

## Full Length Article

US economy-wide decarbonization: Sectoral and distributional impacts<sup>☆</sup>

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## ABSTRACT

This paper investigates the sectoral and distributional welfare impacts of reaching net-zero CO<sub>2</sub> emissions in the US by 2050. We simulate several net-zero projections using a CGE model linked with an electricity capacity expansion model to try to understand what a transition to net-zero might look like and the role played by different policies and technologies. Reaching net-zero leads to high carbon prices in 2045 and 2050, which drives deployment of direct air capture (DAC) technology. The electricity sector reaches negative emissions by 2050. Electrification is the predominant means for decarbonizing the buildings and transportation sectors, whereas industrial sectors are assumed to have limited electrification potential and prefer carbon management. The negative emissions in the power sector are primarily achieved through biomass-fired electricity generation with carbon capture and storage. In our scenarios, decarbonization is progressive (i.e., burden increases with income) due to our modeling assumption of lump-sum recycling of carbon permit revenues. In 2050, we find a break in the progressive trend when capital-intensive DAC technology enters, as permit revenue distributions that benefit the lowest income groups are directly substituted for returns to capital from DAC deployment that benefit the highest income groups. Our other non-CCS and non-DAC technology improvement cases in the buildings, transportation, and industrial sectors led to a more evenly distributed benefit across households as these mitigation channels are less capital intensive. When the Inflation Reduction Act (IRA) is included, the net-zero emissions limit does not bind as early, the need for DAC is reduced, and industrial CCS investment occurs earlier and in greater amounts. These effects highlight the importance of considering interactions between technologies, policies, and fiscal decisions when prescribing net-zero pathways around a distributional goal.

## 1. Introduction

The 37th Energy Modeling Forum (EMF 37) was initiated to help model builders, model users, and decision makers better understand the potential role of electrification in economy-wide decarbonization pathways in different economic sectors. Since the inception of the EMF 37 study, net-zero CO<sub>2</sub> emissions targets have gained significant policy relevance, and the scope of the study has evolved to improve the energy modeling community's ability to analyze net-zero pathways. Furthermore, this modeling is policy relevant since it is estimated that the temperature goals established in the Paris Agreement require global emissions to reach net-zero emissions by mid- to late-century.

In this paper, we seek to understand what a transition to net-zero CO<sub>2</sub> emissions by 2050 might look like for the U.S. economy

and the role played by different policies and technologies. As EMF 37 participants, we developed several net-zero projections using a linked version of Massachusetts Institute of Technology's (MIT) U.S. Regional Energy Policy (USREP) computable general equilibrium (CGE) model and the National Renewable Energy Laboratory's (NREL) Regional Energy Deployment System (ReEDS) model, known as USREP-ReEDS. We discuss these net-zero policy cases including policy implementation, new model features, physical energy and emissions outputs, and select economic cost and distributional findings. We also simulate an Inflation Reduction Act (IRA) case and layer it into the net-zero pathways to see the policy's effects on energy system evolution. We extend [1] by drilling down on high-level energy and emissions outputs and with an

<sup>☆</sup> The views expressed in this paper are those of the author(s) and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency (EPA). No official Agency endorsement should be inferred. All errors are our own.

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analysis of economic costs and distributional impacts across a broader range of scenarios.

We find – excluding benefits from reduced greenhouse gas (GHG) emissions and air pollution – that a transition to net-zero by 2050 via an emissions cap<sup>1</sup> is costly to the U.S. economy and leads to high carbon prices in 2045 and 2050. A carbon price near 800 USD<sup>2</sup>/tonne of CO<sub>2</sub><sup>3</sup> in 2050 drives deployment of direct air capture (DAC) technologies in our non-IRA net-zero cases.<sup>4</sup> Accelerated technology assumptions, especially those around carbon management,<sup>5</sup> lead to reductions in the 2050 carbon price to approximately 500 USD/tonne of CO<sub>2</sub>. Electrification plays a dominant role in decarbonizing the buildings and transportation sectors, whereas industrial sectors adopt carbon management. Carbon management technologies complement electrification in reducing emissions. For sectors with limited electrification potential, carbon management technologies are cost-competitive alternatives that lower the cost of abatement, thus saving more expensive deployment of electrification technologies.

The IRA jump-starts the transition to net-zero, leading the linearly-declining net-zero emissions cap to bind later. Layering IRA into the net-zero cases reduces the carbon price and eliminates the need for DAC technologies unless carbon management technology change is accelerated. However, the IRA induces earlier industrial carbon capture and storage (CCS) deployment and in greater amounts than in the non-IRA net-zero variants.

Across our scenarios, the net-zero transition is strictly progressive (i.e., burden increases with income) since we assume that each U.S. household receives an equal lump-sum permit revenue distribution — in fact, the lowest income households are made better off given the relative weight of increased government transfers to income. Said differently, the high CO<sub>2</sub> permit price in later years generates large amounts of income that proportionally help lower income households much more than higher income households. Highly capital-intensive carbon management technology deployment causes a regressive distributional effect as returns to capital (benefit to the highest income group) are substituted for lower permit revenues (benefit to the lowest income group). The non-carbon management accelerated technology cases maintain a progressive trend as these shocks are forced into less capital intensive areas of the economy, which distributes the benefits more proportionally across households.

The paper proceeds with a discussion of selected CGE decarbonization literature in Section 2, an overview of methods in Section 3, a description of our policy and technology scenarios in Section 4, the physical and economic model scenario results in Section 5, followed by concluding remarks in Section 6.

## 2. Literature

While numerical models have been used to assess economy-wide CO<sub>2</sub> abatement policy instruments on cost-effectiveness and equity

<sup>1</sup> All net-zero cases are forced primarily through an economy-wide emissions cap that declines linearly from 2020 emissions levels.

<sup>2</sup> All USD values are in 2017-dollars.

<sup>3</sup> All emissions metrics should be associated with CO<sub>2</sub> and not Carbon.

<sup>4</sup> The EMF 37 overview paper [1] provides 2050 carbon prices for participating models ranging from 100 to 1500 USD/tonne of CO<sub>2</sub> with the majority near 400 USD/tonne of CO<sub>2</sub>. These 2050 carbon prices coincide directly with DAC breakeven cost assumptions in most models and our assumptions are based on the central estimates in [2].

<sup>5</sup> Carbon management technology assumptions are those related to the backstop cost of CCS and DAC technology. Non-carbon management technologies are our other non-CCS and non-DAC technology improvement cases in the buildings, transportation, and industrial sectors.

grounds,<sup>6</sup> these studies rarely provide detailed accounting of technological and distributional impacts. Modeling deep decarbonization comes with many challenges such as representing abatement technologies with sufficient detail, calibrating the evolution of these technologies, and capturing interactions with the broader economy and the pre-existing policy landscape. For these reasons, CGE models have emerged as a central tool (along with linkages with bottom-up models) in assessing the economic effects of reaching net-zero.

Other numerical modeling studies exist within the induced technical change literature that have explored representations of CO<sub>2</sub> abatement technologies such as energy-saving and carbon-saving (e.g., DAC) backstop technologies more abstractly.<sup>7</sup> A subset of these studies explore induced technical change and the role of carbon-saving backstop technology in models with varying carbon pricing stringency and breakeven technology costs [15–18]. While their focus tends towards technology interactions, R&D subsidies, knowledge spillovers, or carbon leakage rather than net-zero stringency and distributional effects, they agree that energy-saving technology is the dominant abatement option so long as the breakeven cost of carbon-saving technology is relatively high.<sup>8</sup> Becker et al. [15] suggests that once the policy becomes stringent enough for DAC to be financially viable (or if the breakeven cost falls below the carbon price) it has strong potential to dominate marginal abatement for carbon prices beyond its breakeven cost, preserves fossil fuel demand, and reduces carbon leakage.

Only recently have welfare and distributional effects of deep decarbonization been considered. As part of EMF 37, Bistline et al. [21] performs an intermodel comparison looking at equity concerns of decarbonization across models. Consistent with existing carbon pricing literature they find, as we do, a progressive effect on households due to the lump-sum distribution of permit revenues and a regressive direct effect of the carbon price ex-permit revenues. We show the distributional implications of different technology assumptions and concentrate further on DAC technologies. Bistline et al. [21] does not consider the IRA. We focus on the time path of consumption and distributional metrics while they analyze specific years or present value metrics. Gilmore et al. [22] employs the Global Change Assessment Model (GCAM) combined with Environment Canada's Multi-Sector, Multi-Regional (EC-MSMR) CGE model to explore the economic effects of net-zero pathways for North America and finds an important role for CCS and DAC. They find similar results in that DAC reduces mitigation costs and preserves fossil fuel demand, but they do not discuss distributional consequences of DAC deployment and their regional aggregation is broader than our US-focused analysis.

## 3. Methods

We combine a CGE model of the US economy (USREP) and a bottom-up US electricity capacity expansion model (ReEDS). Below, we provide an overview of USREP, ReEDS, and the linkage approach with an emphasis on important enhancements for this study. A further documentation of the version of USREP-ReEDS used for this study is available in [23].

<sup>6</sup> Examples using carbon pricing mechanisms include: Macaluso et al. [3], Wang et al. [4], Burtraw et al. [5], Fullerton and Heutel [6], Fullerton et al. [7], Rausch et al. [8], Rausch et al. [9], Caron et al. [10], Goulder et al. [11], Hafstead and Williams [12], Williams et al. [13], Caron et al. [14].

<sup>7</sup> Related work within the induced technical change literature: Becker et al. [15], Otto et al. [16], Otto and Reilly [17], Schroyen and Durmaz [18], Popp [19], Gerlagh and van der Zwaan [20].

<sup>8</sup> These studies acknowledge wide uncertainty bands around scale limitations of DAC.

### 3.1. USREP

The U.S. Regional Energy Policy model (USREP), developed at the MIT Joint Program on the Science and Policy of Global Change, is a multi-region, multi-sector CGE model designed to simulate the U.S. economy [24]. It contains 12 regions and 14 sectors, with a recursive-dynamic solving approach in 5-year time steps from 2020 to 2050. The model features five representative households per region, categorized by income, who consume goods, services, and leisure. A government agent, endowed with a fixed reference budget deficit, manages revenue, expenditure, and transfers, and the agent's welfare is determined by marginal deficits from the counterfactual scenario.

USREP sectors include transportation, fossil fuels, services, agriculture, and electricity. Firms in each sector optimize production activities considering prevailing prices and technologies, while capital stocks are vintaged with no substitution possibilities. The model ensures zero economic profit for firms, with revenues fully allocated to various expenses. Prices are determined to maintain market clearance. Multiple technologies exist for transportation and energy sectors, with households having options for personal transportation services like internal combustion, plug-in hybrid, or fully electric vehicles. Fuel economy standards influence vehicle choices.

USREP divides regions according to U.S. Census divisions west of the Mississippi River, with separate modeling for California, Texas, and Alaska. Additionally, USREP includes individual state representations for Florida and New York. In the eastern United States, regions are adjusted from census divisions to accurately reflect electricity markets, state-level GHG policies such as the Regional Greenhouse Gas Initiative and renewable portfolio standards, as well as National Climate Assessment regions. In this study, we focus on the U.S. aggregate results.

National accounts data come from the Wisconsin National Data Consortium (WiNDC) data platform version 3.1, a publicly accessible suite of data and programs designed to process national accounts and energy consumption data into state-level representations of the economy [25]. GHG emissions are calibrated based on fuel-specific combustion coefficients, with energy data sourced from the EIA State Energy Data System (SEDS)<sup>9</sup> via WiNDC's BlueNOTE routine [26].

Significant developments were made to USREP to analyze the effects of IRA and net-zero policies, including migration to WiNDC 3.1 for national accounts data. The WiNDC routine was also used to refine the disaggregation of transportation sectors and to enhance the allocation of transportation energy consumption across sectors. This update aimed to more accurately represent the varying demand for different fuels across transportation modes and between residential and other sources of transportation demand. Previous work to update the sector disaggregation routine and to ensure coherence between national accounts and SEDS energy data integration are also reflected in the version of USREP used in this study. Details can be found in [23].

### 3.2. ReEDS

The Regional Energy Deployment System (ReEDS) is a linear program that solves for the cost-minimizing combination of investment and operation of the US electric power system; details of the assumptions and data sources in ReEDS can be found in [27]. The default geographical resolution is 134 balancing areas and 33 representative dispatch days with 6 representative timeslices per day including a peak net day; in this work, given the computational complexity involved in the elastic demand formulation, we reduce the temporal resolution to 22 representative timeslices per year. In addition to the detailed geographical and temporal resolution, ReEDS is capable of representing variable renewable energy (VRE) through both the technological breadth as well

as the operational details including investment decisions at up to 50 thousand individual sites, each with their own unique capacity factor and grid connection cost parameterization.

The default foresight in ReEDS maintains a myopic perspective — the objective function is structured such that the target of the optimization is the minimization of overnight investment costs, inclusive of construction financing, plus the 20-year present value of operating costs weighted via a capital recovery factor. In this sense, ReEDS steps forward through years sequentially and, after optimizing a specific year, will fix the variables at their optimal values for that year.

ReEDS is publicly available<sup>10</sup> as open-source software. It is required to have a license for the General Algebraic Modeling System (GAMS) and it is highly recommended to have a commercial linear programming solver such as CPLEX or Gurobi.

### 3.3. Linkage

The linked modeling approach is motivated by a need for combining rich technical detail and physical system responses from the bottom-up model with the market spillover effects, endogeneity, and income responses by agents in the top-down model. Bottom-up electricity models incorporate a richer technology set, physical system constraints (e.g., generation, storage, and transmission capacity), process details (e.g., line losses, capacity type, timing, reserves), and process substitution and efficiency differences. Top-down models capture higher-level substitution patterns through smooth functional forms but incorporate market feedbacks into other industries and agents (e.g., government, households) as well as income effects on households [28,29]. Additionally, the details and market responses of targeted new clean energy policy such as clean electricity tax credits associated with the IRA can be more accurately captured in a bottom-up model.

We link USREP and ReEDS using the methodology adopted from [29] and also implemented in [9,30], and [31]. Under this setup, the electricity sector capital, labor, and fuel demand quantities are sent from ReEDS to USREP, which then returns those respective prices to ReEDS. To create price responsive demand, the ReEDS model is converted to a quadratically constrained program (QCP) with an objective function that maximizes the area under the electricity demand and non-electricity CO<sub>2</sub> emissions demand curves; calibration parameters (quantity, price, and local elasticity) are estimated in USREP. The models iterate within each solve year until converged when electricity, CO<sub>2</sub> emissions, and fuel price and quantity deviations are minimized and stable across iterations.

The linkage also accounts for policy costs and fiscal effects from the electricity sector policy counterfactuals. For example, in ReEDS the IRA policy is implemented as production and investment subsidies. These subsidy values are passed from ReEDS to USREP so that they can be accounted for in the government's budget.<sup>11</sup> Furthermore, demand for capital and labor from the electricity sector (i.e., ReEDS) is also accounted for in aggregate (i.e., combined fossil and renewable) so that the net changes to capital and labor demands will affect household incomes. The general equilibrium aspects of USREP imply that losses and gains in specific industries translate across household income; for example, reductions in returns to fossil generation primarily impact the higher-income capital owners but also impact the lower-income groups through reduced labor demand and wages. Similarly, increased returns from renewable generation are also accounted. The net effects of factor returns on household income will ultimately help determine distributional outcomes.

<sup>10</sup> See: <https://www.nrel.gov/analysis/reeds/>.

<sup>11</sup> The government's budget is balanced by an uncovered fiscal deficit (i.e., it is assumed not to balance) for the IRA policy component of subsidy costs. This is explained in Section 5.2.1.

<sup>9</sup> <https://www.eia.gov/state/seds>, accessed April 19, 2024.

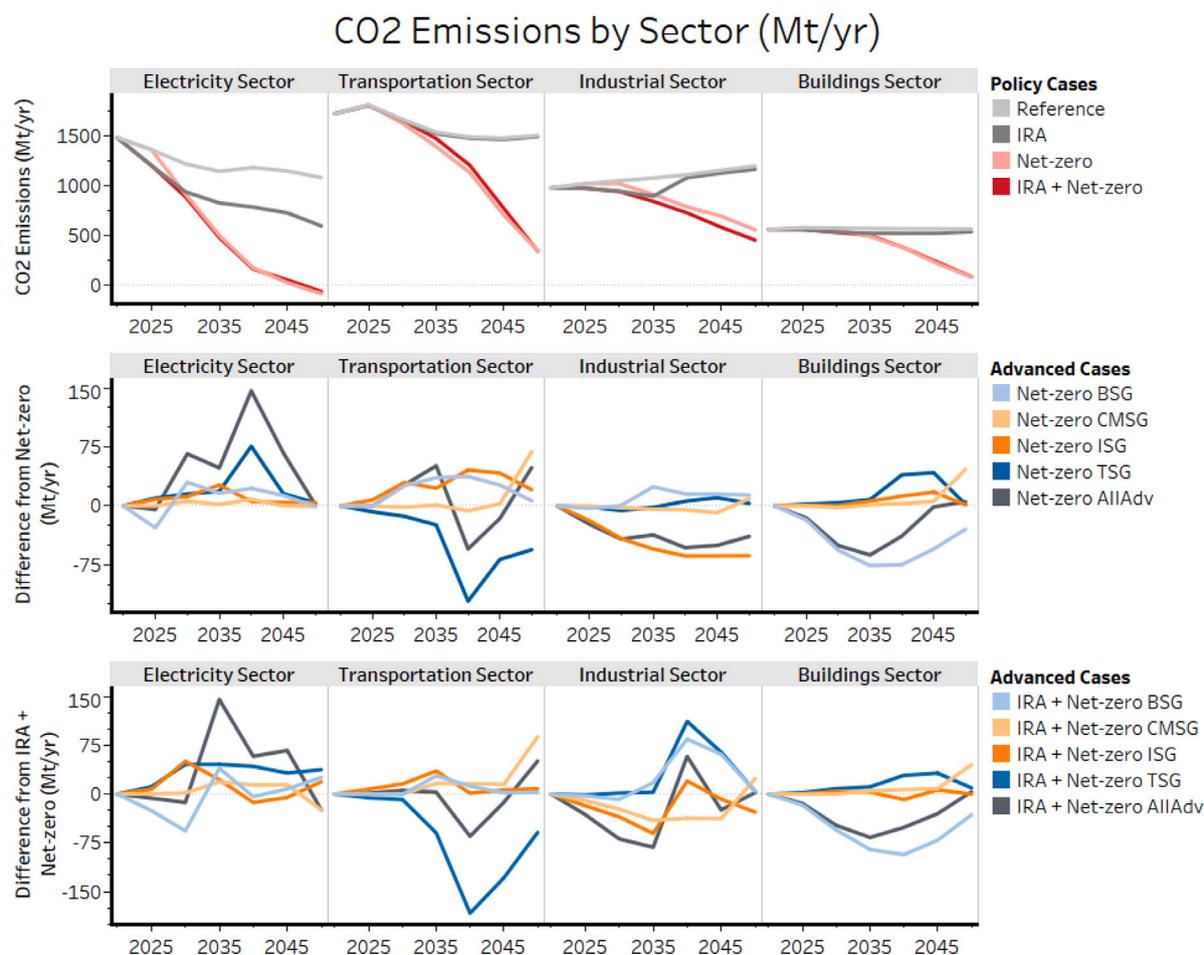


Fig. 1. Sectoral emissions in Mt between 2020 and 2050. Absolute emissions for the core policy cases are shown in the top panel, while differences between advanced cases and the Net-zero case and IRA + Net-zero case are shown in the second and third panel, respectively.

#### 4. Scenarios

Scenarios for EMF 37 are designed to assess the economy-wide implications of various policy, technology costs, and behavioral preference assumptions [1]. Four policy combinations are used to evaluate the impact of the IRA and net-zero emissions targets:

1. A reference case with representation of all federal policies enacted as of September 2022, with the exception of the IRA. The 2021 Bipartisan Infrastructure Law (BIL) is included as part of the reference case.
2. An IRA policy case with representation of 30 IRA provisions across the electricity, transportation, industry, and buildings sectors, as well cross-cutting technologies such as DAC.
3. A net-zero policy case with representation of a net-zero carbon dioxide (CO<sub>2</sub>) emissions target by 2050. Net-zero is achieved by an emissions cap that starts at 2020 reference emissions and increases stringency linearly until the 2050 target is reached. This includes an estimated 800 Mt of CO<sub>2</sub> reduction from land sinks across the country.
4. A combined policy case, including representations of the IRA and a 2050 net-zero target.

For the net-zero (NZ) and combined policy cases, we examine the impact of optimistic decarbonization assumptions across buildings, industry, transportation, and carbon management sectors (i.e., CCS and DAC). Table 1 presents the matrix of scenarios analyzed. Additionally,

Table 1  
Scenario Matrix - each "X" represents a modeled scenario.

Decarbonization	Sectors	Policy cases			
		Reference	IRA	Net-zero	Combined
Default	All Default	X	X	X	X
	Buildings			X	X
Advanced	Carbon Management			X	X
	Industry			X	X
	Transportation			X	X
	All Advanced			X	X

we run two subsequent sensitivity scenarios specifically focused on the evolution of the electricity sector under the IRA that can be found in appendix C. The details of the advanced scenarios are discussed in the following section.

##### 4.1. Advanced scenarios

Advanced scenarios were designed with additional policy, technology, and behavioral preference mechanisms to represent optimistic assumptions on the potential for decarbonization. As shown in Table 1, we implement individual advanced scenarios separately across 4 sectors, (i.e., *buildings advanced scenario*, *carbon management advanced scenario*, *industry advanced scenario*, and *transportation advanced scenario*) and simultaneously across these sectors (i.e., *all advanced scenario*).

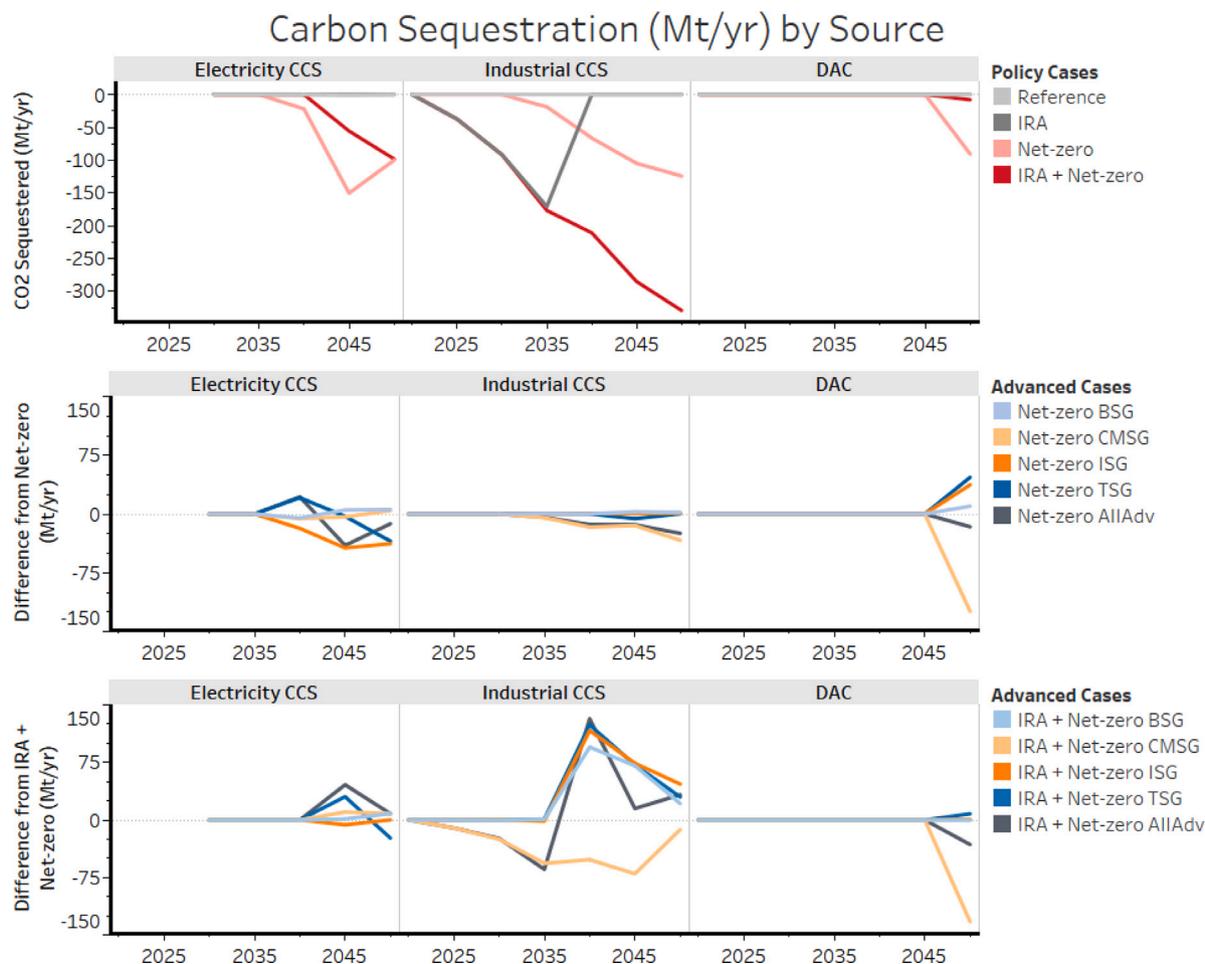


Fig. 2. CO<sub>2</sub> Captured from Direct Air Capture (left), CCS on electricity generators (center), and CCS on Industrial sources (right). The effect on total emissions for the core scenarios are shown in the top row, the advanced technology cases difference from net-zero is shown in the middle row, and the bottom row shows the difference from IRA + Net-zero.

This represents efforts to achieve net-zero targets in 2050 under the maximally optimistic technological assumptions across the economy. The assumptions for each of the individual advanced scenarios are discussed in greater detail here. To ensure consistent terminology with the EMF 37 sectoral study groups, we adopt acronyms consistent with study group names for advanced technology cases associated with a given sector.<sup>12</sup>

#### 4.1.1. Buildings advanced scenario

The *buildings advanced scenario*, or buildings study group (BSG), is intended to represent increased optimism in the rates of energy efficiency improvements in residential and commercial buildings via the pathways of electrification, weatherization of structures, etc. This includes technologies such as heat pumps and efficient water heaters. Residential and Commercial buildings energy efficiency improvements are informed by a set of “measure impact” scenarios from [32,33]. We impose an energy efficiency improvement rate consistent with the percentage differences in aggregate buildings site energy use between the [32,33] aggressive benchmark case and low benchmark case.<sup>13</sup>

<sup>12</sup> Study groups focus on sectoral considerations across models for buildings, industry, transportation, and carbon management (e.g. alternate assumptions about technologies, markets, and policies [1].

<sup>13</sup> The specific cases from [32,33] correspond to the percentage difference in site energy use between the “3.1: Aggressive Benchmark (BM) w/ early

retrofits” and the “1: Low BM” which also coincides with the “3.4: Aggressive BM w/o EE/DF” case.

#### 4.1.2. Carbon management advanced scenario

The *carbon management advanced scenario*, or carbon management study group (CMSG), is designed to represent increased optimism in the costs and rates of adoption for carbon reduction/replacement technologies across the economy. Specifically, we focus on the adoption of carbon capture and storage (CCS) technologies in industrial sectors (CCS in the electricity sector is treated separately) and of Direct Air Capture (DAC) technologies. CCS in the advanced scenario is made available to industrial firms at a cost reduced by 20 percent relative to the reference. DAC technology is built upon [34] and [2] with starting cost around \$800/ton of CO<sub>2</sub>. In the advanced scenario, the starting cost is lowered to around \$300/ton CO<sub>2</sub> by lowering capital cost and increasing the learning-by-doing rate so total cost falls faster over time once DAC is adopted [35,36].

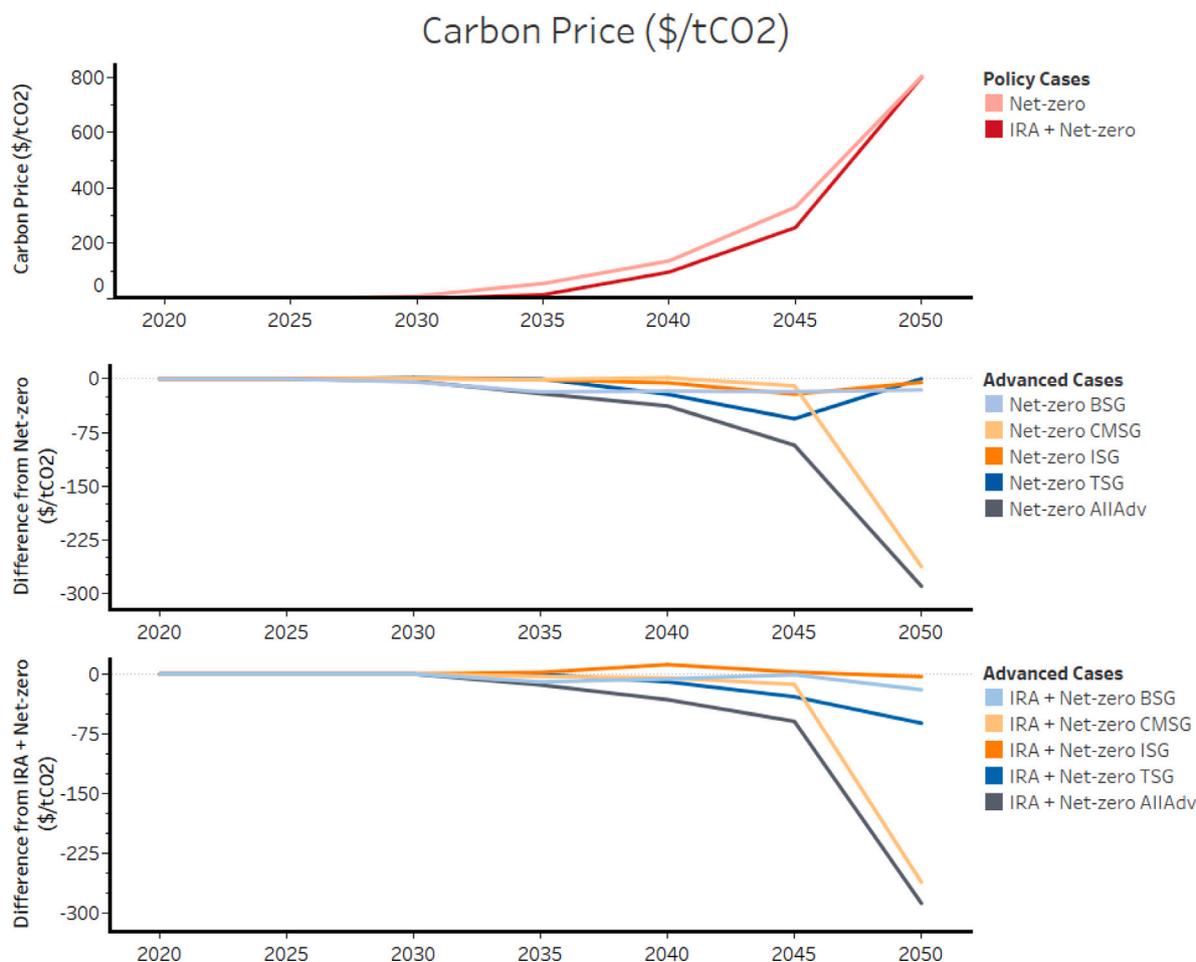


Fig. 3. Estimated carbon price in dollars per tonne of CO<sub>2</sub> emitted between 2020 and 2050. Carbon prices for the NZ and IRA + NZ cases are shown in the top panel, the middle row shows differences in carbon price by scenario from the NZ case, and the bottom row shows differences in carbon price by scenario from the IRA + Net-zero case.

#### 4.1.3. Industry advanced scenario

The *industry advanced scenario*, or industry study group (ISG), is crafted to represent increased optimism in the rates of efficiency improvements and progression towards adoption of low-carbon technologies in industrial facilities. This scenario includes an accelerated electrification rate in sectors classified as energy intensive and also the agricultural sectors. We take most of the assumptions from this scenario from a detailed exploration of decarbonization pathways in industry [37]. We are able to adopt many of the assumptions from this study, in which the authors estimate emissions reductions due to energy efficiency improvements in industry, material efficiency improvements in industry (including refining), carbon reductions due to additions of CCS and transitions to low-carbon fuels such as hydrogen and renewables, and carbon reductions due to decarbonization of the power grid. The improvements from [37] are provided as changes in industrial emissions rates, which we interpret directly as energy efficiency improvements in the model due to a fixed emissions coefficient with energy demand sources.<sup>14</sup>

<sup>14</sup> Energy efficiency options studied in [37] include data analytics, additive manufacturing, efficient process design, combined heat and power (CHP), waste heat recovery, efficient motor systems, and energy management practices. Material efficiency options studied include recycling, promoting reusable materials, and reduced production of energy-intensive primary materials in favor of energy-efficient alternatives [37].

#### 4.1.4. Transportation advanced scenario

The *transportation advanced scenario*, or transportation study group (TSG), is meant to represent increased optimism in the rate of the transition away from fossil-fuel-based modes of transportation towards electric and other low-emissions options. In this scenario we apply a 20% reduction to the overall capital costs of electric cars, trucks, buses, and also plug-in hybrid cars. We also adjust the efficiency of new vehicles to match a set of more aggressive projections from NREL’s Annual Technology Baseline (ATB). We also assume household demand for light duty vehicles reduces by 5%, starting in 2025, relative to the model’s base year (2017) to represent a shift towards usage of ride sharing, e-mobility, and other more less fuel-intensive modes of transportation.<sup>15</sup> Finally, under this scenario we update the existing Corporate Average Fuel Economy (CAFE) standards for light duty vehicles to the latest data under the final rule from NHTSA (fleet average 49 mpg by 2026) [38]. A degradation factor of 81.2% is multiplied to CAFE standards to convert from test value to real-world value and included in the model [39,40].

The CAFE standard is formulated as a permit market (i.e., output-based rebating) for new vehicles. Total permits are assumed to coincide with total energy consumption required under the CAFE standard. New vehicles with lower fuel economy (e.g., internal combustion) would

<sup>15</sup> The 5% ridesharing adjustment is applied once in 2025 and persists for all remaining years.

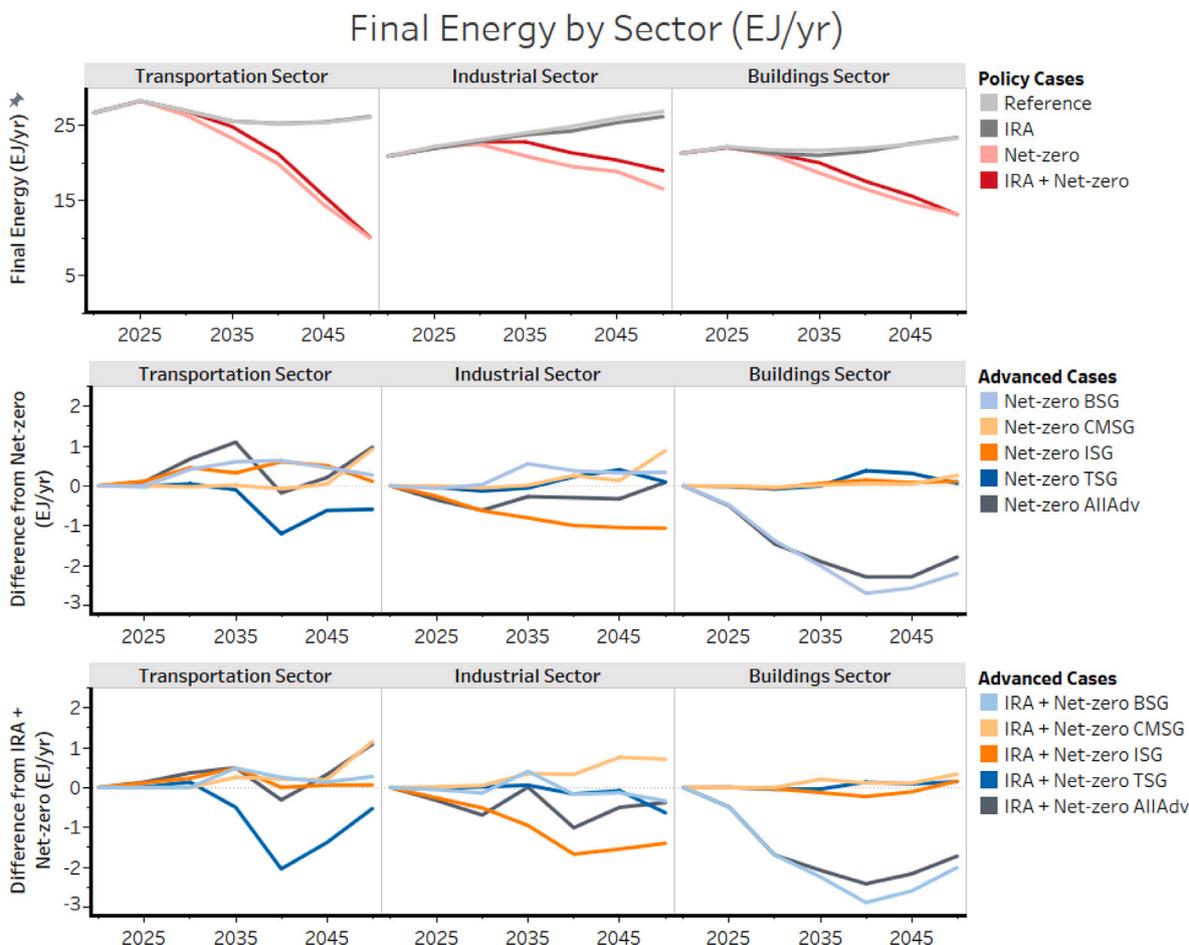


Fig. 4. Sector-specific final energy consumption quantities between 2020 and 2050. Absolute final energy for the core policy cases are shown in the top panel, while differences between advanced cases and the Net-zero case and IRA + Net-zero case are shown in the second and third panel, respectively.

need to buy permits — the difference between own energy usage and the standard determines the penalty. Vehicles with higher fuel economy (plug-in hybrid, electric) would receive permits that could be sold. Permits are traded to ensure the amount sold by the more efficient powertrain are equal to the amount bought by less efficient powertrains — permit markets clear at a market clearing price. Efficiency improvement in internal combustion vehicles and expansion of electrical vehicles lower the costs of meeting the standard. Efficiency improvements and subsidies to electric vehicles make the standard less effective at reducing transportation sector emissions [41].

## 5. Results

The results proceed first with a discussion of energy and emissions outputs from our suite of scenarios followed by selected welfare results.

### 5.1. Energy and emissions

Economy-wide emissions by sector are shown in Fig. 1 (total emissions by scenario can be found in appendix A, figure 11). DAC negative emissions are not accounted for in Fig. 1. They are shown in the rightmost column of Fig. 2.

The IRA reduces economy-wide emissions by 564 Mt per year in 2035 (−13% from reference) and 560.7 Mt in 2050 (−13% from reference). 57% of the 2035 reductions occur in the electricity sector, followed by 32% in industry, 8% in buildings, and 3% in transportation.

Reductions per year due to the IRA remain steady across sectors. In industry, large emissions reductions occur in early periods, but shrink substantially in later periods after modeled credits for carbon capture technologies in IRA expire.

In the net-zero cases, emissions reductions follow the linear decline prescribed by the emissions cap starting in 2020, with little variation based on study group scenarios (see figure 11 in appendix A). To achieve a linear decline in emissions, early periods see rapid decreases in electricity emissions. Substantial reductions in transportation emissions occur following the 2030 period, and buildings emissions decline steadily after 2035. Transportation emissions in the IRA + Net-zero case are greater than in the Net-zero case due to preference towards Industrial CCS abatement from the IRA subsidies. Industrial emissions reductions intensify over time in net-zero scenarios with uptake of CCS and DAC. In the IRA case, emissions decline initially with CCS uptake and rebound when CCS goes offline once CCS credits from IRA expire. The negative emissions in the power sector are primarily achieved through biomass-fired electricity generation with carbon capture and storage.

Emissions are sensitive to all of the advanced scenarios. The TSG case leads to increased electricity sector emissions and decreased transportation sector emissions. Accelerated electricity demand growth in ReEDS (induced by lower costs of electric vehicles in the TSG and AllAdv cases) is generally met with natural gas-fired electricity generation. The Net-zero CMSG case leads to increased transportation sector emissions in 2050 due to DAC with little change in emissions in other sectors. The IRA + Net-zero CMSG case leads to a more noticeable

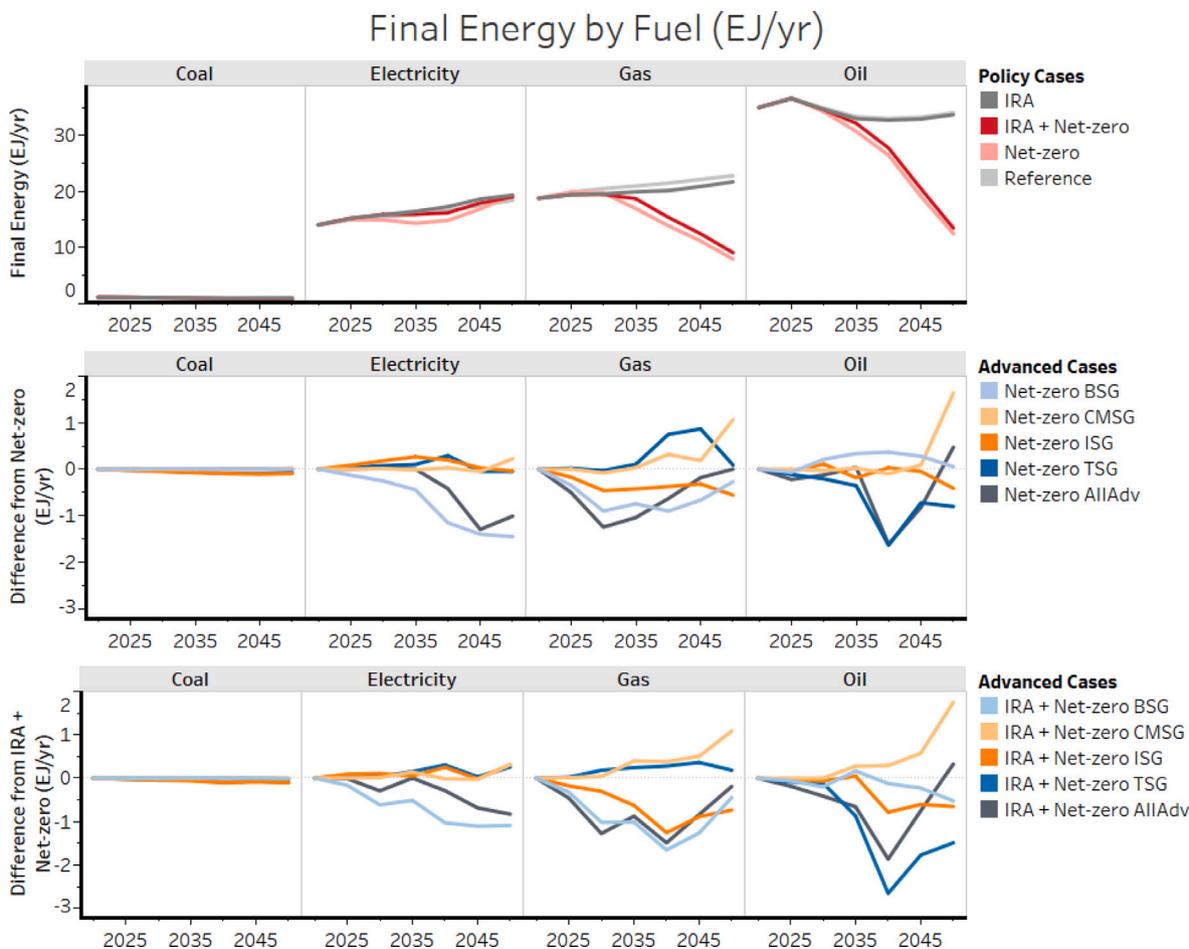


Fig. 5. Fuel-specific final energy consumption quantities between 2020 and 2050. Absolute final energy for the core policy cases are shown in the top panel, while differences between advanced cases and the Net-zero case and IRA + Net-zero case are shown in the second and third panel, respectively.

reduction (increase) in industrial (other sector) emissions since the IRA subsidies make industrial CCS more attractive relative to abatement options elsewhere. Buildings emissions in all the Net-zero advanced cases rise relative to their Net-zero counterpart, except BSG, because decarbonization options in transportation and industry are preferred and it is thus cheaper to decarbonize elsewhere. The BSG case leads to buildings sector emissions reductions via electrification and energy efficiency improvements. Reduced demand for energy in buildings leads to lower energy prices that increase energy use and emissions in transportation and industry. Similarly, efficiency improvements in the ISG case drive emissions reductions in industry with a slight rebound in other sectors. In comparing the IRA + Net-zero cases, the ISG case leads to a downward shift in emissions while also leaving industrial CCS deployment unchanged through 2035. Furthermore, comparing the IRA + Net-zero ISG, CMSG, and AllAdv cases through 2035 suggests that industrial abatement via efficiency improvements versus CCS is not mutually exclusive, but complementary, since the efficiency improvements also benefit industry with CCS.

Fig. 2 shows CCS and DAC sequestration over time by scenario and source. IRA induces heavy adoption of industrial CCS through 2035, or 170.8 Mt/yr by 2035, which is the primary driver of industrial emissions reductions between 2025 and 2035. These effects are greater than those induced by a net-zero policy, without IRA, with only 18.9 Mt/yr of industrial emissions captured in 2035. However, without net-zero policies, carbon sequestration falls to zero when IRA subsidies lapse. While IRA policies are modeled through 2035, actual availability

of IRA subsidies may extend beyond these years. Optimistic assumptions on input prices with CMSG and all advanced scenarios further increase adoption of CCS in all periods. With net-zero constraints alone, 124.2 Mt/yr are sequestered by 2050 with CCS. Layering IRA increases sequestration to 329.2 Mt/yr in that time, and layering optimistic carbon management assumptions induces 341.8 Mt/yr 2050.

In the reference and IRA-only cases, there is no deployment of DAC through 2050. All non-IRA net-zero cases see DAC deployed in 2050, with the largest deployment shown using optimistic CMSG assumptions (214.7Mt). Under the BSG, ISG, and TSG net-zero cases, energy efficiency improvements and electrification reduce DAC deployment via reduced carbon prices. While the proportional differences are relatively small, comparing the 2nd and 3rd rows of Fig. 2 shows industrial CCS is very sensitive to the CMSG assumptions when IRA subsidies are active. DAC under the CMSG case looks similar when comparing the 2nd and 3rd rows because no IRA subsidies exist in 2050 when it is deployed. Electricity sector CCS is more responsive in the Net-zero advanced scenarios than in the IRA scenarios.

Fig. 3 shows implied carbon prices for the Net-zero and the IRA + Net-zero cases. The DAC backstop carbon price in 2050 is 801.5 USD/tonne in the default net-zero case. IRA and optimistic decarbonization assumptions lead to a downward shift in carbon price. Among non-IRA Net-zero cases, the lowest prices are shown in the CMSG case (538.5 USD/tonne in 2050) and AllAdv case (510.9 USD/ton). Carbon prices are low in the TSG case prior to 2050, but without cheaper DAC, the carbon price converges on the 2050

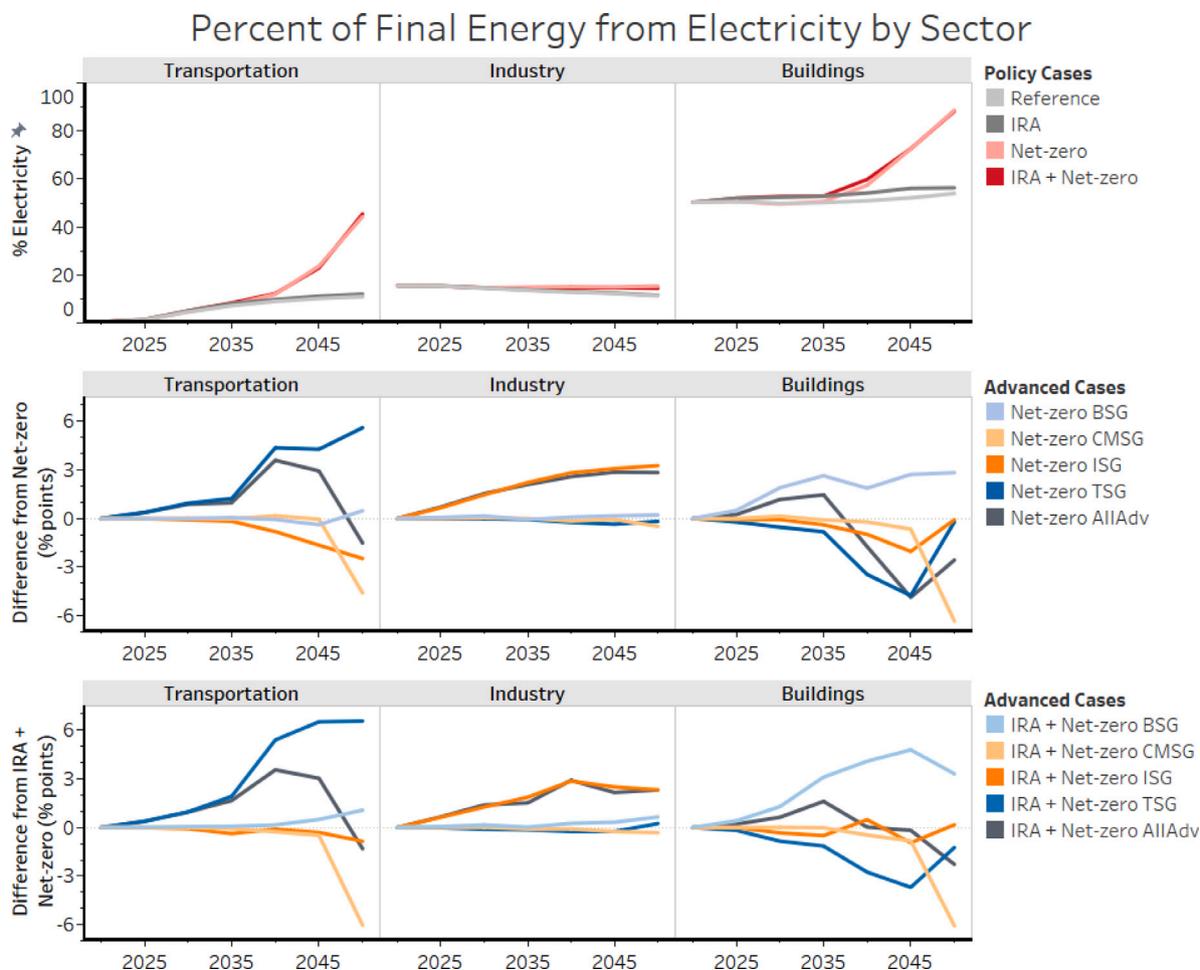


Fig. 6. Estimated percentage of final energy from electricity for each sector between 2020 and 2050. Percent of energy from electricity for the core policy cases are shown in the top panel, while percentage point differences between advanced cases and the Net-zero case and IRA + Net-zero case are shown in the second and third panel, respectively.

breakeven DAC cost. In the IRA + Net-zero cases, the TSG scenario reduces carbon prices enough to eliminate the need for DAC. Again, the tradeoff between improved efficiency and electrification in ISG, BSG, and TSG assumptions shows a crowding out of DAC via reduced carbon price.

Figs. 4 and 5 contain final energy demanded by sector and by fuel, respectively.<sup>16</sup> All sectors reduce final energy demand and economy-wide total final energy demand decreases in the net-zero cases after 2030, dropping from over 65 EJ/yr to around 40 EJ/yr by 2050. Final energy demand is slightly higher in the IRA + Net-zero case versus the non-IRA net-zero cases. Differences across the study-group scenarios are proportionally small. In Fig. 4, the TSG case drives the largest changes in final demand in the transportation sector whereas the ISG case affects the industrial sector most. The CMSG and TSG assumptions work in opposition in 2050 as DAC drives increased demand for fossil fuels. The ISG and BSG cases decrease energy demand in their respective sectors, as expected.

Fig. 5 shows electricity demand is relatively preserved in the net-zero cases (except for the BSG case) relative to large declines in oil and gas demand, indicating substantial decarbonization through electrification in the non-BSG cases. Optimistic carbon management assumptions drives additional gas demand, as it induces additional

CCS in the natural gas production sector as well as DAC deployment that allows for more gas and oil consumption economy-wide as a substitute for electrification and clean energy production in order to meet policy requirements.<sup>17</sup> Energy demand in the IRA case without net-zero increases slightly from 2035 through 2050, though it remains lower than in the reference case, and it reduces gas demand by 5% in 2050 relative to the reference case.

In Fig. 6 we see that electrification across net-zero scenarios occurs most in the buildings and transportation sector, and are buoyed by IRA subsidies for electric appliances and vehicles, respectively. There is less electrification in industry, which relies heavily on CCS to meet emissions targets. CMSG assumptions reduce electrification in all sectors, due to lower gross of CO<sub>2</sub> fossil fuels prices resulting from cheaper DAC. This is especially evident in the difference between 2045 and 2050 in the transportation and buildings sectors when DAC is deployed. The ISG and BSG assumptions increase the proportion of final energy from electricity in industry and buildings, respectively. This is because fossil fuel efficiency is being decremented by more, electricity is getting cleaner, and ease of shifting between fossil fuels and electricity is improved.

Fig. 7 shows electricity generation by technology by scenario. With the exception of the BSG case, the Net-zero and IRA + Net-zero scenario variants are clustered around their respective core cases, which

<sup>16</sup> Final energy consumption of coal in Fig. 5 does not include demand from power generation, so it is small.

<sup>17</sup> We see a small amount of primary biomass production in 2050 that is used in electricity production and grouped within oil liquids.

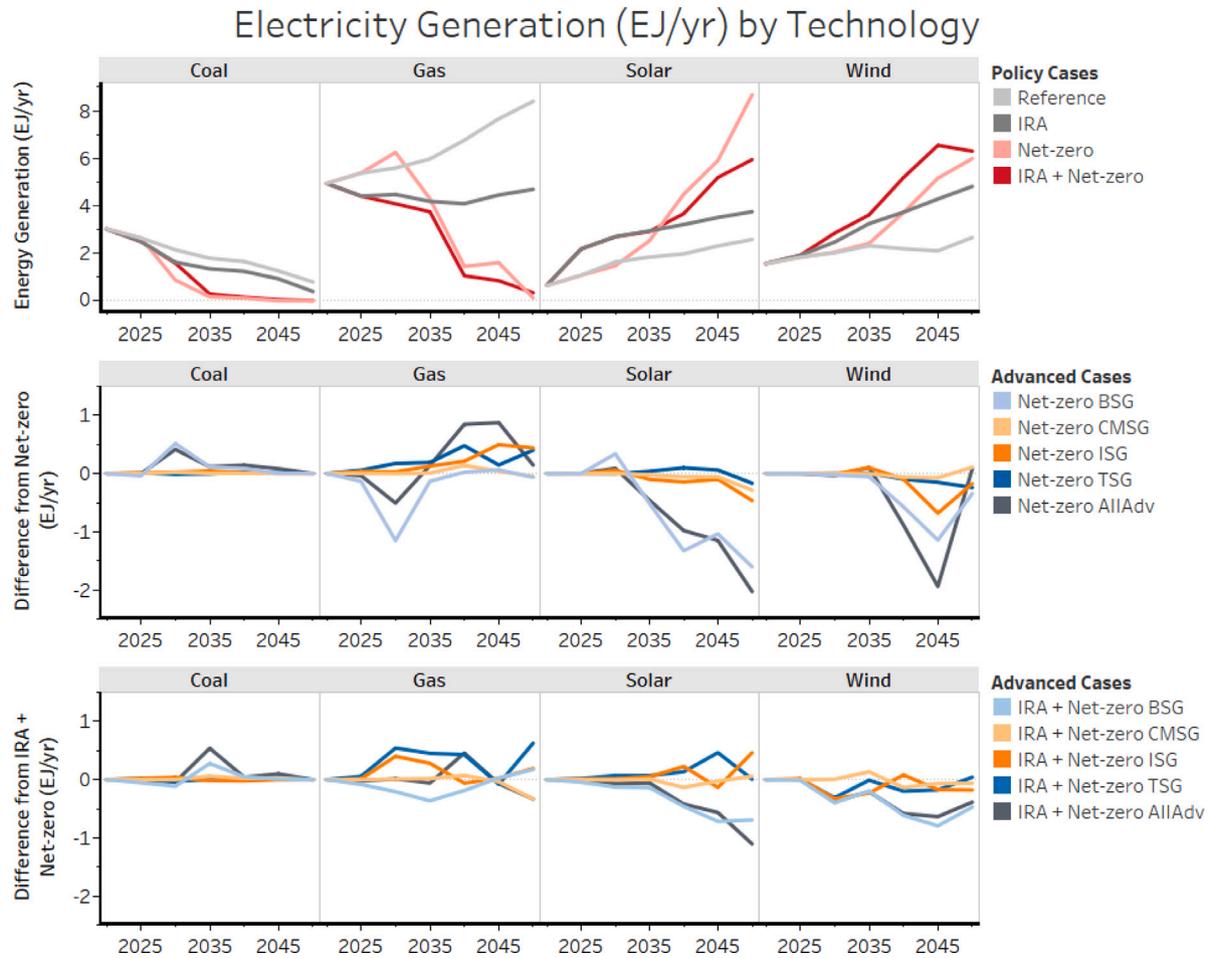


Fig. 7. Estimated electricity generation (EJ/yr) by technology for five prominent generation technologies between 2020 and 2050. Absolute electricity generation for the core policy cases are shown in the top panel, while differences between advanced cases and the Net-zero case and IRA + Net-zero case are shown in the second and third panel, respectively.

indicates relatively small indirect effects of the alternative study-group assumptions on electricity generation. For the BSG case, the effect of reduced electricity demand from buildings can be seen in across generation technologies at different points in time; the BSG scenario affects gas, solar, and wind generation at different sections of the time horizon with solar being reduced the most. In all Net-zero cases, coal and gas generation fall while renewables and storage increase. In the Net-zero cases, from 2025 to 2030, gas generation increases due to a very low carbon price that drives coal-to-gas switching without inducing a transition to renewables. Once the emissions limit becomes more stringent, gas-to-renewables switching occurs through 2050.

IRA induces an earlier transition away from coal and gas towards renewable energy and the timing of the IRA subsidy phaseout coincides with the emission limit's path to net-zero. The IRA + Net-zero variants are consistent with the IRA case until the emissions limit binds in 2035, at which point fossil-to-renewables switching occurs through 2050. Interestingly, IRA + Net-zero cases result in a delayed phaseout of coal (and total fossil) generation relative to the non-IRA net-zero cases; the near-term expansion of VRE requires greater firm capacity that incentivizes coal capacity sufficiently to avoid retirement. Also, IRA subsidies result in lower carbon prices, benefiting the most emission-intensive technologies, such as coal units. IRA accelerates the transition to renewables and storage. Once the cap binds beyond 2035, Net-zero cases see a more pronounced wind and storage deployment given the need for replacement of fossil-based generation throughout the

entire day; said differently, the net-zero cases require generation and storage that can replace fossil-fired power without interruption. Wind deployment decreases and gas generation increases from 2035–2045 in the ISG, TSG, and AllAdv cases as a result of reduced electricity demand in the BSG case and lower natural gas prices from reduced gas demand in the BSG and ISG cases.

### 5.2. Household consumption and distributional impacts

In this section, we discuss some selected economic consumption effects for our suite of scenarios. Equivalent variation is a measurement of the amount of income that needs to be adjusted to make a consumer's utility level the same as it would be if an economic event had happened — said differently, the amount a consumer would be willing to pay (or receive) to avoid a policy outcome. In our model, this is measured as the percentage change in the quantity of household full consumption (i.e., leisure plus goods consumption as a proxy for utility), as is standard practice in CGE models. For clarity, we instead use “consumption effect” to refer to this measurement. First, we cover the IRA scenario results followed by the net-zero by 2050 scenarios without IRA. Special care is taken in this section to consider important assumptions when interpreting the results. Importantly, these results do not consider benefits from reducing CO<sub>2</sub> and air pollution.

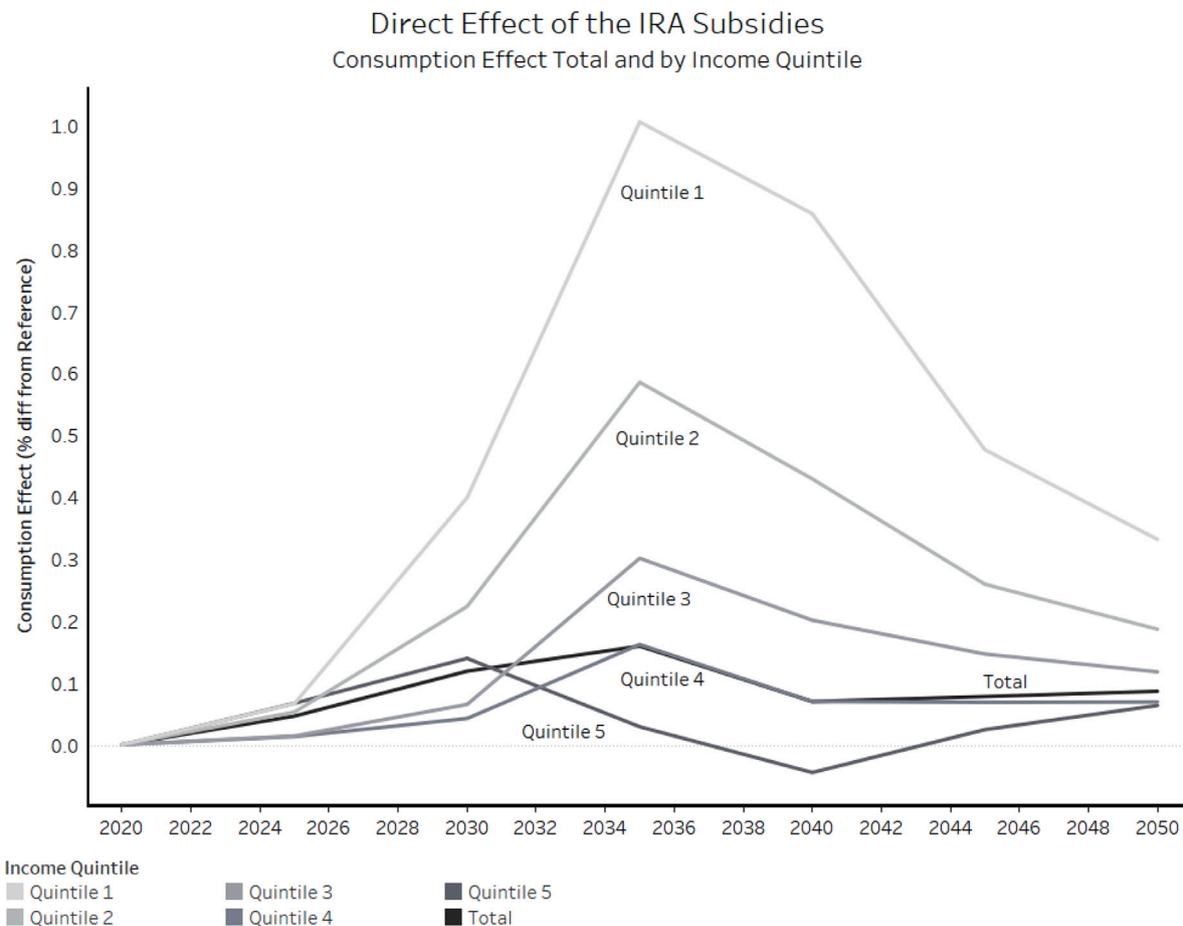


Fig. 8. IRA - Direct Effect on % change in Total Full Consumption and Distribution of these Consumption Effects across Income Quintile – These consumption effects are incomplete as they only show the direct effect of IRA on prices and not the budgetary costs to the government and households – a full accounting of costs would show negative total equivalent variation.

5.2.1. IRA

In the IRA case, we assume a closure rule where the government provides the subsidies but it does not pay for them through increased taxes, reduced spending, or debt issuance — the IRA subsidies are cost-free. This allows us to remain neutral on the funding source, which is expected to produce a deficit [42] that must eventually be covered, but also implies that all IRA policy costs go unaccounted for in our model.

In reality, the “subsidy-based” instruments employed in IRA generate costs to the government and ultimately the household. Not accounting for these costs is equivalent to modeling optimistic technology assumptions, which can be useful in decomposing the “direct effect” of the price change induced by the policy, presented in Fig. 8. However, we must acknowledge that this closure assumption makes our IRA household consumption effect in Fig. 8 incomplete. Furthermore, we make exogenous assumptions about IRA-induced technical change (e.g., energy efficiency improvement), which makes households look even better off under IRA. This is why our model produces positive consumption effects while other IRA studies with fully-closed models show the opposite [31,42].<sup>18</sup> It is worth mentioning that while this

<sup>18</sup> In most cases, to do a proper cost benefit analysis of an entire policy the chosen closure should be one that captures the entire value of the policy cost (full debt repayment) and acknowledges any potentially compromising assumptions. Due to our modeling assumptions and that we are only interested in segments of the full time horizon, we only present the path of consumption changes while acknowledging the welfare analysis is incomplete.

closure choice can have meaningful consumption effects, the effects on emissions are trivial [43].

Fig. 8 shows the direct effect of the IRA as the policy induced percentage change in the quantity of full consumption for the US economy as a whole and by household income quintile. The IRA leads to a positive direct consumption effect and a progressive distributional pattern with lower income groups being more positively affected than higher income groups. This progressive effect arises through lower commodity prices for energy and subsidized goods faced by households. There is also a regressive distributional effect where the clean subsidies induce a shift towards more capital intensive technologies, which increases returns to capital relative to labor. The highest income households (Quintile 5) derive most of their income from capital whereas household Quintiles 3 and 4 derive a large portion of their income from labor.

Again, given that the IRA subsidies are assumed cost-free, this scenario is equivalent to one with more optimistic technology costs. The consumer outcomes are largely driven by the share of energy expenditure and factor income distribution. Lower energy prices disproportionately benefit the lowest income groups, while the increase in factor income from clean technologies predominantly favors the highest income groups.

5.2.2. Net-zero by 2050

With respect to the net-zero cases, the model maintains government revenue neutrality via a population-weighted lump-sum instrument and

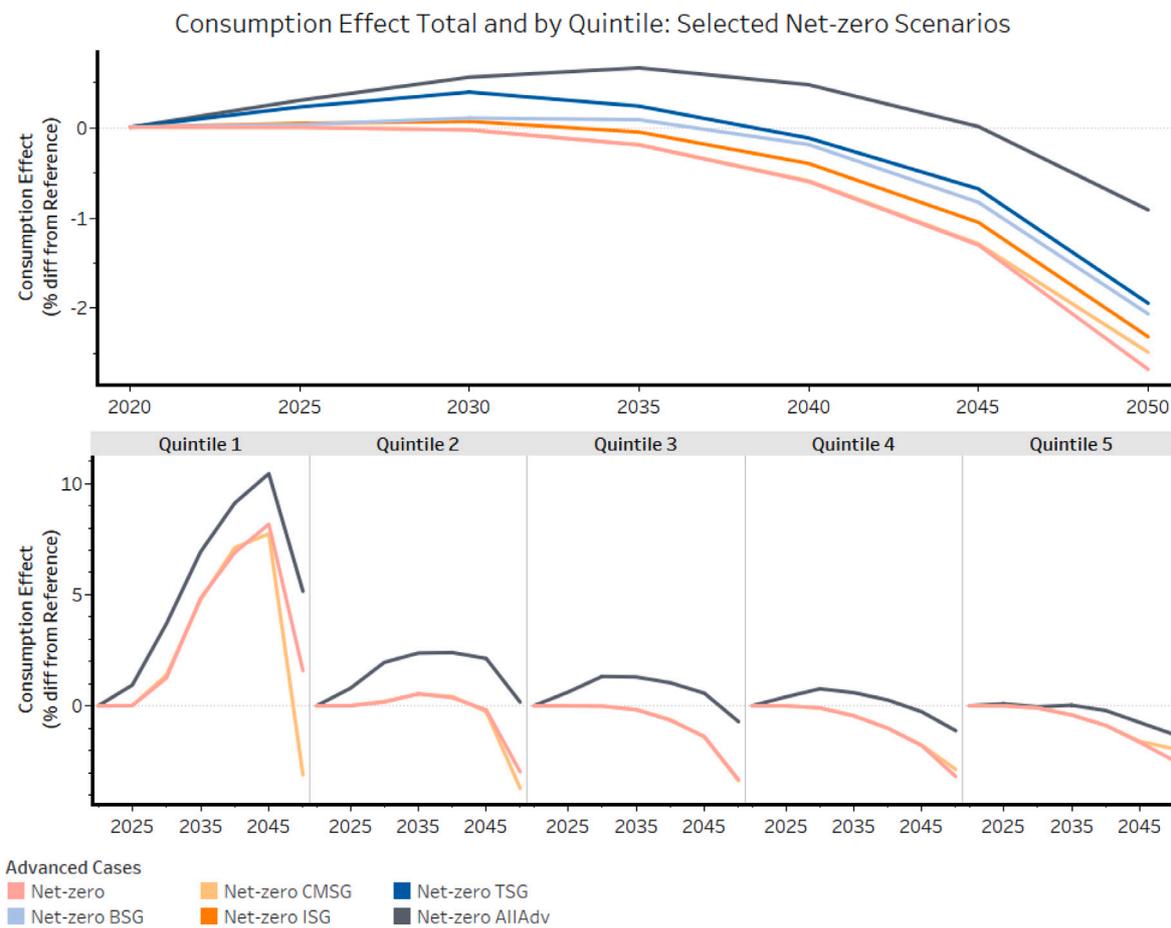


Fig. 9. Net-zero - % change in the quantity of Full Consumption Total (top) and Distribution of % change in the quantity of Full Consumption across Income Quintile (bottom).

thus accounts for revenues earned from the emissions cap. We do not report results for the net-zero with IRA cases since our IRA-specific uncovered fiscal deficit assumption discussed in Section 5.2.1 would bias our distributional analysis in the net-zero case.

Fig. 9 presents the paths of total and distributional consumption effects for the no-IRA net-zero policies. The top panel of Fig. 9 shows the path of total consumption effect for our net-zero policy suite. Total consumption effect (pink line) decreases monotonically throughout the time horizon as the price for carbon rises. The study group cases with more advanced technology assumptions lead to upward shifts in these consumption paths as expected. Early on, this means improvements relative to the reference case. However, as the cap binds with a higher permit price in later years, the impact turns negative. The TSG and BSG groups are the largest contributors to consumption improvements.

The bottom panel of Fig. 9 shows percentage changes in quantity of household full consumption by income quintile. The distributional effects are strictly progressive in the net-zero-2050 case due to the lump-sum distribution of permit revenues; Quintile 1, the lowest-earning income quintile, benefits greatly. Fig. 3 shows that carbon prices exceed \$300 USD/tonne of CO<sub>2</sub> by 2045 and \$800 USD/tonne by 2050. Fig. 10 translates these high carbon prices into permit revenues (yellow bars) and contextualizes them within the broader changes in income, showing that permit revenues can make a large proportional impact on lower income households when distributed lump sum.

Surprisingly, in Fig. 9 from 2045 to 2050 we see a break in the progressive trend that is most noticeable in Quintile 1 and Quintile 5 – Quintile 1 falls while Quintile 5 flattens. This break in trend is due to the entrance of DAC technology, which becomes economically viable in 2050 at a breakeven carbon price of roughly \$800 USD/tonne of CO<sub>2</sub>. DAC is modeled as a capital intensive perfect substitute for

CO<sub>2</sub> emissions. As such, relative to no DAC, DAC production caps the carbon price and reduces permit revenues that can be distributed back to households in exchange for returns to capital that directly benefit the high income capital owners. A comparison between the Net-zero (pink line) and Net-zero CMSG (purple line) cases confirms this intuition.

While this behavior is most evident in Fig. 9 with respect to DAC, it would apply to any abatement technology whose cost-effective deployment substitutes increased demand for capital for decreased permit revenues. While DAC is the most capital intensive and direct example of this tradeoff, other examples include a shift towards more capital-intensive wind and solar electricity.<sup>19</sup> This regressive shift is also apparent in Fig. 10 by comparing the NZ and NZ CMSG columns for Quintile 1 and Quintile 5, and is stark in our model because of DAC's interaction with the lump-sum closure rule and that the cap is nearing zero emissions.<sup>20</sup>

When comparing the Net-zero case with the Net-zero AllAdv case we see a progressive shift and all income groups benefiting, opposite from what we see with the Net-zero CMSG case. While these technology cases reduce permit revenues, the shocks are forced into less capital intensive areas of the model, which distributes the benefits more evenly across households. For example, carpooling helps reduce the carbon price and is not capital intensive.

<sup>19</sup> While regressive in this sense, cost-effective deployment of energy transition technologies helps to reduce the total economic cost of CO<sub>2</sub> abatement.

<sup>20</sup> As the emissions limit approaches zero emissions, permit revenues will approach zero.

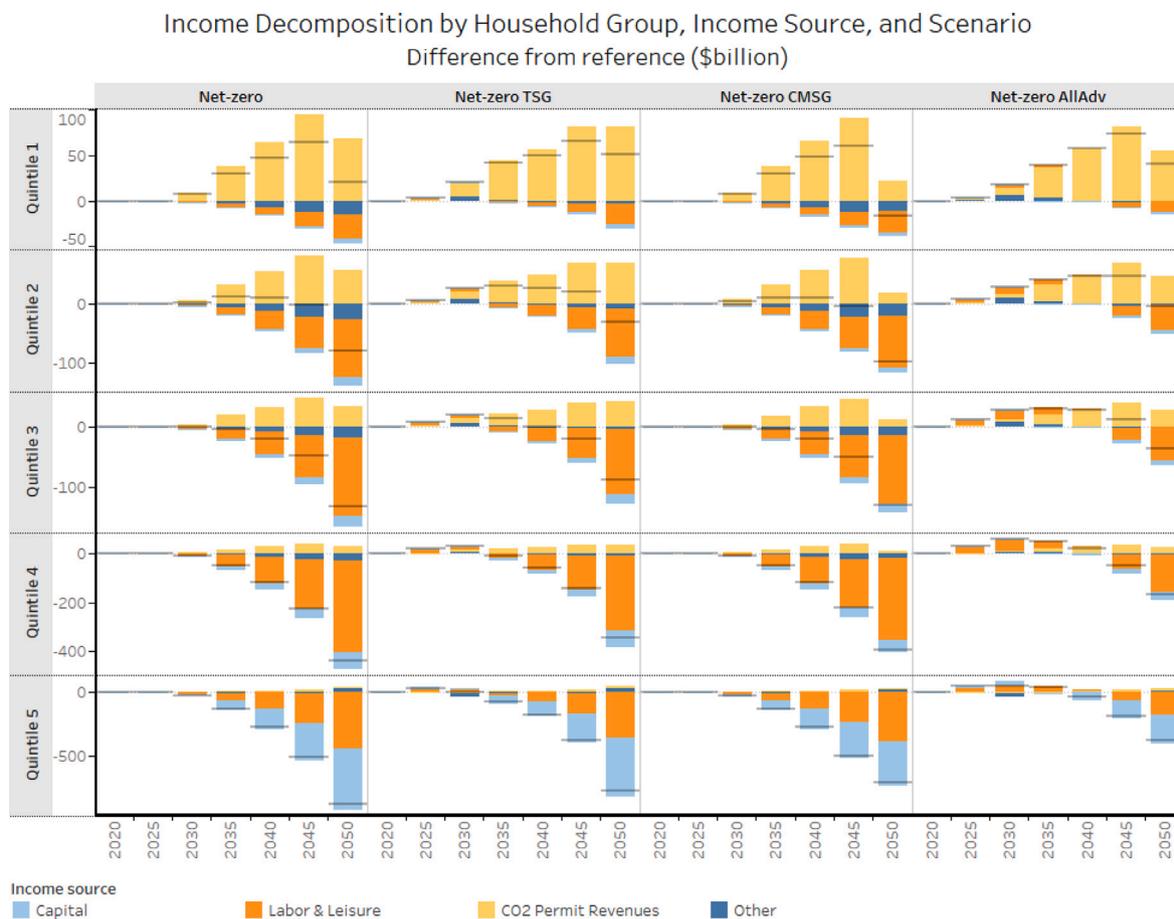


Fig. 10. Net-Zero difference in income by source category from the reference case — decomposition of the household’s income balance condition that ensures income can cover full consumption expenditures.

### 6. Conclusion

The results in this paper demonstrate the roles of renewable energy, electrification, and negative emissions technologies in reaching net-zero CO<sub>2</sub> emissions by 2050 as well as the macroeconomic and distributional consequences of various net-zero pathways. Electrification and negative emissions technologies compete on costs with an emergence of DAC later in the time horizon as the emissions cap becomes very stringent. The differing characteristics of various energy transition technologies are borne out in the model scenarios. For example, carbon capture technologies reduce electrification and increase demand for fossil fuels. An important caveat is that we do not model hydrogen or bioenergy with CCS as substitutes for refined petroleum and natural gas. Including these would add competition for the technologies we modeled and is left for future work.

We find that emerging technologies reduce economic costs of decarbonization and that the relative cost-effectiveness of various abatement technologies can have material effects on distributional outcomes that differ depending upon their input cost structure. This highlights a need for future research on the economic effects of net-zero emissions targets under canonical emissions cap scenarios with different technology assumptions and revenue recycling mechanisms. Furthermore, alternative technology pathways may have distributional consequences that could be specific to the country and its existing policy and natural resource landscape.

Here, we have identified and distinguished some unique roles for different technology classes across sectors and time frames, which can help inform a strategy to support technologies effective in the short-term and foster those that will likely be needed in the long-run

to achieve climate goals. Whether market-based or more prescriptive policy regimes, policymakers can use CGE models to inform policies that meet domestic decarbonization, equity, and fiscal goals.

### CRedit authorship contribution statement

**Jonathon Becker:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Maxwell Brown:** Writing – review & editing, Writing – original draft, Software, Methodology. **Morgan Browning:** Writing – review & editing, Project administration. **Yongxia Cai:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Daden Goldfinger:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **James McFarland:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Sergey Paltsev:** Writing – review & editing, Supervision, Project administration. **Shane Weisberg:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Mei Yuan:** Writing – review & editing, Validation, Software, Methodology, Formal analysis.

### 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.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.egycc.2025.100181>.

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