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Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution

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Abstract

There are many technological pathways that can lead to reduced carbon dioxide emissions. However, these pathways can have substantially different impacts on other environmental endpoints, such as air quality and energy-related water demand. This study uses an integrated assessment model with state-level resolution of the energy system to compare environmental impacts of alternative low-carbon pathways for the United States. One set of pathways emphasizes nuclear energy and carbon capture and storage, while another set emphasizes renewable energy, including wind, solar, geothermal power, and bioenergy. These are compared with pathways in which all technologies are available. Air pollutant emissions, mortality costs attributable to particulate matter smaller than 2.5 μm in diameter, and energy-related water demands are evaluated for 50% and 80% carbon dioxide reduction targets in 2050. The renewable low-carbon pathways require less water withdrawal and consumption than the nuclear and carbon capture pathways. However, the renewable low-carbon pathways modeled in this study produce higher particulate matter-related mortality costs due to greater use of biomass in residential heating. Environmental co-benefits differ among states because of factors such as existing technology stock, resource availability, and environmental and energy policies.

Graphical abstract

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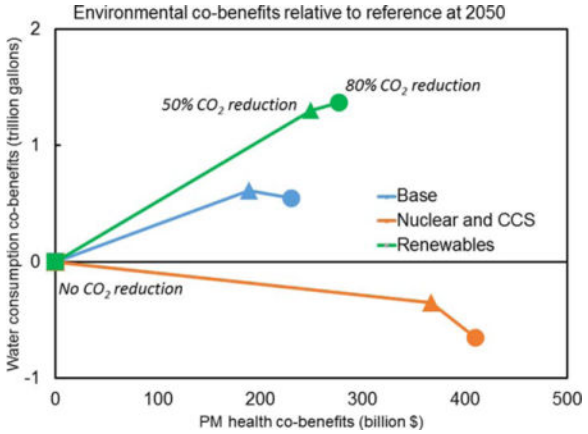

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1. Introduction and research objectives

CO_2 is the primary greenhouse gas (GHG) emitted through human activities. In the U.S., CO_2 accounts for 82% of all anthropogenic GHG emissions, with fossil fuel combustion in the electricity production, industry, transportation, and buildings sectors comprising 93% of anthropogenic CO_2 emissions [1]. A variety of measures are available for reducing CO_2 emissions, including transitioning to low-carbon fuels or renewable energy sources, capturing carbon emissions from exhaust gases, and promoting end-use energy efficiency. A pathway that significantly reduces CO_2 likely would include a combination of these approaches [2]. However, the specific pathway that is taken is important since low-carbon technologies can differ with respect to cost, reliability, and environmental impacts [3,4]. Thus, any large-scale transformation of the energy system will benefit from the simultaneous consideration of climate, environmental, and energy objectives [5].

Several studies have been conducted to assess alternative technology pathways for meeting climate targets. For example, in the Energy Modeling Forum 24 (EMF 24) exercise, modeling teams evaluated the costs of meeting two levels of GHG reduction targets using a number of different pathways [2]. However, EMF 24 did not evaluate environmental implications such as air pollution or water demand.

Other studies have examined the environmental co-benefits of curbing GHG emissions, such as air quality improvements that lead to human health benefits [6–8] and reductions in energy-related water demand [9–11]. Trail et al. [12] found that a relatively aggressive carbon tax could lead to significantly improved $PM_{2.5}$ air quality in the U.S. West et al. [13] estimated that economic and energy system transformations under the RCP4.5 climate mitigation scenario would reduce air pollutant emissions and thereby avoid 1.3 million premature deaths globally from $PM_{2.5}$ and ozone exposures in 2050, including 37,000 premature deaths avoided in the U.S. Similarly, Shindell et al.[14] found that deeply curbing U.S. GHG emissions from the transportation and energy sectors, consistent with a 2-degree warming target, could prevent 36,000 premature deaths in 2030. Ou et al. [15] showed that natural gas combined-cycle power plants, which provide an increasing fraction of electricity production in the U.S., require significantly less water than coal-fired power plants. However, adding carbon capture and storage (CCS) would increase on-site and life-cycle water withdrawals significantly, illustrating that GHG reduction measures can also yield disbenefits. None of these co-benefit applications used an experimental design like EMF 24 to evaluate alternative technology pathways under different CO_2 reduction targets. Furthermore, none used a state-level integrated assessment model, and thus they were unable to incorporate state-specific considerations or show state-specific results.

This study expands upon EMF 24 by exploring the environmental impacts of alternative low-carbon technology pathways. Future energy scenarios are evaluated using an integrated assessment model (IAM) with state-level resolution for the U.S. Following the EMF 24 study design, U.S. energy choices and environmental impacts are estimated for a range of scenarios that represent combinations of an economy-wide CO_2 reduction target in 2050 and assumptions about the cost and availability of technologies. For each scenario, the endpoints considered include emissions of the air pollutants nitrogen oxides (NO_x), sulfur dioxide (SO_2), and primary $PM_{2.5}$. In addition, impact factors have been added to GCAM-USA to estimate the health effects of $PM_{2.5}$ and energy-related water use. These endpoints are evaluated across the scenarios, informing the discussion of tradeoffs among low-carbon pathways and providing information about their energy and environmental consequences.

2. Analysis method

The Global Change Assessment Model (GCAM) is a dynamic-recursive partial equilibrium IAM that represents the demand and supply of market goods, primarily energy and agricultural goods [16]. GCAM has been developed to examine scenarios of the evolution of the global economy, energy, land use, and climate systems. The economic system component represents population and labor productivity. The energy system component includes fuel extraction, refineries, electricity production, and energy use within the residential, commercial, industry, and transportation sectors. The land use component characterizes the competition for land between agriculture and other uses. The climate system component translates greenhouse gas emissions into global CO_2 concentrations and global mean temperature changes.

GCAM uses a logistic choice methodology to determine the market shares of competing power generation technologies, industrial fuels, and transportation modes, based on the relative prices of each option [17]. In GCAM v4.3, there are 32 global regions, and GHG constraints can be applied in one or more regions or globally so that at each time step, technology, fuel, and control choices are adjusted to meet emission targets. Technology availability, cost, and performance over time are supplied exogenously.

GCAM simulates the evolution of the energy and land use systems from the view of a social planner. The projected technology and fuel shares represent the model's estimate of the most economically feasible and technically viable combination of existing technologies and new investments. The results may be different than if technology and fuel choices were made from the private investor perspective, which would focus on attributes such as revenue stream and return on investment. The marginal price of new investments within each model period are then passed through to end-use consumers, where end-use demands can respond to these prices.

GCAM has been widely used in studies exploring low-carbon policies [18], the potential role of emerging energy technologies, and the GHG consequences of specific policy measures [19], as well as in global emission scenario generation activities, including the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios [20], the Representative Concentration Pathways [21], and quantification of the Shared Socioeconomic Pathways [22]. GCAM's big picture perspective provides insights into how human and earth systems respond to changing assumptions about population and economic growth, to the adoption of policies such as emission caps and taxes, and to the introduction of a new technology. However, the model does not re-present highly detailed behavior, such as electricity dispatch decisions, electric grid bottlenecks, and whether a market is regulated or perfectly competitive.

GCAM-USA is an extension of the global GCAM in which U.S. energy supply and demand markets are disaggregated to the state level [23,24]. Technology stock and resource availability are calibrated for each state for the 2010 model year. Calibration also includes calculating technology- and fuel-specific parameters that approximate historic regional preferences and other unmodeled factors that affect future technology choices.

As GCAM-USA simulates technology and fuel choices, it also produces state- and technology-level emissions estimates of GHGs (CO_2, CH_4, N_2O), short-lived forcing agents (BC and OC), and air pollutants (CO, SO_2, NO_x, and $PM_{2.5}$). The version of GCAM-USA used in this study accommodates representations of many U.S. air quality and energy regulations, including those either defined or implemented at the state or regional levels [4]. Shi et al. [4] evaluated NOx,SO and PM2.5 emissions for the GCAM-USA reference case and found them generally to agree well with EPA emission inventories and projections that have been used in recent regulatory impact analyses. We have extended GCAM-USA here by incorporating impact factors for water withdrawal and consumption, as well as for the monetized cost of PM-related mortality.

2.1. Environmental impacts

2.1.1. Air pollutant emissions—GCAM-USA calculates air pollutant emissions in the U.S. as the product of an activity (e.g., energy input or output of a specific technology) and an emission factor (EF). EFs for historical years are calibrated to the U.S. national emissions inventory [25]. For future years, we modified EFs to represent the implementation of current U.S. air quality regulations, such as New Source Performance Standards [26] and the Tier 3 mobile vehicle fuel and emission standards [27]. A re-presentation of the Cross-State Air Pollution Rule (CSAPR) is also included that constrains electric sector emissions of NO_x and SO_2 in affected Eastern states [28]. The Clean Power Plan (CPP) is not represented in the results presented here since CPP implementation is currently under stay by the U.S. Supreme Court [29] and a replacement is under development [30]. The Corporate Average Fuel Economy (CAFE) standard [31] for passenger vehicles is included, but efficiency standards for medium and heavy duty vehicles are not included. While these efficiency standards may be added to future versions of GCAM-USA, we do not expect their omission to have a major impact on air pollutant emission estimates. Further details about the air pollution policy representations and detailed EFs for technologies included in GCAM-USA are provided by Shi et al. [4]. EFs for regions outside the U.S. are unchanged from the release version of GCAM [16].

2.1.2. PM-related health costs—

Fann et al. [32] conducted a suite of chemical transport model runs to estimate the contributions of 17 emissions source sectors to $PM_{2.5}$ concentrations in the U.S. They then applied epidemiologically-derived concentration-response functions to obtain monetary impact factors representing $PM_{2.5}$-attributable mortality per ton of emissions in each sector. The analysis was conducted for 2005 and 2016, considering projected changes in emissions, baseline mortality rates, population distribution, and value of statistical life (VSL) due to income growth over that period [33]. The mortality attributable to $PM_{2.5}$ is dominated by primary emissions of $PM_{2.5}$, but also includes secondary $PM_{2.5}$ formation from SO_2 and NO_x [32]. Direct health impacts of gas-phase SO_2 and NO_2 are not included. PM morbidity costs are also neglected since reduced premature mortality has comprised 95–99% of total monetized benefits in $PM_{2.5}$ benefits assessments [32,34].

In this work, mortality impacts per ton of pollutant emissions derived from Fann et al. [32] are calculated for every 5 years from 2010 to 2050 for the electric, industrial, transportation, and buildings sectors. Values are adjusted for population and income growth in each future modeling year using GCAM-USA socioeconomic inputs [33]. Additional details are provided in the Supplemental Information (SI). National average estimates of health benefits per ton are used for each sector, and the same sector-specific coefficients per ton of emissions are applied in each state. Doing so allows comparisons of multiple scenarios or emissions pathways for each state. However, these values do not permit comparisons of benefits from one state to another because the benefits-perton estimates are not state-specific and do not account for differences such as population density and proximity of the population to sources. Since the work presented here was conducted, Millstein et al. [35] have conducted regional health impact analysis. Such regional health impact factors will be considered for inclusion in GCAM-USA in the future.

2.1.3. Water use—

The electric power sector is one of the largest users of water in the U.S., with withdrawals for electricity generation being approximately the same magnitude as those for agriculture [36]. Water use can be quantified either as water withdrawal, which is the total amount taken from a water body (a river, lake, ocean, groundwater aquifer, or municipal water system), or as water consumption, which represents the quantity that is not returned to the source (e.g. due to evaporation). Both withdrawal and consumptive uses of water for electricity generation are tracked in GCAM-USA.

Water use for electricity production can be calculated as the product of energy output from each power generation technology (EJ) and the associated water withdrawal or consumption factors (gallons/EJ). Water use factors are obtained from a comprehensive review [37]. Only on-site water use is included since plant operation for electricity generation dominates the life cycle water use for fossil-fuel fired power generation. Also, a high degree of uncertainty exists in other life cycle stages. For example, hydraulic fracturing for natural gas extraction uses approximately 10 times more water than conventional drilling, yet our current model does not represent which fuel extraction technologies are being used. The water use factors adopted in this study are summarized in the SI. Water supply is not constrained in this version of GCAM-USA.

In the electric sector, water is primarily used for cooling in thermal power plants (coal, gas or nuclear plants). CCS further increases water use due to the need for additional cooling. The quantity of water used depends on which cooling technologies are employed. Water cooling technologies typically are characterized as being once-through flow or closed-loop. Once-through cooling withdraws a greater amount of water but consumes relatively little, while closed-loop cooling with-draws much less water but has higher water consumption.

The market shares of cooling technologies for existing plants are from Averyt et al. [38]. All future thermoelectric plants are assumed to use closed-loop cooling technology, which is realistic for new builds considering increased future water demands [39]. Although some cooling technologies use air rather than water to cool the generation units, the implementation cost of air cooling is much higher than water cooling. Hybrid and dry cooling schemes are not considered in this study but could be economically feasible in areas with very limited water supply, such as in the Southwest U.S. [40]. Wind power does not require any on-site cooling water. Distributed solar photovoltaics (PV) require only minimal amounts of water for panel cleaning [41], while concentrated solar power (CSP) typically requires substantial amounts of water for evaporative cooling [42].

2.2. Scenario design and assumptions

The scenario matrix design of EMF 24 [2] is used to assess how different low-carbon pathways affect the U.S. energy system when meeting two hypothetical CO2 reduction goals. The matrix consists of a CO2 target dimension and a technology availability dimension (Table 1). Each scenario adopts one option along each dimension, yielding a total of nine scenarios.

In this study, the set of reference scenarios (with names ending with REF in the first column) explicitly include on-the-books air pollutant emissions and energy regulations, as described in Section 2.1. This definition of “reference” is distinct from “business-as-usual” scenarios in the IAM literature. “Business-as-usual” scenarios typically assume that emission reductions will occur into the future, beyond what has been legislated to date. This distinction is important when comparing this study to others in the literature. Including only already-adopted air pollutant regulations can help identify areas where further regulations might be needed in the future.

In addition to the reference scenarios, the next two columns in Table 1 show economy-wide CO_2 reduction targets of 50% and 80% by 2050, relative to 2005 levels. For each emission reduction target, intermediate targets for the years between 2015 and 2050 are linearly interpolated. These “low-carbon” scenarios were selected to be consistent with EMF 24. While real-world cap-and-trade programs may not follow a linear trajectory because of policy design features (e.g., banking and borrowing of emission trading permits), linear interpolation facilitates comparisons across scenarios for any modeled year.

The reduction target applies to sources across all sectors (electric, industrial, residential, commercial, and transportation). For the rest of the world, complementary carbon prices are applied throughout the modeled time horizon to be broadly consistent with the U.S. target (SI). Pricing carbon prevents an unrealistic modeling outcome in which the U.S. simply imports large amounts of low-cost biomass to meet the target, ignoring competition for that biomass with other parts of the world [43]. While the U.S. could import additional power from Canada and Mexico to offset stringent CO_2 caps [44], international electricity imports currently are not included in the model.

Three sets of technological availability assumptions are considered, one for each row of Table 1. BASE represents baseline assumptions in which all energy supply technologies are available at baseline cost estimates. RE (renewable energy) assumes faster technology cost reductions for renewable technologies (wind, solar, biomass and geothermal), and also includes constraints that do not allow CCS, new nuclear plant builds, or lifetime extensions of existing nuclear plants. In RE, existing nuclear plants are retired based on both an exogenously-specified schedule and endogenously-determined, cost-based retirement decisions. Thus, the market shares of nuclear decrease in future years, but do not reach zero by 2050. In contrast, NUC/CCS (nuclear and CCS) includes faster technology cost reductions for nuclear and CCS technologies, and also greatly restricts biomass supply. Thus, nuclear and CCS technologies are favored in achieving CO_2 reductions. For the BASE set of scenarios, default GCAM-USA technology costs developed by Muratori et al. [45] are used, consistent with Shi et al. [4]. The technology cost assumptions for the alternative low-carbon pathways (SI) are derived from Iyer et al. [24]. Both sets of assumptions include only moderate decreases in solar PV and wind power costs between 2010 and 2015. Sensitivity runs were conducted in which more aggressive renewable cost reductions were explored. We found that these alternative costs did not change the overall conclusions of this study (SI).

The model includes versions of wind and solar technologies, both with and without integrated energy storage. Storage results in a higher capital cost, but no system integration constraints. Biomass supply restrictions are adopted from Calvin et al. [46]. The effect of biomass restrictions is further discussed in the SI.

In reality, a response to a carbon target would likely include a mix of renewables, CCS, and potentially nuclear power. The approach of evaluating several very different technology pathways was chosen with the goal of uncovering important system dynamics, such as within- and cross-sector interactions and state-level differences. These dynamics may not have been apparent with incremental changes. Beyond EMF 24, similar alternative technological assumptions have been adopted in previous studies [47–49].

GCAM-USA is run from 2010 to 2050 in 5-year time steps. This time horizon was selected to examine near- and mid-term impacts, while also accounting for longer-term emission trajectories. All model runs are made using a Windows PC platform (64-bit operating system, 16 GB RAM), requiring approximately two hours per run.

3. Results

In this section, GCAM-USA model results are presented, including technology adoption, electric sector water use, system-wide CO_2 and air pollutant emissions, and the associated PM-related health co-benefits. All scenarios discussed in this section use the names given in Table 1.

3.1. BASE scenarios

Fig. 1a shows CO_2 emissions by sector for the set of BASE scenarios. In 2010, the transportation sector accounted for 42% of total CO_2 emissions, followed by the electric (27%) and industrial sectors (20%). In BASEREF, CO_2 emissions increase over time, driven largely by increased electricity production from coal and natural gas. Under the 50%CO_2 reduction target, CO_2 emissions gradually decrease after 2030, driven by technology and fuel changes in the electric and industrial sectors. Changes in emissions from the transportation sector are relatively minor, so that their contribution to the national total increases to 54% in 2050. Under the 80% CO_2 reduction target, emissions from the electric sector are largely eliminated, while emissions in the industrial sector become negative by 2050 due to large-scale adoption of biofuel production coupled to CCS.

The evolution of electricity generation technology mix for the BASE scenarios is shown in Fig. 1b. In 2010, conventional coal and gas (i.e., without CCS) and nuclear comprised 45% (7.1 EJ), 22% (3.4 EJ) and 19% (3.0 EJ) of total generation, respectively. The share of solar, wind and biomass technologies together was 3% (0.5 EJ). When no CO_2 target is applied, generation from fossil fuels grows so that in 2050, 44% (4.4 EJ) and 27% (2.7 EJ) of the increased generation is from conventional gas and coal, respectively. A 50% CO_2 reduction target reduces the market shares of conventional coal and gas in the future, as part of the conventional coal capacity is replaced with new coal capacity paired with CCS. An 80% CO_2 reduction target further reduces the share of conventional coal by 2050. In BASE80, nuclear, coal and gas with CCS, and renewables make up 31%, 18% and 26% of total power generation, respectively.

The following sections further examine energy system impacts under alternative technology assumptions, focusing on the year 2050. Trajectories of CO_2 emissions, electricity generation and environmental impacts from 2010 to 2050 are provided in the SI.

3.2. Energy system response by sector

Several of the major energy system responses to the low-carbon trajectories occur in the electricity production and bioenergy supply sectors. Fig. 2a illustrates how electricity is produced in 2050 for each of the scenarios. Under the RE and NUC/CCS scenarios, the favored technologies together dominate the electricity production mix by 2050. Changes also occur concurrently in other sectors, such as increased biorefinery activity (Fig. 2b). While more expensive than traditional refining, the ability to produce liquid fuels that are carbon neutral or even net negative drives increased market share under either CO_2 target. In the 2010 model results, 97% of the refined liquids come from conventional oil refining. By 2050, the biofuel market shares reach 48% in BASE80, and 63% in RE80. In contrast, NUC/

CCS80 has more limited biofuel production (37%) in 2050 due to the assumed constraint on total biomass supply.

While all pathways can achieve lower CO_2 emissions, two distinct end-use energy supply patterns can be identified. First, the NUC/CCS scenarios result in greater electrification of end-uses since the generation costs of the NUC/CCS scenarios are lower than those in the corresponding RE scenarios. As a result, in the industrial sector the share of electricity in 2050 in NUC/CCS80 is 37% (7.7 EJ) versus 27% (5.8 EJ) in RE80. Second, the RE scenarios have higher utilization of bioenergy. In the transportation sector, the service outputs of biofuel increase by 0.7 trillion passenger-km/year for light duty vehicles (LDV) and 0.5 trillion ton-km/year for heavy duty vehicles (HDV) from 2010 to 2050 in BASEREF. RE80 has the highest share of biofuel in 2050, accounting for 40% (4.6 trillion passenger-km/year) and 55% (3.1 trillion ton-km/year) of the total service output of LDV and HDV, respectively (SI).

The final energy used in the buildings sector is dominated by electricity and varies by at most 4% under the two CO_2 reduction targets. Thus, energy efficiency does not appear to be playing a major role in reducing emissions in the residential and commercial sectors. While fuel switching and electrification both are allowed, we can conclude that the major mechanisms for cost-effectively lowering carbon emissions are available in other sectors. Additional information on end-use energy supply patterns can be found in the SI.

3.3. Environmental impacts

3.3.1. Water use in power generation—While the alternative pathways exhibit similar levels of electricity generation, electric sector water use can be very different (Fig. 3). Without CO_2 targets, BASEREF decreases total water withdrawal by 67% (35 trillion gallons), while increasing total water consumption by 86% (1.6 trillion gallons). These shifts occur because of the evolution of cooling technologies from once-through to recirculating.

Projections of electric sector water use differ considerably across the BASE set of low-carbon scenarios, with nuclear power becoming an increasingly dominant user of water as the CO_2 reduction target becomes more stringent. Under BASE80, nuclear provides 31% of total power generation in 2050, but comprises 54% of water withdrawal and 48% of water consumption within the electric sector.

Water use in the scenarios with alternative technology assumptions diverge from the BASE scenarios. In the RE scenarios, water withdrawal and consumption dramatically decrease because fossil fuel combustion technologies that require water for cooling are phased out or greatly reduced. Geothermal accounts for 67% of the total water consumption in RE80 because geothermal energy has five times the water consumption intensity of nuclear power [37]. Geothermal energy is adopted primarily in the Southwest U.S. Given the limited water supplies, hybrid or dry cooling technologies might be used under such a scenario despite their greater cost. While CSP has a high water intensity, its very low market share results in very limited water use (Fig. 1).

In contrast, water withdrawal and consumption are considerably higher for the NUC/CCS scenarios than for BASE and RE. Compared with BASE80, NUC/CCS80 requires 53% additional water consumption (1.5 trillion gallons) in 2050, while RE80 instead results in a savings of 48% water consumption (1.4 trillion gallons). Water withdrawals in 2050 are much less than in 2010 due to large-scale adoption of recirculating cooling technology. Nevertheless, the water withdrawal in NUC/CCS80 in 2050 is 87% higher (5.2 trillion gallons) than in RE80, which could place significant water demand pressure on areas with higher risk of droughts.

3.3.2. CO_2 and air pollutant emissions—Because the CO_2 reduction targets are applied economy-wide, the resulting emission reductions are apportioned by GCAM-USA across sectors (electric, transportation, industrial, and buildings) and states based upon where CO2 emission reductions are most cost effective. Fig. 4 shows sectoral CO2, primary PM2.5,NO, and SO2 emissions across the scenarios.

Biofuel production with CCS is especially competitive under CO_2 reduction targets (Fig. 2b) because the model treats it as having net negative CO_2 emissions from the end-use perspective (note, however, that changes in land-use and associated emissions from changes in biomass production are consistently accounted for within GCAM). However, this option becomes prevalent only under the BASE scenarios because it requires both CCS (constrained in RE) and expanded supply of biomass (limited in NUC/CCS). By using biorefineries with CCS, BASE80 achieves greater negative emissions in the industrial sector compared with RE80 or NUC/CCS80. In RE80, more CO_2 emission reductions are achieved in the transportation sector compared with BASE80 and NUC/CCS80, primarily through higher biofuel utilization.

Air pollutant regulations result in significant NO_x and SO_2 reductions relative to 2010 across all scenarios. In BASEREF (no CO_2 target), NO_x emissions decline 53% by 2050, mainly due to the state-level electric sector caps on NO_x from CSAPR and the Tier 3 emission standards in the transportation sector. SO_2 emissions decline 56% by 2050, also primarily due to CSAPR.

Application of the CO_2 constraints results in additional pollutant emission reductions. Comparing values in 2050, NO_x emissions of BASE50 and BASE80 are 23% and 30% lower than BASEREF, respectively. SO_2 emissions are reduced even further, declining by 44% and 55%. $PM_{2.5}$ emissions decline by 27% and 32% from BASEREF under BASE50 and BASE80, respectively.

Comparing BASE80 and BASEREF in 2050, the electric sector accounts for 41% of the reduction in NO_x emissions, 58% of the reduction in SO_2, and 38% of the reduction in $PM_{2.5}$. These changes are largely a result of the substitution of renewables and nuclear power for conventional coal and natural gas. Also, CO_2 capture systems require reducing NO_x SO and $PM_{2.5}$ from flue gas to avoid degrading the sorbents used for capture. Thus, CCS typically results indwer emissions of these air pollutants. The industrial sector accounts for 46% and 61% of the reduction in NO_x and primary $PM_{2.5}$ emissions, respectively, driven by reductions in coal and petroleum use. These system-wide air pollutant emission reductions demonstrate that broad technology changes made under low-carbon pathways can bring about significant air quality co-benefits.

The results also illustrate that alternative pathways produce different levels of co-benefits, and some pathways can even result in dis-benefits. Relative to BASE80, NUC/CCS80 has 21% lower NO_x and 44% lower SO_2 emissions in 2050, due to higher industrial electrification. Primary $PM_{2.5}$ emissions in NUC/CCS80 are also 46% lower than in BASE80, mostly attributable to reduced use of biomass for residential heating in the buildings sector. In contrast, RE80 has greater $PM_{2.5}$ emissions compared to NUC/CCS80, again driven by residential biomass. NO_x and SO_2 emissions also increase relative to BASE80. Thus, while biomass can be an important low-carbon option, its use may worsen air pollutant emissions, especially in the buildings sector. This point is discussed further in Section 4.

3.3.3. PM-related health co-benefits—The alternative pathways also have differing implications for human health. The health co-benefits of avoided PM-attributable mortality from CO_2 constraints are estimated as the difference between health costs of a scenario with CO_2 constraints and BASEREF. Annual PM health co-benefits increase over time, especially after 2025. Fig. 5 summarizes the annual PM health co-benefits in 2050, relative to BASEREF, for the alternative pathways and for both 50% and 80% CO_2 reduction targets. BASE50 brings about $190 billion (all monetary amounts in 2010 USD) in annual PM health co-benefits in 2050, mainly coming from the industrial and electric sectors. BASE80 achieves $41 billion additional annual health co-benefits beyond BASE50, mainly in the industrial ($23 billion of additional health co-benefits, 56% of the total increase) and buildings sectors ($15 billion of additional health co-benefits, 37% of total increase). Very few additional health co-benefits occur in the electric sector in BASE80 because it already has been largely decarbonized by 2050 in BASE50.

In general, substantial PM health co-benefits are achieved regardless of the pathway taken to meet the CO_2 reduction targets. However, there are important differences among the pathways. Although NUC/CCS and RE have additional co-benefits in 2050 compared to BASE, NUC/CCS80 achieves annual $PM_{2.5}$ health co-benefits of $410 billion, which is 48% and 78% higher than those of RE80 and BASE80, respectively. The major difference between RE80 and NUC/CCS80 is in the buildings sector. Unlike RE80 and BASE80, NUC/CCS80 has restricted overall biomass supply, which avoids a significant amount of primary $PM_{2.5}$ emissions from residential wood combustion. Note that residential wood combustion is not a necessary consequence of a renewable energy strategy, but rather a function of the choice of which technologies and fuels are considered to be renewable and other constraints in the modeling exercise. Our modeling choices were driven by a goal of maintaining consistency with the EMF24 design.

While national health co-benefits from the alternative pathways are a useful indictor, the geographic distribution of the impacts may be even more important for long-term energy planning and regional emission control strategy development. As noted previously, the use of national average impact factors to represent PM mortality is not well-suited for quantifying state-level co-benefits since emissions can be carried across state boundaries.

Fig. 6a and b shows regionally-aggregated distributions of the additional PM health benefits of NUC/CCS80 and RE80 relative to BASE80 in 2050 for all sectors. Fig. 6c–j further examines these results by sector.

NUC/CCS80 results in additional PM health co-benefits for all regions (Fig. 6a). The additional co-benefits in the Northeast and the Midwest regions are mainly from the buildings sector (Fig. 6i), while the additional health co-benefits in Southeastern states are mainly from the industrial sector (Fig. 6e). Both NUC/CCS80 and RE80 have negligible additional health impacts in the transportation sector. The additional health co-benefits of RE80 shows a mixed pattern (Fig. 6b), in which the electric sector has additional health co-benefits for all regions (Fig. 6d), while the buildings sector has lower co-benefits relative to BASE80 across the Midwest and the Northeast regions. This pattern for the buildings sector stems from residential biomass combustion, as regions with colder climates and a historical pattern of greater biomass use continue to do so in the future. The 50% CO2 reduction targets have a similar geographic pattern of additional health co-benefits in 2050, although the magnitudes are smaller (SI).

4. Discussion

We find that NUC/CCS80 results in 48% greater PM health cobenefits compared to RE80 on the national scale. This result is driven by the restricted biomass supply and greater end-use electrification in NUC/CCS80. However, NUC/CCS80 also has 192% higher water consumption and 87% higher withdrawal. This tradeoff could be a concern, especially for regions with considerable biomass potential but also limited water resources such as California.

Our results are comparable with previous studies focused on air quality or water separately. Shindell et al. [14] estimated that a clean energy and clean transportation policy in the U.S. consistent with an 80% CO2 reduction in 2030 would result in 36,000 fewer premature deaths annually due to avoided PM and ozone pollution. In our study, BASE80 results in $130 billion PM-related health benefits relative to BASEREF in 2030, which is equivalent to 14,000 premature deaths using the projected VSL in 2030. The major difference comes from the choice of baseline scenarios for co-benefit estimation. Shindell et al. [14] used RCP8.5 for their baseline, for which electric sector SO2 and transportation sector NOx emissions decreased by 0.5 and 0.8 Tg, respectively, in 2030 relative to 2010. Our study includes on-the-books U.S. air pollution regulations in BASEREF at the state level, which leads to significant air pollutant emission reductions relative to 2010. In particular, electric sector SO2 and transportation sector NOx emissions decrease by 2.6 and 4.8 Tg, respectively, in 2030 relative to 2010. Therefore, compared with the baseline in Shindell et al. [14], BASEREF in our study has less air pollutant emissions available to be reduced through CO2 targets, and thus has fewer PM health benefits in 2030.

This comparison highlights the importance of baseline assumptions in co-benefit analyses. In our study, existing air quality regulations are explicitly included in the reference scenarios, and therefore our estimation can better capture the additional PM health co-benefits from CO_2 reductions that are added onto current regulations. In addition, Shindell et al. [14] estimated combined $PM_{2.5}$ and ozone-related health impacts, while this study only addressed PM2.5-related health impacts.

Although PM2.5-related mortality damages consistently dominate the overall air quality health damages across different emission sectors [50], future work should seek to integrate both PM and ozone health impact factors into GCAM-USA, allowing the overall air quality health impacts to be estimated more fully. Besides mortality costs, future work could be expanded by including morbidity costs and other impacts of air pollution such as lost productivity.

This study considers only already-adopted air pollutant regulations, and therefore illustrates areas where further emissions controls might become necessary. For example, the buildings sector has very limited contribution to the overall CO_2 reduction compared with the electric, industrial, and transportation sectors, but its environmental impacts and public health implication can be significant. Penn et al. [51] estimated 10,000 premature deaths per year in the U.S. in 2005 from residential combustion (wood, coal and oil), driven by direct $PM_{2.5}$ emissions. In BASE80, residential biomass combustion provides less than 1% of the total energy use in the buildings sector in 2050 but is responsible for 94% of the primary $PM_{2.5}$ emissions from buildings and 31% of the system-wide primary $PM_{2.5}$ emissions. Unlike point sources such as power plants, residential biomass combustion is widely distributed and can be difficult to regulate, especially in rural areas with abundant local biomass resources. Although EPA tightened standards for new residential wood heaters in 2015 [52], the turnover rate for existing low-efficiency wood stoves and fireplaces is highly uncertain. Some states, such as Colorado, have more stringent residential wood burning regulations for certain months of the year when secondary pollutants form more readily. Furthermore, we do not represent regional- and state-specific CO_2 mitigation targets, nor do we represent state-level renewable portfolio standards. Inclusion of such policies into the reference case could change the baseline emission levels and could affect the dynamics of the response to low-carbon constraints.

Our finding that co-benefits attributable to the buildings sector are small in BASE50 and BASE80 differs from the conclusion drawn by Zhang et al. [53], who found the residential sector to be a major source of co-benefits. Zhang et al. used emission inputs from an earlier version of GCAM, while GCAM-USA is based on a version of GCAM with a more detailed representation of specific energy services in the building sector as well as the additional changes outlined by Shi et al. [4]. The structural difference in the building sector in GCAM-USA results in less substitution toward biomass in response to a carbon price [54]. Another is likely our treatment of residential wood burning in our baseline. We extrapolated trends in residential wood use and assumed a gradual changeover to lower-emitting devices. As a result, our residential $PM_{2.5}$ emissions are relatively flat over time. In contrast, residential $PM_{2.5}$ emission projections by Zhang et al. grew on a trajectory that more closely followed population.

Another difference between these analyses was our use of state-level resolution, which allowed consideration of historic state-level market shares of residential wood combustion.

This can also change-substitution dynamics because the heating energy fuel and technology mix differs across states.

These factors, included at the state-level in GCAM-USA, will result in changes in fuel market share and model dynamics in future years. The aggregate USA region in GCAM is not able to represent such state-level variation and trends.

For water use impacts, several previous studies have used GCAM and GCAM-USA to estimate global or regional energy-related water demands under climate mitigation goals [47,49,55,56]. Liu et al. [47] compared state-level water demand for electricity generation under different technological pathways, showing that renewables have much less water withdrawal and consumption compared with nuclear and CCS technologies in 2095 under RCP4.5. The state-level responses in Liu et al. [47] are also consistent with the current paper.

We assumed that all future thermal generation technologies will use closed-loop cooling. Though others have made this same assumption [10], it may be too restrictive for regions with abundant water supply. However, determining the adoption of different cooling systems in the future is inherently uncertain. Davies et al. [55] assumed the conversion of cooling system shares progressed linearly from the base year to 2020, after which cooling system shares were held constant for new plants. Kyle et al. [49] assumed equal shares of evaporative cooling towers and dry/hybrid cooling systems for CSP and geothermal technologies for all future years because their current deployment rate was too low to determine future shares. Since the main purpose of our paper is to examine multiple environmental endpoints under different technological pathways, rather than exploring detailed dynamics in the water-energy nexus alone like the aforementioned studies, the current simple assumption for future cooling systems is clear and provides in-sights into situations or regions where these assumptions might need to be explored in more detail. Further efforts are needed to better characterize the drivers of future water demands in the electric sector, including the adoption of water-saving technologies and the trade-off between withdrawal and consumption.

This study only considered water use for electricity production. Although water use beyond the electric sector is outside the scope of this analysis, large-scale biofuel production would lead to a considerable increase in water demand [57]. Bonsch et al. [58] estimated that producing 300 EJ/yr of bioenergy in 2095 from dedicated bioenergy crops is likely to double agriculture water withdrawals globally if no explicit water protection policies are applied. Future versions of GCAM-USA are expected to include water supply constraints, which also may affect our results.

Our results and comparisons with other studies highlight the importance of the state-level resolution of GCAM-USA, which allows consideration of factors such as state-level technology stock, energy resources, and policy constraints (e.g., the Cross-State Air Pollution Rule). Together, these factors help shape the state-level technology, fuel, and environmental implications of each pathway.

The integration of impact factors into GCAM-USA is also a novel aspect of this work. In previous co-benefit studies using integrated assessment models, authors have used full-scale chemical transport models and health benefit models to evaluate health impacts of the IAM results [13,53]. Using full-scale models is challenging since these models are complex and can be computationally intensive. Furthermore, the models are often run by different sets of modelers, necessitating transfer of data from one group to another. These factors complicate the iterative process of proposing and evaluating candidate management strategies that is necessary in supporting real-world decision-making.

In contrast, incorporating impact factors directly into the IAM provides a rapid and efficient approximation of health impacts. Further discussion is included in the SI. However, the adoption of health impact factors assumes a linear relationship between changes in emissions and impacts. This assumption may be appropriate for small perturbations, but its accuracy may diminish for large changes in emissions. Furthermore, the impact factors used here are year-, technology-, and pollutant-specific and are taken as national averages, so they are applied uniformly across states. Therefore, the different environmental impacts across regions (Fig. 6) capture the specific energy structure and resource limitation of each state, but only approximately represent the influence of emission location on air pollution-related health impacts in terms of the pollutant formation, differing magnitudes of exposed population, and differing demographics and health status [59–61]. Our use of national-average, sector-specific benefits per ton of emissions supports comparisons of the health benefits of different scenarios and pathways for single states or regions, as we have demonstrated here. However, this approach is problematic for comparisons of health benefits between different states since we are not differentiating how exposure levels change from one state to another. Future efforts should consider the adoption of impact factors that better capture spatial heterogeneity.

Furthermore, if environmental impacts can be monetized, these impacts can be endogenized and considered simultaneously in the development of cost-effective and robust management strategies. Such a co-control framework has been demonstrated for air pollutants and GHG reductions in Mexico City [62], China [63,64] and Switzerland [65]. A similar approach could be conducted for the U.S., potentially achieving additional societal benefits beyond that suggested when climate, environmental, and energy goals are considered in isolation from each other. Similarly, this exercise could be repeated for other countries or regions of the world as the air-energy-water nexus is a global challenge. Considering the heterogeneity of energy structures, domestic policy and geopolitical issues among different regions, the impacts of different technological pathways may be very different.

5. Conclusions

This study shows that assessing multiple environmental impacts within an integrated assessment modeling framework allows consideration of interactions and tradeoffs among air pollution, low-carbon pathways, energy system and environmental goals. To our knowledge this is the first study to estimate state-level water and regional air pollutant co-benefits associated with alternative technology pathways for meeting CO_2 reduction targets. This study demonstrates that different pathways leading to a 50% CO_2 emission reduction target in 2050 can result in very different magnitude and geographic distribution of PM-health benefits and water demands for thermal electricity production. Furthermore, an 80% CO_2 emission reduction target would yield significant additional air quality co-benefits beyond the 50% reduction for each of the technology pathways. On the national scale, the RE pathway provides greater benefits for reduced water use while the NUC/CCS pathway achieves higher PM health benefits. However, the pathway that achieves the greatest PM health benefits differs among regions due to the heterogeneity of existing technology stock, resource availability, and environmental and energy policies.

One important difference between NUC/CCS and RE is the extent of biomass utilization. Even if residential biomass burning plays only a minor role in reducing CO_2 emissions, its potential for a relatively high level of co-emitted $PM_{2.5}$, particularly in the residential sector, could offset some of the health co-benefits of reducing GHG emissions. While this response appears in these idealized scenarios within the context of a renewable technology pathway, in reality the response of consumers in terms of heating fuel choice is complex, and increased wood consumption could occur regionally in response to the increases in fossil fuel prices associated with GHG reduction pathways. This result has important real-world implications for both how wood energy is included in low-carbon strategies, and also highlights the potential importance of PM emission standards for residential wood combustion devices. We also find that, by comparing to previous results, model structure and spatial resolution for the residential building sector can have a significant impact on the magnitude of any co-benefits.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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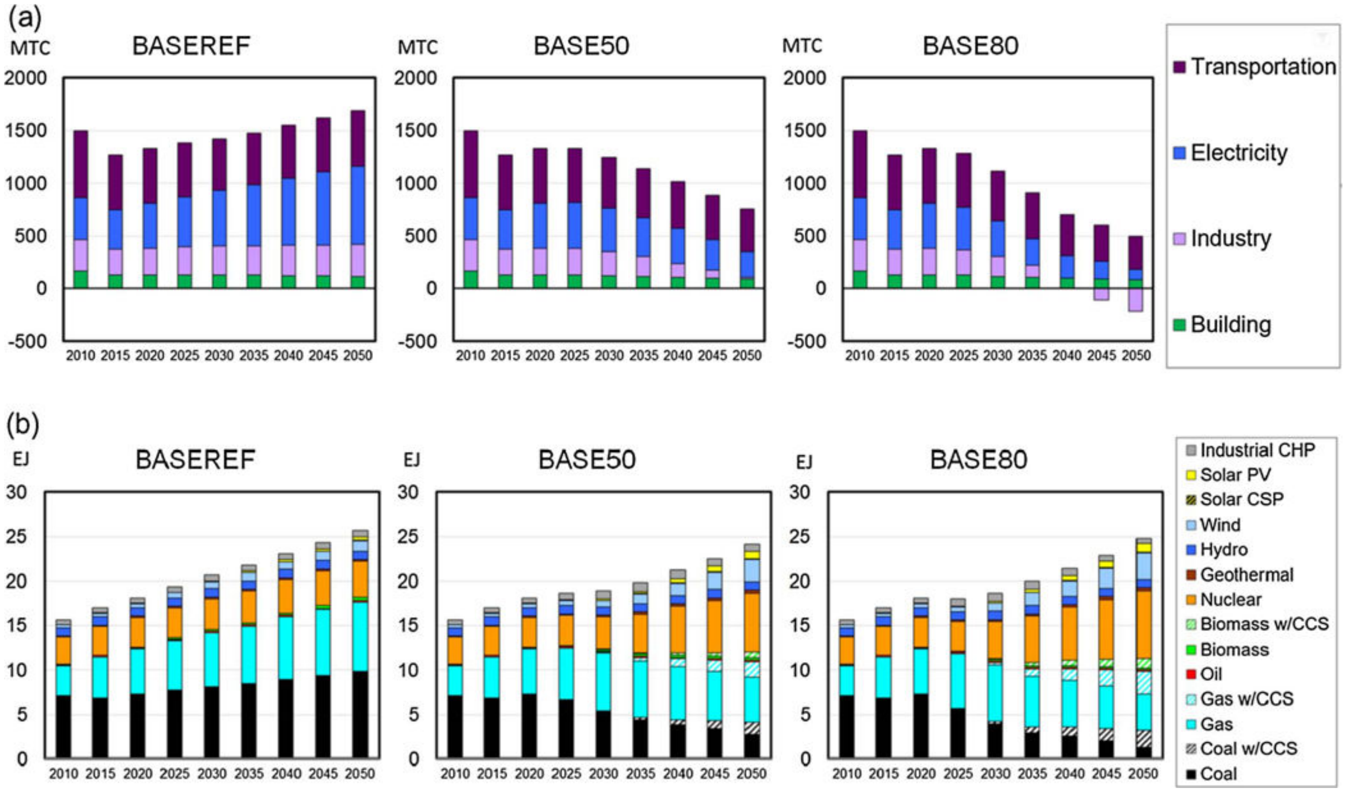

Fig. 1.

(a) CO_2 emission (million tonnes C per year) for the U.S. energy system by sector and (b) electricity generation (EJ per year) by technology for BASE scenarios from 2010 to 2050.

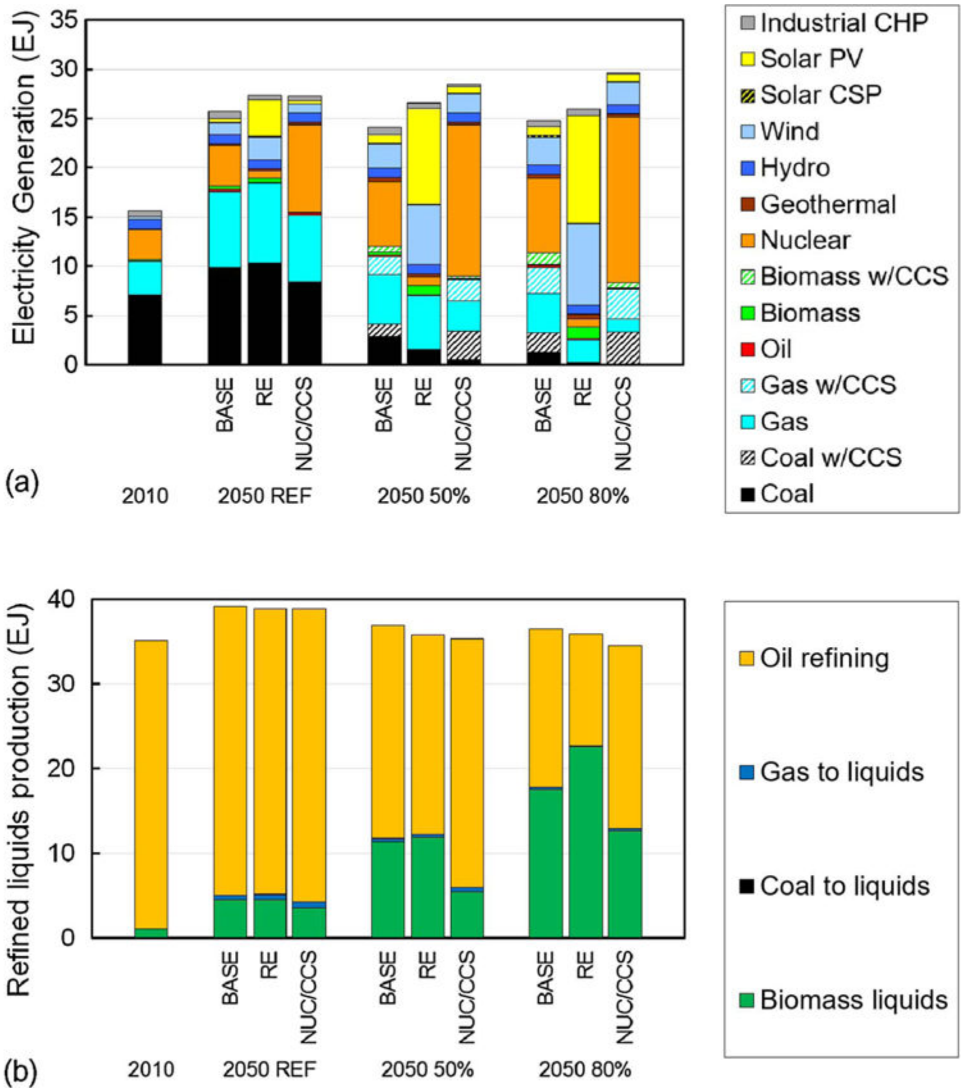

Fig. 2.

(a) U.S. electricity generation (EJ per year) by technology and (b) refined liquids production by technology in 2010 and for each of the technology and CO_2 reduction target scenarios in 2050.

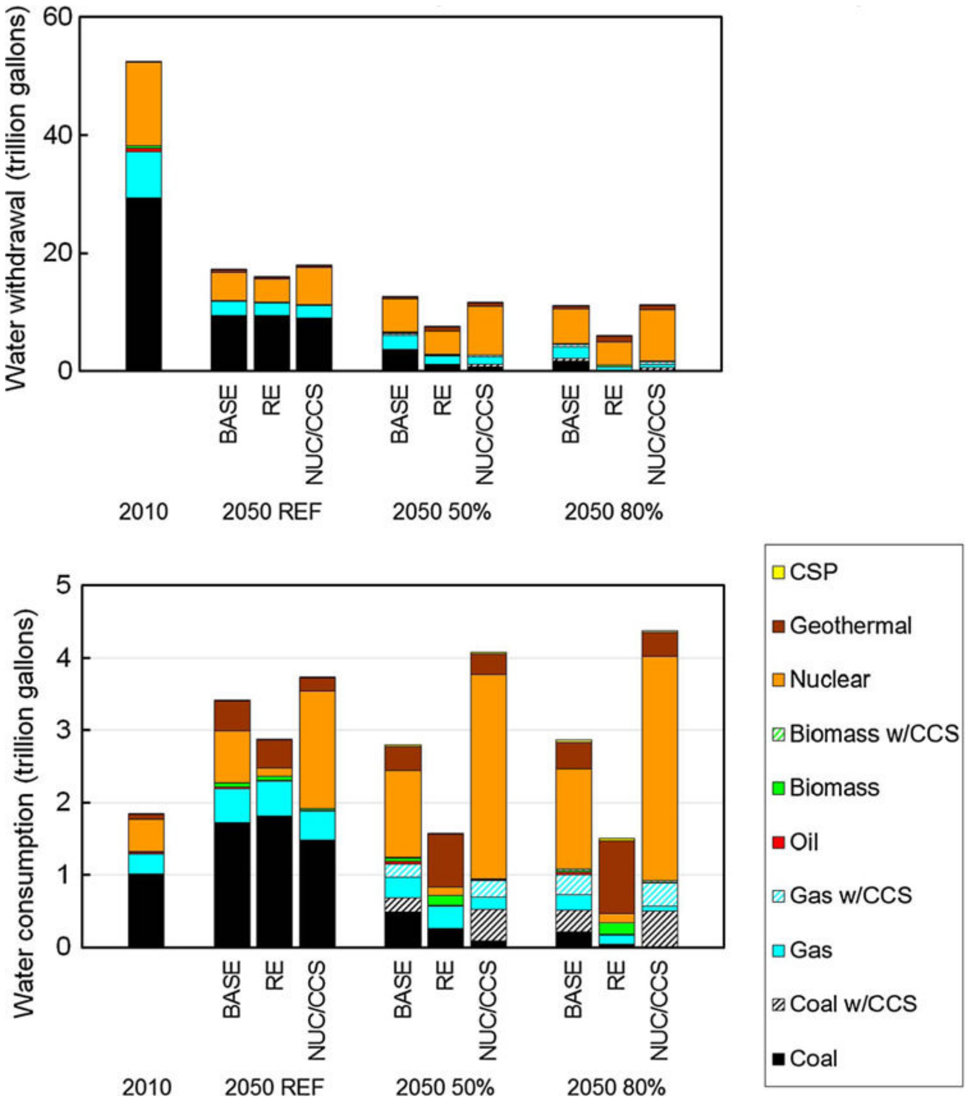

Fig. 3.

U.S. water withdrawal and consumption (trillion gallons per year) for electricity production by technology in 2010 and for each of the technology and CO_2 reduction target scenarios in 2050. PV and wind have negligible water demands during operation.

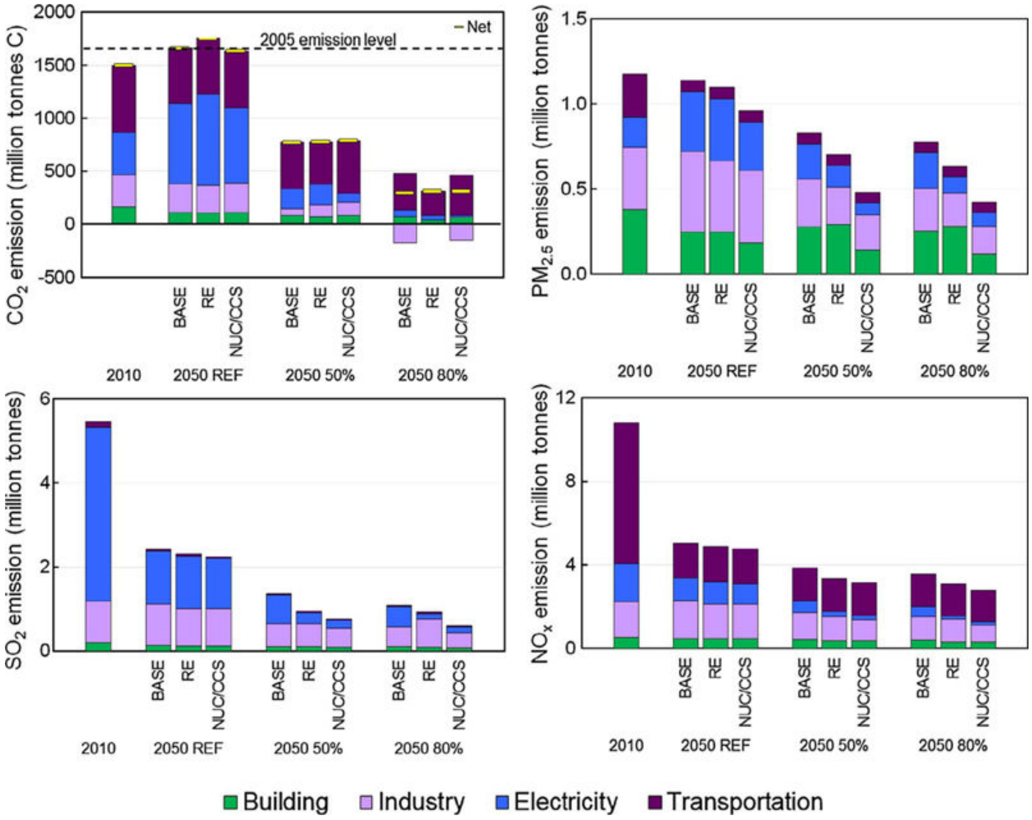

Fig. 4.

CO$_2$ (million tonnes C per year) and air pollutant (primary PM$_{2.5}$, NO$_x$ and SO$_2$) emissions (million tonnes per year) for the U.S. energy system by sector in 2010 and for each of the technology and CO$_2$ reduction target scenarios in 2050.

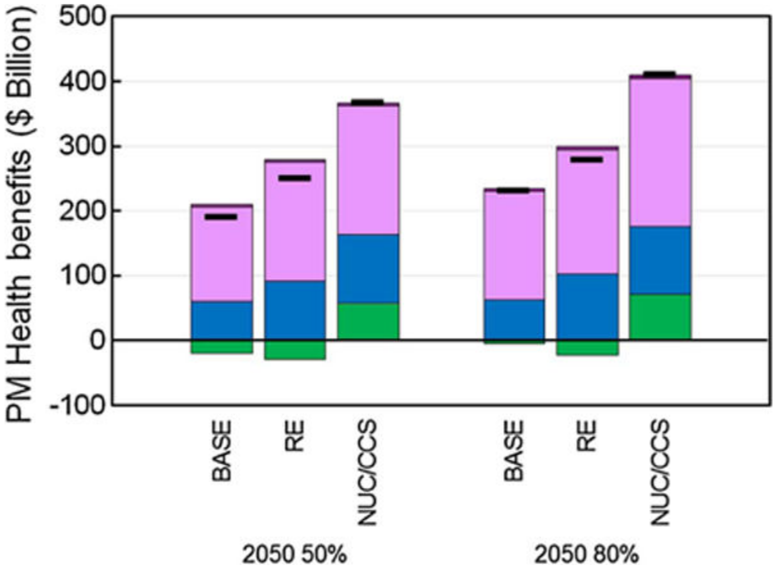

Fig. 5.

Monetized $PM_{2.5}$-related health benefits of CO_2 emissions targets for different technology pathways (billion 2010$ per year) in the U.S. energy system by sector in 2050, relative to BASEREF. Positive values indicate health benefits from pollutant emissions reductions; negative values indicate health damages; the Net value is the sum of positive and negative values for each scenario.

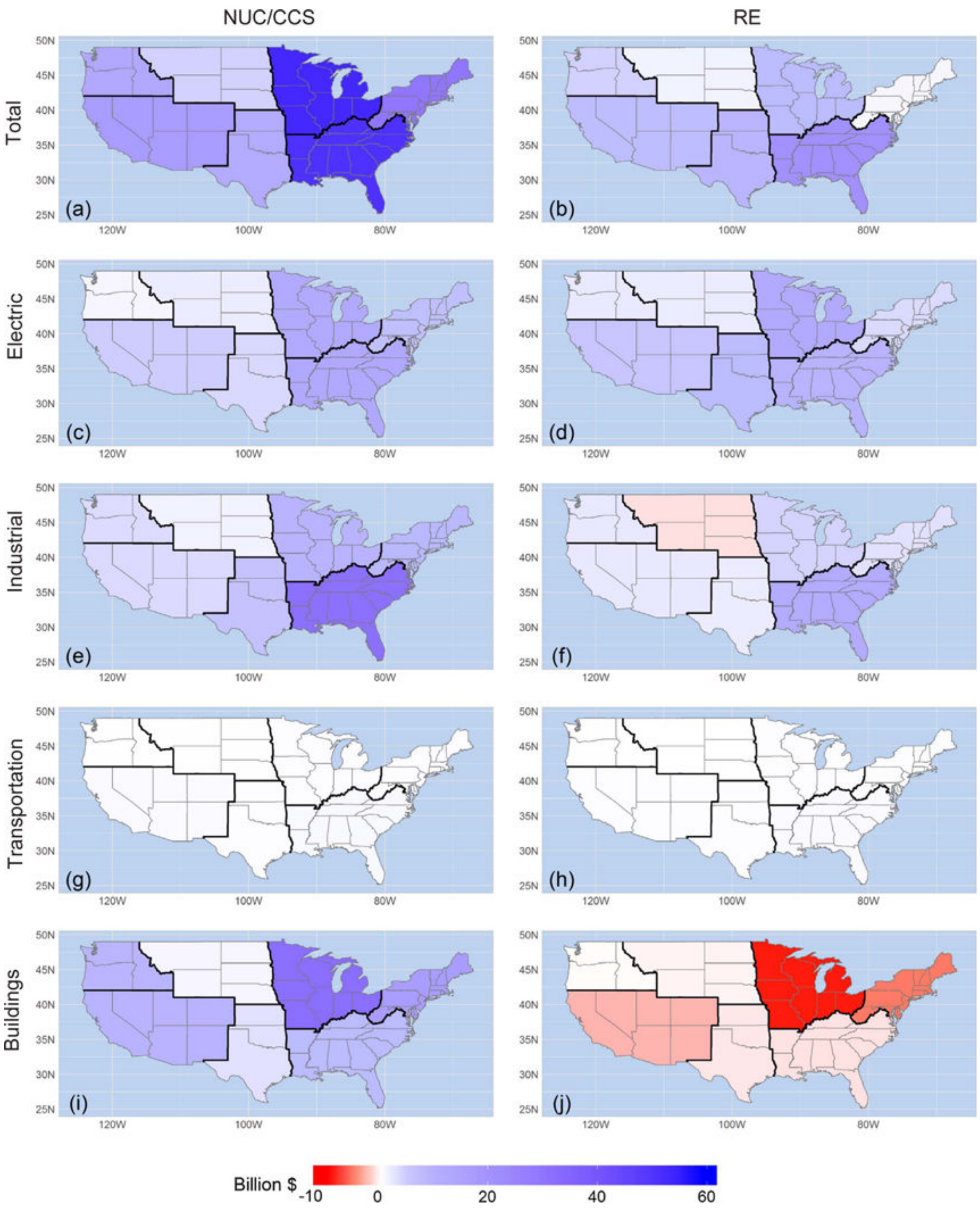

Fig. 6.

Regionally aggregated estimates of annual $PM_{2.5}$ health benefits of NUC/CCS80 and RE80 relative to BASE80 in 2050. Blue colors represent additional health benefits; red colors represent damages (billion 2010$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Modeling scenarios

Technology pathways	**CO_2 emissions reduction targets**[d]		
	None (REF)	**50% reduction**	**80% reduction**
BASE[a]	BASEREF	BASE50	BASE80
RE[b]	REREF	RE50	RE80
NUC/CCS[c]	NUC/CCSREF	NUC/CCS50	NUC/CCS80

[a] Baseline assumptions with all electricity production technologies available.

[b] Rapid reduction in costs of renewable energy technologies; no new builds of nuclear plants; carbon capture unavailable.

[c] Optimistic assumptions about costs of nuclear and CCS technologies; slow decline in costs of renewables; restricted supply of biomass for energy transformation and end-use.

[d] Reduction targets attained in 2050, relative to emissions in 2005.