation sector. The third figure shows the emissions of greenhouse gases and air pollutants.


A) Time Integrated Radiative Forcing through 2050
Percent of baseline TIRF
B) 100-year Global Warming Potential
Percent of baseline GWP
C) National air-quality related health costs in 2015
Percent of S1 health costs
D) National air-quality related health costs in 2020
Percent of S1 health costs
E) National air-quality related health costs in 2030
Percent of S1 health costs
Scenario key:
1 – Baseline (S1)
2 – Rollback (S2)
3 – Baseline w/2030 50% CO_2 cap
4 – Baseline w/2035 50% CO_2 cap
5 – Baseline w/2040 50% CO_2 cap
6 – Baseline w/2045 50% CO_2 cap
7 – Baseline w/2050 50% CO_2 cap (S3)
CO_2
CH_4
OC
NO_x
BC
N_2O
SO_2
Net



2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Electricity Production (EJ) in 2005
Electricity Production (EJ) in 2010
Electricity Production (EJ) in 2015
Electricity Production (EJ) in 2020
Electricity Production (EJ) in 2025
Electricity Production (EJ) in 2030
Electricity Production (EJ) in 2035
Electricity Production (EJ) in 2040
Electricity Production (EJ) in 2045
Electricity Production (EJ) in 2050
Electricity Production (EJ) in 2055
Baseline (S1)
Rollback (S2)
Baseline w/2030 50% CO_2 cap
Baseline w/2035 50% CO_2 cap
Baseline w/2040 50% CO_2 cap
Baseline w/2045 50% CO_2 cap
Baseline w/2050 50% CO_2 cap (S3)
Coal with CCS
Coal
Natural Gas with CCS
Natural Gas
Oil
Municipal Solid Waste
Nuclear
Geothermal Power
Biomass
Hydropower
Wind Power
Solar Power


A) CO_2
B) NO_x
C) SO_2
D) PM_{10}
E) $PM_{2.5}$
F) VOC
G) CO
H) N_2O
I) CH_4
J) BC
K) OC
Emissions relative to 2005
2005
2020
2035
2050
Baseline (S1)
Rollback (S2)
Baseline w/2030 50% CO_2 cap
Baseline w/2035 50% CO_2 cap
Baseline w/2040 50% CO_2 cap
Baseline w/2045 50% CO_2 cap
Baseline w/2050 50% CO_2 cap (S3)