Energy and Climate Change 4 (2023) 100117

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

State-by-state energy-water-land-health impacts of the US net-zero emissions goal

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ARTICLE INFO

Keywords:
National decarbonization
Net-zero emission
Economic and sustainability implications
Integrated assessment model

ABSTRACT

As decisionmakers at various scales begin to design strategies to implement the US net-zero goal, a holistic understanding of its broader economic and sustainability implications at subnational scales is important to shape public support and facilitate implementation. Here, we use an integrated assessment model to explore four different pathways toward the US net-zero goal and investigate their energy-water-land-health implications at the state level. We show that achieving the net-zero goal implies significant capital turnover (170–200 billion USD/year capital investment and 16–29 billion USD/year stranded assets in the power sector), reduced water withdrawal (120–210 km^3/year), avoided air pollution damages (220–300 billion USD/year), and expanded forests (300–500 thousand km^2). However, the economic and sustainability implications of achieving the net-zero goal at the state-level may not be correlated to a state's contribution to national emission reductions. Our study lays the foundations for a deeper understanding of the broader implications of the US net-zero goal to facilitate cost-effective and environmentally sustainable transitions toward that goal.

1. Introduction

During the 2021 United Nations climate conference, the US announced its updated climate pledge [1] "to reduce net greenhouse gas emissions by 50–52 % in 2030 relative to 2005 levels" and to reach "net-zero emissions no later than 2050". Furthermore, the US has set a goal of achieving "100 % carbon pollution free electricity by 2035" [2], providing a step on the path to the net-zero pledge. Such goals are expected to have far-reaching economic and sustainability consequences due to the synergies and trade-offs among carbon emissions reductions and land use, capital mobilization and finance, employment, and air pollution-related health impacts [3–7]. The acceptance and implementation of these overarching goals may hinge on the degree to which these relationships are aligned [7,8], raising an important policy-relevant question: *What do these national decarbonization goals imply for broader economic and sustainability priorities beyond climate?*

Answering the above question is complicated by the subnational heterogeneity in the US in terms of climate policy ambition and capabilities to reduce emissions [9,10]. As a result, the economic and sustainability implications of carbon reductions may be amplified or dampened considerably from one region of the country to another. Hence, understanding and quantifying these impacts at *subnational scales* is important for shaping public support and in the steps of policy design and implementation.

Furthermore, national and subnational implications of the US climate goals would depend critically on a number of technological factors. These factors include the availability of key low-carbon technologies, the ability to deploy carbon dioxide removal (CDR) measures [11], the characteristics of socioeconomic development, the rate of technological advances in low-carbon technologies, the ability to reduce demand through measures such as energy efficiency and behavioral changes, and opportunities to electrify end-use sectors.

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https://doi.org/10.1016/j.egycc.2023.100117

Available online 12 October 2023
2666-2787/© 2023 Published by Elsevier Ltd.

Despite a large body of model-based studies examining US decarbonization pathways [12–14], many studies are based on less ambitious emissions reductions and do not directly represent the latest 2021 climate goals of the US. Recent studies that incorporate the 2021 US climate pledges – including the US Long-Term Strategy report [1] – focus on aggregated, national-scale results [15–17], on specific sectors (such as electricity [18,19] and buildings [20]), or on near-term actions in 2030 [16,21]. Few analyses investigate the implications of US net-zero greenhouse gas (GHG) pathways at subnational scales (Supplementary Text S1). For instance, the Net-Zero America study estimated multiple net-zero pathways and their sub-national implications of energy system transitions, infrastructure, and air quality [3]. Yet, other implications have not yet been explored, including the broader land, energy, and water impacts, including those of negative emissions technologies [5] (see Supplementary Text S1 for an expanded literature review).

We fill these important gaps by exploring a suite of emissions pathways for the US and computing a broad set of economic and sustainability metrics at the state level for those pathways. Our emission pathways incorporate the US 2030, 2035 and 2050 energy and climate goals and vary across assumptions about the availability of carbon capture and storage (CCS) technologies as well as other engineered CDR measures such as direct air capture (DAC), deployment of terrestrial sinks, and the adoption of measures to reduce demand through energy efficiency and behavioral changes. To construct our emissions pathways, we use a US-specific version of the Global Change Analysis Model (GCAM-USA) that simulates the global energy, water, land use, economy, and climate systems through 2100 along with state-level details in the US [22]. For each of our pathways, we compute energy system investments, financial risks associated with stranded assets, water withdrawals, land-use changes, and air quality co-benefits of decarbonization at both national and sub-national scales. In doing so, our study builds off and extends previous modeling studies that have explored US decarbonization pathways [1,3,16] by assessing subnational decarbonization actions and cross-sector implications.

2. Material and methods

2.1. The global change analysis model (GCAM) and GCAM-USA

GCAM is an open-source integrated assessment model developed and maintained at the Joint Global Change Research Institute in Pacific Northwest National Laboratory. This study uses the Global Change Analysis Model (GCAM) v6.0 (available at https://github.com/JGCRI/gcam-core/releases). The full documentation of GCAM is available on the GCAM documentation page (http://jgcri.github.io/gcam-doc/), and the description here is a summary of the online documentation. A detailed model description is included in Supplementary Text S3.

GCAM represents energy, economy, agriculture and land use, water, and climate systems at different spatial scales. Economy and energy systems are resolved in 32 geopolitical regions across the globe. Land allocation, water use, and agriculture production are represented across 384 land subregions and 235 water basins. GCAM is a dynamic recursive model that solves the equilibrium prices and quantities of over 1300 energy, agricultural, water, land-use, and GHG markets in each region and in each modeling period (from 2015 to 2100 with 5-year time-steps, and 2015 as the final calibration year). The equilibrium prices and quantities for each market and each modeling period are driven by exogenous assumptions of population growth and labor productivity, as well as the prescribed representations of resources (resource curves), technologies (such as various cost components, lifetime, and learning rate), and policy (such as emission taxes). Technology choice is endogenously determined by market competition, represented by a logit model [23,24] to represent decision-making among competing options when only some characteristics of the options can be observed and avoid a "winner take all" response.

GCAM-USA is a version of GCAM with subnational detail in the USA [25]. GCAM-USA is built within the global GCAM but contains 51 state-level regions (50 states plus the District of Columbia) that represent the US economy and energy systems. These state-level regions contain explicit representations of socioeconomic drivers, resource endowments, energy transformation sectors, and final energy services; agriculture and land use activity and water resources are represented at the HUC-2 river-basin level, while fossil resource extraction and livestock are represented at the national level. State-level regions are connected to the rest of the world through global markets for primary energy carriers, and the USA is linked to the rest of the world via agricultural markets. Thus, subnational outcomes in the US are consistent with global conditions.

GCAM-USA contains heterogeneous state-level assumptions about population and economic growth (labor productivity) that are broadly consistent with the Shared Socioeconomic Pathway 2 (SSP2) assumptions [26]. GCAM-USA features a detailed energy system, including multi-scale energy supply, transformation, and demand. GCAM-USA also represents key energy transformation processes at the state level (electricity generation, refining, fertilizer production), with a few sectors still modeled at the national level (gas processing, hydrogen production). These transformation sectors produce energy carriers that are consumed and ultimately translated into energy services in the building, transportation, and industry end-use sectors. Inter-state electricity trade and regionally differentiated fuel prices for key energy carriers (electricity, refined liquids, natural gas, and coal) are captured in the GCAM-USA. A summary of geographic scopes for key energy parameters is presented in Table S1.

The electricity generation sector in GCAM-USA incorporates US-specific power sector technology cost assumptions, state-specific coal retirements, and state-specific nuclear retirements. While GCAM-USA does not specifically factor in power plant siting due to transmission capacity or geographic constraints, future capacity additions are influenced by changes in demands and technological competition. Similar to the global 32-region model, electricity generation is projected in five-year increments. GCAM-USA represents load duration curves (LDCs) at the level of the fifteen grid regions, capturing the supply-side dynamics related to the seasonal and diurnal variation of electricity demand. Each LDC is divided into four segments (baseload, intermediate, sub-peak, and peak load). The shape of the LDC in each grid region is determined by the share of loads and hours in each segment. Within each segment, technologies compete based on their levelized costs, encompassing capital cost, O&M cost, fuel cost, and others. Renewable resources are represented at the state level, while fossil resources are supplied via a national market (Table S1). GCAM-USA's electricity technology cost assumptions are based on the Base Case scenario presented in the National Renewable Energy Laboratory's (NREL) 2019 Annual Technology Baseline (ATB) [27]. These assumptions entail significant capital and O&M cost reductions for most technologies, especially solar and wind technologies. Additionally, GCAM-USA includes the investment tax credit (ITC) and production tax credit (PTC) for certain generation technologies [28]. This modeling was conducted prior to the enactment of the Inflation Reduction Act (IRA), so these credits are at their pre-IRA levels.

Demands for final energy services are represented at the state level in GCAM-USA. Final demands include residential and commercial building floor space and energy services such as space heating and lighting; industrial energy use, including for combustion, feedstocks, cement production, and fertilizer production; and transportation services including passenger-kilometers traveled, and freight-tonne-kilometers shipped. GCAM-USA includes electrification options in the transportation sector, including electric vehicles and electric trucks. Transportation cost and energy intensity assumptions are based on NREL's Electrification Futures Study [29].

GCAM-USA endogenously represents water supplies and demands at a water basin scale, described in detail in Kim et al. [30] and Turner et al. [31]. The model represents water supplies from three distinct freshwater sources: renewable water (surface and ground), nonrenewable groundwater, and desalinated saltwater. Additionally, saltwater is available for the cooling of thermal power plants (and treated as an unlimited resource) in coastal states. These water resources are represented at the HUC-2 river basin level and include extraction costs and availability limits for each resource type, such that water prices escalate as demand increases. GCAM-USA endogenously tracks water demands from all sectors – primary energy, agriculture (irrigation), livestock, electric power, manufacturing, and municipal in both withdrawals and consumptions. Water withdrawal represents the total volume of water extracted from the supply system. In contrast, water consumption represents the fraction of withdrawals not directly returned to the system for immediate re-use. Water resource availability and demands are endogenously resolved through a water market pricing mechanism at the river basin level. Water demand for electricity generation, manufacturing, and municipal water use are represented directly at the state level. In the electric power sector, GCAM-USA includes an endogenous competition among cooling systems (once-through, seawater once-through, recirculating, cooling pond, dry cooling, and dry-hybrid cooling systems) for each thermal electricity generation technology. Wind power is assumed to have no water demands (withdrawals or consumption), while photovoltaic solar (PV) requires a small amount of water for plant operations and maintenance. Hydropower has no water withdrawals but some consumption due to evaporation losses associated with impoundment reservoirs. Water demand for primary energy and livestock are modeled at the national level, while water demand for agriculture is modeled by land use region [32].

The agriculture and land system in GCAM-USA is consistent with its representation in the global 32-region GCAM. Land is allocated between alternative uses such as food crops (including wheat, corn, rice, root and tuber, and other grain), commercial biomass, forests, pasture, grassland, and shrubs based on expected profitability according to a logit-share mechanism. The profitability, in turn, depends on the productivity of the land-based product (e.g., the mass of harvestable product per hectare), product price, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. GCAM also tracks land from desert, tundra, and urban land. However, these are excluded from economic competition and assumed to be fixed over time. Yields for all crops are assumed to improve over time. These improvement rates vary by region, with higher improvement rates in developing regions. The energy system and the agriculture and land-use systems are hard-linked. For example, commercial biomass is demanded in the energy system, while its supply is modeled in the agriculture and land-use component. Fertilizer supply is represented in the energy system, while fertilizer demand is modeled in the agriculture and land use system. Traditional biomass is represented through exogenous supply curves that account for the opportunity cost associated with collecting traditional biomass – collecting traditional biomass requires labor, which becomes increasingly expensive as incomes rise. The fundamental geographic unit for the land system in GCAM-USA is still the GCAM land use regions (water basins intersected with 32 core GCAM regions), 23 of which lie in the US. While the interconnections between agriculture and other systems in GCAM-USA often involve the state regions (for instance, fertilizer production is represented at the state level; agricultural water demands are tracked at the state level), agricultural activity is not tracked at the state level or directly impacted by state-level policies, technologies, or other drivers. In this analysis, changes in land use at the state level are post-processed from the 23 land use regions according to the proportion of each state's area within those regions.

GCAM-USA tracks emissions of a variety of GHG species: CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and SF6. CO_2 emissions result from the direct combustion of fossil fuels and conversion to other forms (such as upgrading of unconventional oil). GCAM-USA tracks non-CO_2 emissions from resource production at the national level, emissions from agricultural and land-use systems at the basin level, and emissions from electric generation, buildings, transportation, industrial energy use, industry processes, urban processes, cement, and refining sector at the state level. Historical emissions of CH_4, N_2O, and F-gases are harmonized with the 2019 EPA Global Non-CO_2 Greenhouse Gas Emission Projections and Mitigation Potential report [33]. Historical emissions of air pollutants (BC, OC, $PM_{2.5}$, PM_{10}, NO_x, SO_2, NMVOC, CO, and NH_3) are derived from US National Emissions Inventory [34] and scaled to the Community Emissions Data System (CEDS) [35] for consistency with the global model. Future emissions are estimated as the product of the projected economic activity, the corresponding emission factor for a given technology. For non-CO_2 GHGs, marginal abatement cost curves are based on the 2019 EPA Global Non-CO_2 Greenhouse Gas Emission Projections and Mitigation Potential report [33]. For air pollutants, future emission factors in general reflect rules and legislation in each sector [36], such as the Tier 3 Motor Vehicle Emission and Fuel Standards and the New Source Performance Standards (see GCAM-USA documentation page https://jgcri.github.io/gcam-doc/gcam-usa.html for more details).

GCAM-USA used in this study assumes the availability of three carbon dioxide removal (CDR) options: afforestation, bioenergy in combination with CCS (BECCS), and direct air capture (DAC) technologies. Afforestation is modeled as changes in land use for each land use region. BECCS and DAC are represented at the state level. BECCS technologies are deployed in a variety of sectors within the GCAM energy system, including refining (cellulosic ethanol CCS and FT biofuels CCS), electricity generation (biomass-fired plants with CCS), and hydrogen production (coal CCS, gas CCS, and biomass CCS). Our assumptions for DAC technologies are documented in Fuhrman, McJeon [5], and Fuhrman, Clarens [11].

2.2. Emissions pathways

This study constructs four different US net-zero decarbonization pathways. All pathways include the implications of COVID-19 on the economy, characterized by short-term energy demand reduction (Table S1), as well as the latest technological trends described in the previous sections. Furthermore, all pathways incorporate existing state-level energy and emission policies, including state-specific Renewable Portfolio Standards (RPS) and Clean Energy Standards (CES), Regional Greenhouse Gas Initiative (RGGI), Corporate Average Fuel Economy (CAFE) standards, Zero-Emission Vehicle (ZEV) program, and existing nuclear moratoria. See Supplementary Text S2 for detailed modeling assumptions related to baseline parameters (Table S2) and GCAM-USA representation of current policies (Table S3).

Building upon existing energy and emissions policies across states, we constructed four net-zero pathways with two national targets: 1) the US Long-Term Strategy [1], aiming at a 50 % net-GHG emission reduction by 2030 relative to 2005 level and net-zero GHG emissions by 2050, and 2) US power grid achieves clean-grid by 2035 [2]. This pathway reflects more ambitious climate targets that may imply additional decarbonization actions beyond the current policy levels, including what would have been implied by the newly passed IRA [37]. In the central *NetZero* pathway, all mitigation technologies are available, reflecting a relatively balanced mitigation pathway as well as a starting point for additional sensitivity analyses regarding different net-zero pathways.

To account for uncertainties in the availability of key low-carbon technologies, carbon removal technologies, and behavioral changes in decarbonization pathways, we additionally modeled three alternative net-zero pathways. These three illustrative pathways have the same overarching emission pathways as the central *NetZero* pathway but widely different sectoral contributions (Fig. 1). Specifically, *NetZero–NoCCS* assumes no carbon capture and storage technologies (power plants with CCS, industrial CCS, BECCS, and DACCS) in any sector. *NetZero–LowLUC* assumes low availability of land-based carbon sinks, such as afforestation. *NetZero–LowDemand* assumes low demand in

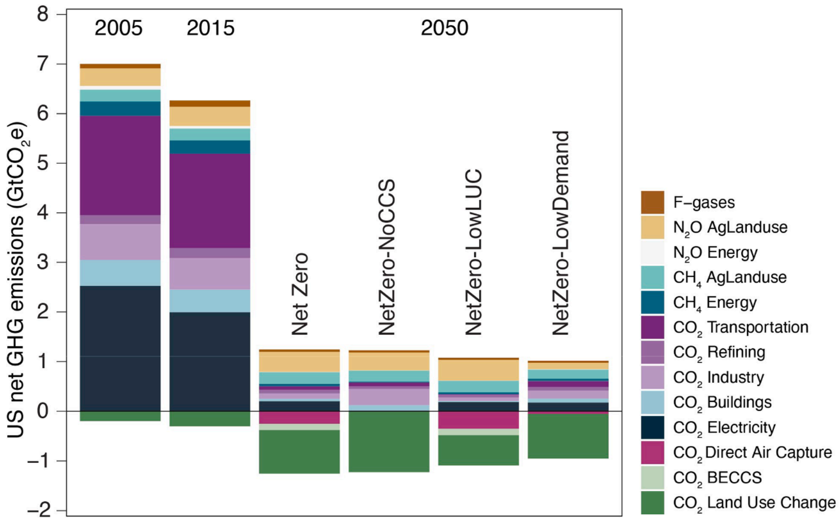

Fig. 1. US annual GHG emissions by sector in the pathways modeled using the global change analysis model with US state-level details (GCAM-USA).

mobility and housing demand and pricing of nonCO$_2$ GHGs (as a fraction of carbon price), leading to lower demand in their emitting sources, such as agricultural products. See Table 1 for detailed modeling assumptions for these net-zero pathways.

For all net-zero pathways, the rest of the world is assumed to achieve their latest Nationally Determined Contributions (NDCs) and net-zero pledges. Countries without net-zero pledges assumed a minimum 8 % decarbonization rate (measured by reductions in GHG emissions per GDP) per year after 2030. Globally, these net-zero pathways are consistent with a 1.5 °C-consistent mitigation pathway [38].

2.3. Capacity and capital stock turnover in the electric power sector

The estimation of capacity and capital stock turnover in the electric power sector follows the same approach documented in Iyer et al. [39] and Binsted et al. [40]. GCAM-USA tracks power plant capital by state, technology, and vintage over the lifetime of the technology. For a given fleet, power plants can be retired through two mechanisms: natural retirement at the end of the physical lifetime or profit-induced premature retirement (stranded assets) (Eq. (1)):

$$G_{T,V,r}(t) = G_{T,V,r}(t-1) \times \left[1 - f^{N}_{T,V,\ r}(t)\right] \times \left[1 - f^{P}_{T,V,\ r}(t)\right] \tag{1}$$

where $G_{T,V,r}(t)$ represents the electricity generation by technology T and vintage V in region r in modeling period t. $f^{N}_{T,V,\ r}(t)$ and $f^{P}_{T,V,\ r}(t)$ are the fraction of natural- and profit-induced retirement in modeling period t.

An open-source R package *plutus [41]* was developed to conduct the calculation through the following three steps:

1) The power generation by technology and vintage is extracted from GCAM-USA output.
2) For each new vintage fleet, natural retirement factions ($f^{N}_{T,V,\ r}$) for each lifetime are calculated based on an “S Curve Shutdown” function [42].
3) Compare GCAM’s actual power generation output and the “expected” natural retirement trajectory in Step 2 to estimate the premature retirement and stranded assets. Stranded assets are calculated as the product of premature retirement and the corresponding capital cost of each technology.

Notably, the calculations of stranded assets are also subject to many uncertainties, including real-world plant lifetimes, capacity dispatch, costs of financing, power plant contractual arrangements, and perceived risks regarding the future policy and regulatory environment.

2.4. State-level PM$_{2.5}$-related mortality costs (PMMC) in GCAM-USA

Exposure to fine particulate matter (PM$_{2.5}$) from fuel combustion significantly contributes to global and US mortality. PM$_{2.5}$ is directly produced from fuel combustion and weathering processes (primary PM$_{2.5}$). In addition, secondary PM$_{2.5}$ is formed from chemical reactions of precursor pollutants (such as SO$_2$ and NO$_x$) in the atmosphere. We evaluated PM$_{2.5}$-related mortality costs (PMMC), which account for over 90 % of the total monetized PM$_{2.5}$ health impact [43]. PMMC is modeled in GCAM-USA by multiplying a pollutant-, source category-, and state-specific PMMC coefficient ($/Tg) derived from the Estimating Air pollution Social Impact Using Regression (EASIUR) model [44] with the corresponding pollutant emissions (Tg) for each technology. EASIUR is a reduced-form model derived from the regression of outputs of a chemical transport model. It has estimated the PM$_{2.5}$-attributable deaths within the US per tonne of inorganic air pollutant emissions (primary PM$_{2.5}$, SO$_2$, NO$_x$, and NH$_3$) from each county in 2005. These county-level death-per-tonne estimates were aggregated to the state level for the electricity, industry, transportation, and building sectors in 2005, based on the emission-weighted sum for each sector, and then adjusted for each future time period modeled in GCAM-USA (2010–2050 in 5-year increments) to account for future changes in population exposure, baseline mortality rates, and value of statistical life [45]. The state-level mortality costs presented here represent the mortality impact of emissions from that state on the population within that state and all downwind states. Our previous research [46–48] demonstrated that integrating PMMC coefficients into GCAM-USA provides an efficient and rapid approximation of PM$_{2.5}$ mortality impacts, allowing it to be used for evaluating large numbers of scenarios to support decision-making.

3. Results

3.1. Emissions pathways and sub-national decarbonization

The four net-zero emission pathways each suggest that achieving the 2050 net-zero pledge entails rapid reductions of GHG emissions from all sectors (Fig. 1). Over the next several decades, the electricity and transportation sectors will dominate the overall decarbonization. By 2050, the net-zero GHG emissions are comprised of a combination of approximately one gigatonne (Gt) of residual CO$_2$ and non-CO$_2$ GHG emissions from hard-to-abate sources (e.g., rice cultivation, livestock management, and fertilized soils) and an equal amount of CDR to offset these emissions. Even in a pathway with low energy demand (*NetZero-LowDemand*), where non-CO$_2$ emissions are further reduced,

Table 1
Modeling assumptions for net-zero pathways. All net-zero pathways include core assumptions and policy assumptions in Supplementary Tables S2 and S3.

Net-zero pathway	Pathway description	Clean-grid 2035 target	Net-zero by 2050
NetZero	Central net-zero pathway, all low-carbon technologies are available.	State and federal renewable energy targets are implemented by setting a minimum % of the total electricity load to be met by renewable generation and aggregated to the grid region, ramping up to 100 % clean electricity by 2035.	A national total net-GHG constraint is applied to achieve a 50 % reduction in 2030 relative to 2005 and net-zero GHG by 2050. 10 % of the modelled carbon price will be applied to the land-use sector in 2025 and linearly increase to 100 % by 2050, reflecting the growing focus on managing carbon emissions in this sector.
NetZero-NoCCS	An extremely high carbon storage cost is applied to prohibit all carbon capture and storage technologies in electricity, industry, and direct air capture.		
NetZero-LowLUC	A constant 10 % carbon price is applied to the land-use sector from 2025 to 2050.		
NetZero-LowDemand	Lower demand in mobility and housing, accelerated industrial efficiency improvement, and pricing on nonCO_2 GHG emissions.		

considerable CDR is still necessary. The scale of CDR determines the amount of “headroom” available for the energy system to emit [49]. For example, the *NetZero* pathway has an annual 20 % higher residual emission level in 2050 compared to *NetZero-LowLUC* because of their varying CDR levels. Our net-zero pathways have different magnitudes and combinations of afforestation, bioenergy with carbon capture and storage (BECCS), and DAC. The overall magnitude of CDR in our mitigation pathways lies within the range explored in the literature [1,50] (Fig. S2). However, the successful implementation of large-scale carbon removal technologies would depend on a variety of factors such as technological feasibility, cost-effectiveness, public acceptance, and regulatory support [51–55].

Spatially, the GHG reductions are dominated by a small subset of states such as Texas, California, and Florida (Fig. 2**a, b**) due to the presence of large industries in these states that are able to implement signification emissions reduction measures. For all pathways, Texas contributes to the largest CO_2 reduction of annual 600–700 Mt in 2050 relative to 2005, followed by California, Florida, Pennsylvania, and Ohio (300–400 Mt CO_2 each). Broadly, the top 10 contributors together account for nearly half of the national total CO_2 reductions (Fig. 2**c**), with deep decarbonization from all sectors. For most of these states, decarbonizing the electricity sector dominates their overall reductions. Together, the top 10 states have over 1000 Mt CO_2 emission reductions from the electricity sector. As an exception, transportation is the leading decarbonization sector in California, contributing to 60–66 % of California’s overall CO_2 reductions among all net-zero pathways. This is because California’s power system is already heavily decarbonized, as the nation’s top producer of electricity from solar, geothermal, and biomass energy [56]. On the other hand, California is also the largest consumer of jet fuel and second-largest consumer of motor gasoline among the 50 states [56], thus decarbonizing these sources would result in significant reductions of transportation-related emissions. The state results mirror the national decarbonization trend (Fig. 1), which calls for an “all-sector” decarbonization effort and also demonstrates the diverse sectoral priorities among states.

Besides CO_2 reductions in energy sectors, carbon removal technologies are also disproportionately distributed across states (Fig. S3). Engineering-based carbon capture technologies, including CCS in power plants, industrial sources, and direct air capture techniques, are required to pair with geologic storage so that the captured CO_2 could be permanently sequestered. In the *NetZero* pathway, Texas contributes to the highest geologic CO_2 capture and storage, more than the combined carbon sequestration from all the rest states. This is because Texas has a large number of suitable geologic formations for storing CO_2, including depleted oil and gas reservoirs, saline aquifers, and un-mineable coal seams. Still, wide deployment of geologic carbon storage would require continued investment in CO_2 transport and storage facilities, as well as policy incentives like the 45Q tax credit [57].

3.2. Investments and stranding in the power sector

Investment in clean electricity is widely recognized as a crucial element in the process of system-wide deep decarbonization [15,16]. In January 2021, the US announced a goal of achieving a clean, modern, and more resilient electric grid by 2035 [2]. As discussed earlier, we explicitly modeled the “clean-grid 2035” target as a key component to all net-zero pathways. This entails accelerated investment in renewable energy sources such as solar and wind, as well as premature retirement of fossil fuel capacity, including coal and natural gas power plants. In all net-zero pathways, the rate of capacity additions for wind and solar range from 72 to 114 GW per year over 2021–2050, which is 4.5–7 times the historical average rates (Fig. 3). The rapid renewable capacity expansion is driven by several factors. First, as the cost of clean energy technologies continues to decline, it is increasingly cost-effective to invest in wind and solar technologies relative to traditional sources [58]. Second, achieving system-wide deep decarbonization would require a

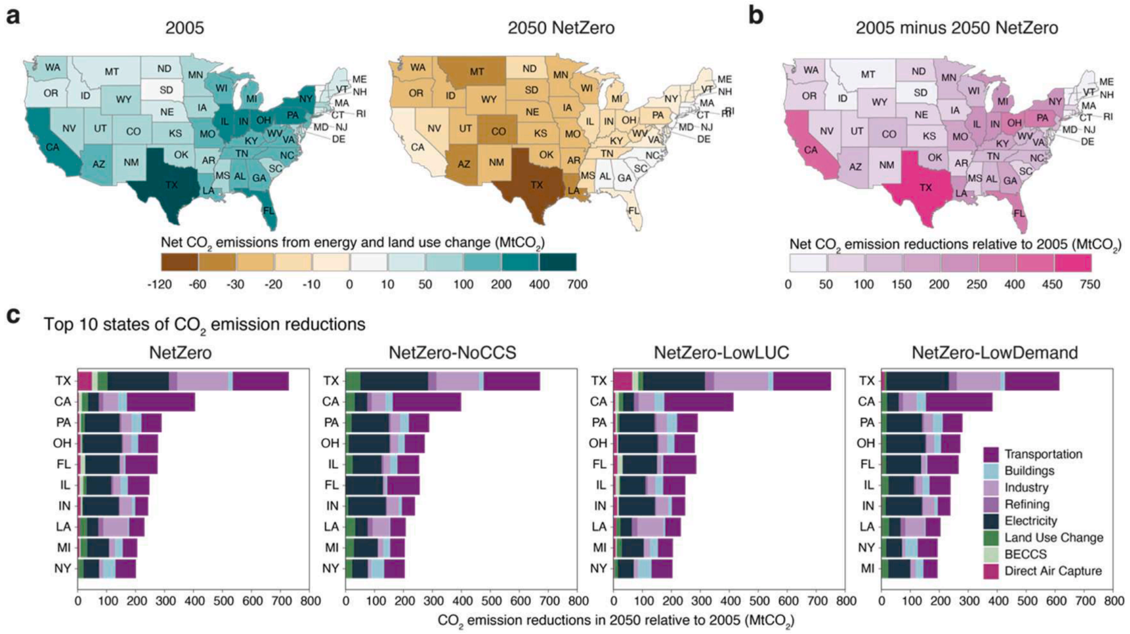

Fig. 2. Subnational net CO_2 emission reductions for the NetZero pathway. (a) spatial distribution of annual CO_2 emissions from the energy and land use change sectors in 2005 and 2050 for the NetZero pathway. (b) state-level CO_2 reductions in NetZero in 2050 from the 2005 level. (c) annual CO_2 reductions across four net-zero pathways for the top 10 states with the highest CO_2 reductions in 2050 relative to 2005.

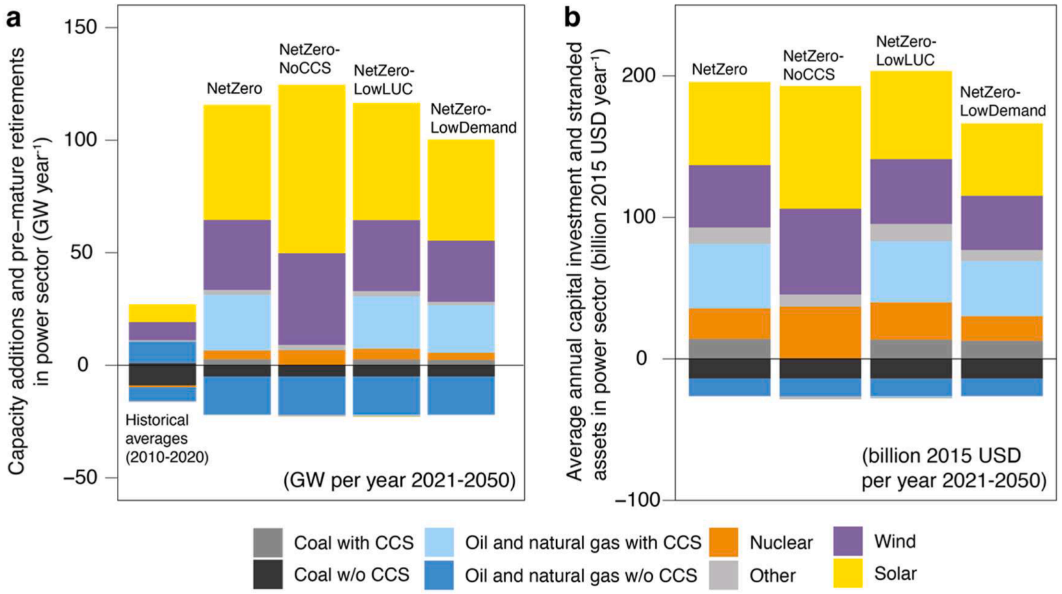

Fig. 3. Capacity and capital turnover in the power sector. (a) average annual capacity additions and premature retirements in the power sector (GW per year), (b) average annual capital investment and premature retirements (stranded assets) (billion 2015 USD per year).

massive shift towards end-use electrification, increasing the overall electricity demand. Across all four decarbonization pathways, nearly all new sales in passenger transport and freight sectors are projected to be electric and hydrogen-fueled vehicles by 2050 (Fig. S4). The clean-energy actions across states, including end-use electrification, are discussed in subsequent sections.

Rapid capacity expansion and capacity turnover also suggest significant financial implications. From 2021 to 2050, we estimate that achieving system-wide net-zero GHG requires approximately 170–200 billion 2015 USD per year capital investment in clean electricity technologies, which is five to six times the investment scale in history (~33 billion 2015 USD per year). This expansion entails massive capital mobilization, reaching 5–6 trillion 2015 USD cumulative capital investment from 2021 to 2050, consistent with the cumulative capital mobilization (~5 trillion USD) for power generation estimated by the Net-Zero America report [3]. In addition to the investment in power generation technologies estimated here, system-wide electrification would also require considerable investment in electricity transmission and distribution networks [3]. Together, the sheer scale of this investment suggests a strong role for financial institutions in facilitating the transition to net-zero emissions.

The large-scale capital investment needs are accompanied by non-trivial financial risks, which may hinder the pace of capacity turnover. All net-zero pathways indicate about 16–29 billion per year of stranded assets in the power sector, equally shared by stranded coal and gas capacities. However, it's crucial to highlight that our scenarios did not consider the allocation of power plants during fluctuating loads and the capacity payments made to utilities to offset capital and other unmet costs in wholesale energy markets. Considering such payments, operating certain natural gas power plants without CCS during peak load periods may still be cost-effective. Nevertheless, despite a smaller scale compared with investment, the magnitude of stranded assets still suggests political ramifications because the potential losses are concentrated on an important set of stakeholders in certain sectors and states [39,40].

The spatial distribution of capacity and capital turnover further reveals the regional implications of the transition to net-zero. Achieving net zero requires rapid capacity expansions for all states, especially for populous states such as Texas, California, and Mid-Atlantic states (Fig. 4**a**). During 2021–2050, Texas has the highest cumulative capacity addition of 420 GW in the *NetZero* pathway. On the other hand, Texas also has the highest stranded capacity of about 70 GW (Fig. 4**b**). In addition to capacity expansion, achieving net-zero will also increase the intra-state electricity trade (Fig. S6). States with abundant renewable resources (such as Montana, Wyoming, and Utah) may have excess clean electricity that could be exported to other states. On the other hand, states with higher demand (such as California) may still need to import electricity from other regions in order to meet their own clean energy goals.

One useful metric to demonstrate the financial implication in a regional context is the ratio between capacity capital investment (or stranding assets) to local gross domestic product (GDP) (Fig. 4**c, d**). This ratio measures the size of the capital investment required to support a given level of clean energy capacity relative to the size of the local economy. For example, even though Texas has the largest capacity expansion in terms of physical units (GW), the corresponding annual capital investment is less than 2 % compared to Texas' GDP in 2021. On the contrary, Wyoming is projected to have a moderate level of capacity addition among other states, but the corresponding capital requirement is about 10 % of its 2021 GDP, indicating that the transition to net-zero may not only spur new investments but could also influence the distribution of these investments across states.

3.3. Implications of net-zero pathways for water, land, and health

Decarbonization toward net-zero emissions could imply a range of environmental co-benefits (Fig. 5), such as reduced water usage, lower mortality costs related to $PM_{2.5}$ pollution, and expanded forests. The benefits for water and human health are results of decreasing fossil fuel use and increased electrification in all energy sectors. However, the extent of these benefits and potential trade-offs can vary between different pathways to net-zero emissions. For example, the *NetZero-LowDemand* pathway has the lowest water withdrawal at 176 km^3 in 2050, which is 32 % less than the central *NetZero* pathway and less than half of today's level [59]. On the other hand, *NetZero-NoCCS* has the lowest costs in terms of $PM_{2.5}$-related mortality due to its avoided $PM_{2.5}$ and SO_2 emissions from CCS technologies (Fig. S7). Compared to the 2015 levels, all pathways lead to expansion in forests by 12–22 % (300–500 thousand km^2). Land use requirements for food crops are decreased, driven by the increased crop yield (the harvested production per unit of harvested area for crop products) (Fig. S8). Beyond the water, land, and air quality implications, there are other environmental factors that are worth considering when evaluating different net-zero pathways, such as the demand for critical minerals (Supplementary Text S5 and Fig. S9).

The transition to net-zero could involve complex synergies and trade-offs that are heterogeneous across states (Fig. 6). For example, among the top-20 CO_2 reduction contributors, state-level CO_2 emissions change from −30 % to −89 %, water withdrawal changes from −67 % to +29 %, and $PM_{2.5}$-related mortality cost changes from −61 % to +3 % in 2030 compared to 2015. While absolute CO_2 reductions emphasize the major contributions of larger states, relative reductions give insight into individual state efforts and progress, especially where they may or may not align with current state-level ambitions or intuitive expectations (Figure S10). Note that the economic and sustainability implications of achieving the net-zero goal at the state level may not necessarily be correlated to a state's contribution to national emission reductions. In our central pathway, the transition toward national net-zero emissions in some states with a higher share of fossil electricity, such as Texas, Pennsylvania, and Illinois, results in favorable outcomes for reduced GHG emissions, increased clean electricity, and avoided air pollution but result in large capital turnover. Other states, such as California and Arizona, reduce their emissions primarily through end-use

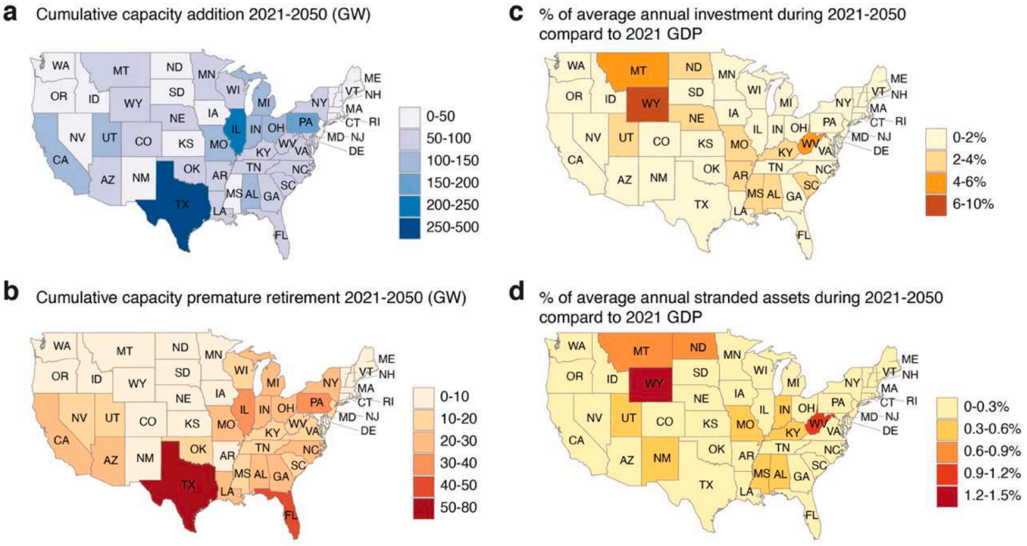

Fig. 4. Subnational electric capacity turnover and financial implications in the NetZero pathway. (a) cumulative capacity addition from 2021 to 2050 (GW), (b) cumulative capacity premature retirement from 2021 to 2050 (GW), (c) the percentage of average annual capital investment in the power sector during 2021–2050 relative to each state's GDP in 2021, and (d) percentage of average annual stranded assets in power sector during 2021–2050 relative to each state's GDP in 2021. The same results for other net-zero pathways are shown in Fig. S5.

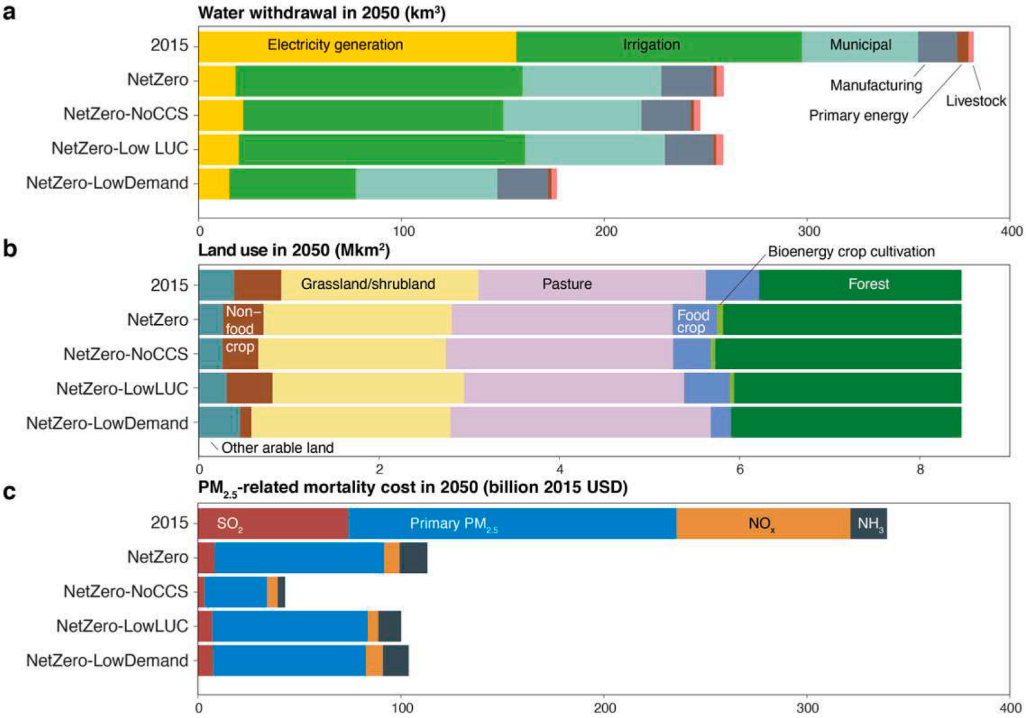

Fig. 5. Synergies and trade-offs of net-zero pathways. (a) annual water withdrawal (km^3) by sector in 2050. (b) annual allocation of land use (million km^2) in 2050 by type. (c) annual $PM_{2.5}$-related mortality cost (billion 2015 USD) in 2050 by pollutant.

electrification, yet could face increased water usage. Furthermore, the sustainability implications vary across the four decarbonization pathways explored in this study (Figs. S11–S18). For example, California's increased water withdrawals range from 18 % (*NetZero-LowDemand*) to 32 % (*NetZero-NoCCS*) by 2030 compared to 2015.

4. Discussion

Ahead of the upcoming Global Stocktake [60], our study provides a comprehensive assessment of the US net-zero pledge to help chart state-level actions and understand their synergies and trade-offs across different net-zero pathways, considering uncertainties in key low-carbon technologies, carbon management strategies, behavioral changes, and state-level policies. Although all net-zero pathways share the similar characteristic of clean electricity investment and end-use electrification, various combinations of mitigation strategies could result in very different economic and sustainability implications for capacity investments, water, land, and air quality across states, implying unique challenges for implementation. Our results emphasize the need to explore decarbonization pathways that focus not only on the climate mitigation goals but also the consideration of the potential synergies and trade-offs of different mitigation strategies, which might be overlooked in highly aggregated analytical frameworks. A few studies have explored such cross-sector implications of deep decarbonization pathways in several countries [9,10,61–65], but more community-wide studies - including inter-model comparison efforts - could help collect robust insights about the multi-sector implications of deep mitigation scenarios at subnational scales.

Our study identifies significant co-benefits of water saving and improved air quality from achieving the US net-zero emissions goal. Compared with the climate benefits of GHG mitigation, these environmental benefits can be achieved in a much shorter timeframe, bringing in additional incentives for implementation. For demonstration, this analysis only considers a set of such environmental benefits, while there could be co-benefits in other environmental and societal systems, such as labor and crop benefits [66]. Regardless of the prevailing climate and environmental benefits, however, heterogeneous patterns of synergies and trade-offs suggest a mismatch between mitigation costs and benefits, at least for some states. This conclusion is conceptually supported by a large and diverse literature discussing the ethical choices behind various burden-sharing approaches [67] but often at the global scale.

In our net-zero pathways, we only consider one burden-sharing approach that all states have an equal marginal carbon price. As expected, states with high population and large-scale energy systems dominate the national emission reductions in all net-zero pathways explored in this analysis. On the other hand, states with the greatest per-capita CO_2 cuts are those with moderate emissions and smaller populations (Fig. S19). Alternative burden-sharing approaches may suggest a moderate increase in overall mitigation cost [10] but arguably reflect a higher degree of political reality [68]. Given that many states have set their own specific emission objectives, future studies could delve into whether certain states might face challenges in reconciling their individual goals with a broader 50-state federal emission target.

We find that achieving a zero-emission electric grid is an undertaking that will require a significant amount of electric capacity and capital turnover. While synthetic gas or biogas can be burned in existing gas plants without extensive retrofits (or fractional blends of hydrogen with minimal retrofit) and meet low emissions targets in electricity sector, to what extent such capacity without CCS is allowed depends on various technical, operational, and institutional conditions. Hence, effective stakeholder engagement will be crucial in ensuring that the necessary investments are made in a timely and efficient manner. For example, the newly passed Inflation Reduction Act (IRA) [69] provides substantial funding for climate and clean energy provisions, including clean energy and EV tax credits, large-scale domestic investments in clean technology manufacturing, and environmental justice measures. Although our analysis did not explicitly model IRA provisions (Table S3), a recent "America is All In" report [21] by a similar team of authors found that existing policies (including IRA) and state-led bottom-up action could collectively reduce US net-GHG emissions up to 39 % below 2005 levels by 2030, whereas a 52 % GHG reduction (consistent with US NDC and the net-zero pathway) could be achieved with additional federal and

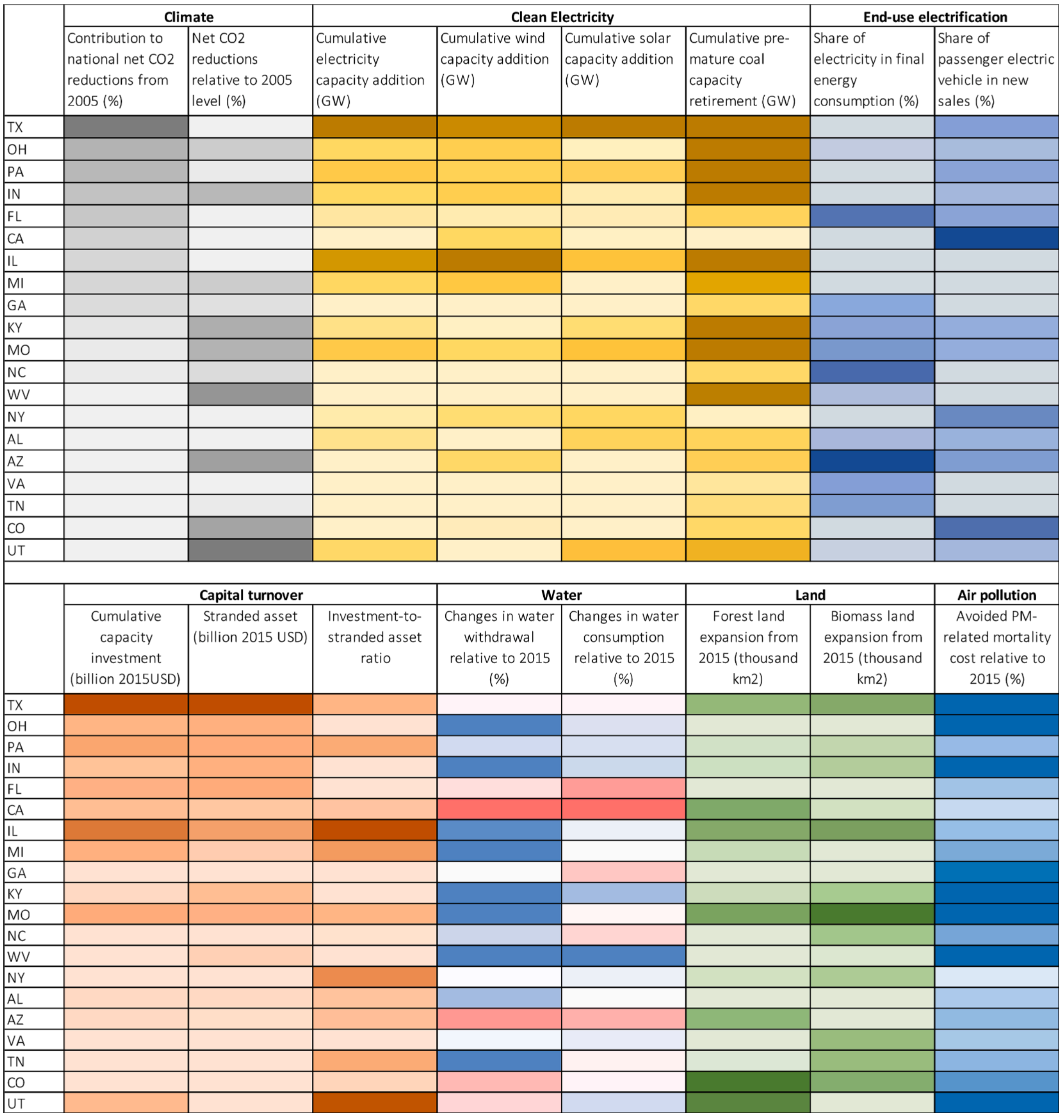

Fig. 6. State-level variations in decarbonization and sustainability metrics in the NetZero pathway for selected states in 2030. The figure presents the top 20 contributors to national net CO_2 reductions in 2030, sorted by their contributions. These states collectively contribute to over 70 % of the national CO_2 reductions in 2030. Illustrative decarbonization metrics include CO_2 emissions, clean electricity, and end-use electrification. Illustrative sustainability metrics include electricity-sector capital turnover, economy-wide water usage, land use changes, and air quality as a proxy of human well-being. The cells in each column are color-coded according to the rank of the respective state in terms of the corresponding metric, and darker shades indicate greater magnitudes in this column. For water-related columns, blue colors indicate reduced water usage, and red colors indicate increased water usage. Numerical results for this figure are presented in Fig. S11. State-level variations in 2050 for the same metrics are presented in Fig. S12. Results for other net-zero pathways in 2030 and 2050 are presented in Figs. S13–S18.

state engagement to accelerate the clean electricity investment, deep decarbonization in end-use sectors, and enhance carbon removals. Similarly, the REPEAT project [70] found the current policies (including IRA) could lead to 37 %–41 % GHG reductions below 2005 by 2030. Therefore, while our current policies set the right direction with initiatives like clean-energy financial incentives and decarbonization regulations, we must amplify and broaden these efforts to ensure a more inclusive approach toward achieving net zero.

While this analysis offers a comprehensive evaluation of the cross-sectoral implications of U.S. net-zero pathways, each component introduces specific uncertainties warranting further discussion. First, the US net-zero target could be achieved by a variety of burden-sharing approaches. While this analysis explored a simple “national market” via a linear GHG reduction pathway, the equitable apportionment of mitigation responsibilities among states could affect the efficacy of state-level mitigation initiatives. Second, operational details beyond GCAM’s structure, such as peak-load dispatch strategies and capacity payments to utilities, coupled with the technical and financial viability of fuel co-firing or CCS retrofitting, could affect the rate and spatial distribution of stranded assets in the energy sector. On the other hand, many technical and financial details could also influence capacity expansion, such as capital disbursement schedule and transmission capacity planning, which are not fully considered in this analysis. Moreover, the health impact assessment involves a multifaceted calculation process, including but not limited to pollutant emission quantification, derivation of health impact coefficients, and intricate atmospheric chemistry and physics. Likewise, other environmental outcomes—ranging from water usage to land use changes—present uncertainties in both source data (such as water use coefficients and land carbon intensities) and modeling structures. Future research efforts should aim to systematically address these uncertainties to enhance the robustness and reliability of both policy formulation and eventual implementation.

More broadly, our study suggests that it will be important to consider the unique circumstances and challenges of each state as efforts are made to achieve the US net-zero goal. This may require a tailored approach that considers the specific energy, water, and land resources of each state, as well as the economic and social context in which the transition is taking place [10]. Yet, our study suggests a strong role for coordination across sectors and scales to ensure cost-effective and environmentally sustainable transitions toward net-zero emissions.

CRediT authorship contribution statement

Yang Ou: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Gokul Iyer:** Conceptualization, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing. **Haewon McJeon:** Conceptualization, Writing – review & editing. **Ryna Cui:** Writing – review & editing. **Alicia Zhao:** Software, Writing – review & editing. **Kowan T.V. O'Keefe:** Software, Writing – review & editing. **Mengqi Zhao:** Software, Writing – review & editing. **Yang Qiu:** Data curation, Writing – review & editing. **Daniel H. Loughlin:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The datasets generated during and analysed in the current study are available from a public repository (https://github.com/ouyang363/godeeep_paper_data).

Acknowledgments

This research was supported by the Grid Operations, Decarbonization, Environmental and Energy Equity Platform (GODEEEP) Investment, under the Laboratory Directed Research and Development (LDRD) Program at Pacific Northwest National Laboratory (PNNL). PNNL is a multi-program national laboratory operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830. HM was supported by the National Research Foundation of Korea (BP Grant: RS-2023-00219466). KO is supported in part by funding from both the Pierre Elliott Trudeau Foundation and the Social Sciences and Humanities Research Council. The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the Environmental Protection Agency or the US government, and no official endorsement should be inferred.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2023.100117.

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