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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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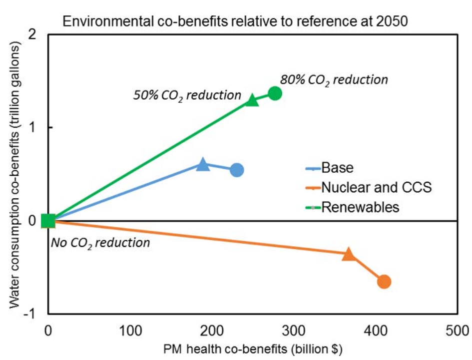
HIGHLIGHTS

- GCAM-USA is modified to include water and PM-related health impact factors.
- Three technology pathways are evaluated for 50% and 80% CO_2 reduction targets.
- Technology pathways include Reference, Renewable, and Nuclear and CCS.
- The Renewable pathway has the lowest water use but highest PM health impacts.
- PM from wood combustion offsets some of the health benefits of low carbon pathways.

GRAPHICAL ABSTRACT



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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

Abbreviations: CAFE, Corporate Average Fuel Economy; CCS, Carbon Capture and Storage; CPP, Clean Power Plan; CSAPR, Cross-State Air Pollution Rule; CSP, Concentrated Solar Power; EMF 24, Energy Modeling Forum 24; GCAM, Global Change Assessment Model; GCAM-USA, Global Change Assessment Model with US state-level representation; GHG, Greenhouse Gas; HDV, Heavy Duty Vehicles; IAM, Integrated Assessment Model; LDV, Light Duty Vehicles; RCP4.5, Representative Concentration Pathway 4.5; US EPA, United States Environmental Protection Agency; VSL, Value of Statistical Life

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residential heating. Environmental co-benefits differ among states because of factors such as existing technology stock, resource availability, and environmental and energy policies.

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 represent 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