Energy and Climate Change 5 (2024) 100154

Contents lists available at ScienceDirect

Energy and Climate Change

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

# Carbon management technology pathways for reaching a U.S. Economy-Wide net-Zero emissions goal

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A R T I C L E  I N F O

*Keywords:*
Emf37
Net-zero
Electrification
Co2
Carbon management

A B S T R A C T

The Carbon Management Study Group of the 37th Energy Modeling Forum (EMF 37) designed seven scenarios to explore the role of three potentially key technology suites – point source carbon dioxide capture and storage (PSCCS), direct air capture of carbon dioxide (DACCS), and hydrogen systems ($H_2$) – in shaping the broader technology pathways to reaching net-zero carbon dioxide ($CO_2$) emissions in United States by 2050. Each scenario was run by up to 13 models participating in the EMF 37 study. Results show that carbon dioxide removal technologies were consistently a major part of successful pathways to net-zero U.S. $CO_2$ emissions in 2050. Achieving this net-zero $CO_2$ goal without any form of carbon dioxide capture and storage was found to be impossible for most models; some models also found it impossible to reach net-zero without DACCS. The marginal cost of achieving net-zero $CO_2$ emissions in 2050 was between two and 10 times higher without PSCCS and/or DACCS available. The carbon price at which DACCS was deployed as a backstop technology depended upon the assumed cost at which DACCS was available at scale. Carbon prices were between \$250 and \$500 per ton $CO_2$ when DACCS deployed as a backstop. The average $CO_2$ capture rate across all models in 2050 in the central net-zero scenario was 1.3 $GtCO_2$/year, which implies a substantial upscaling of capacity to move and store $CO_2$. Hydrogen sensitivity scenarios showed that $H_2$ typically constituted a relatively small share of the overall U.S. energy system; however, $H_2$ deployed in applications that are considered hard to decarbonize, facilitating transition towards net-zero emissions.

## 1. Introduction

The 37th Energy Modeling Forum (EMF 37) model intercomparison study, *Deep Decarbonization and High Electrification Scenarios for North America*, explores paths to net-zero $CO_2$ emissions in the United States and other North American countries by 2050. This goal is broadly consistent with one of the goals of the Paris Agreement of 2015, "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Paris Agreement,

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https://doi.org/10.1016/j.egycc.2024.100154

Available online 12 September 2024

[1]). The EMF 37 model intercomparison study focuses specifically on the role of electrification in deep-decarbonization pathways. Indeed, many studies have observed that electrification plays an important role in achieving net zero $CO_2$ emissions (e.g., [2,3]).

Yet, electrification is only part of the decarbonization story. Societies need a wide range of energy services, not all of which are best delivered by electricity. The Carbon Management Study Group (CMSG) was formed to explore the roles of three potentially important technologies that could, in combination with electrification, enable the economy to reach net zero emissions by the year 2050. Specifically, the CMSG examined two forms of $CO_2$ capture and storage (CCS)[w] – point source emissions capture and storage (PSCCS) and direct air carbon capture and storage (DACCS). The CMSG also explored the potential role of hydrogen systems ($H_2$). Note that a focused EMF 37 paper, Melaina, et al., [4], delves deeper into hydrogen systems. The CMSG explored the roles of these potentially key technology sets (PSCCS, DACCS, and $H_2$) in energy transition pathways to net-zero U.S. $CO_2$ emissions by 2050, as well as how sensitive the deployment of these technologies are to technology advancement and how important these technologies are to achieving the goal of net-zero $CO_2$ emissions in 2050 (by exploring the feasibility and cost of reaching this target without these technologies available).

Hydrogen can be produced from hydrocarbon fuels in combination with CCS, and via pathways that do not include hydrocarbon feedstocks; it was included within the CMSG scenario framework as a potentially important alternative decarbonization pathway, e.g., a replacement for carbonaceous fuels in some "hard to decarbonize" sectors where electrification might be more challenging. A subset of CCS technologies – bioenergy deployed in combination with CCS (BECCS), as well as DACCS – provide carbon dioxide removal (CDR), whereby $CO_2$ is captured from the atmosphere and sequestered, helping to offset unabated emissions. Another form of CDR – terrestrial carbon sequestration (e.g., sequestration of $CO_2$ in forests or other carbon dense landscapes) – was excluded from the CMSG study design because many of the participating models do not endogenously represent the land system, although the "land sink" does contribute to $CO_2$ removals (either by exogenous assumption or endogenous model result) across the CMSG scenarios.

The three CMSG technology sets are potentially important tools in a strategic approach to limiting the concentration of $CO_2$ in the atmosphere. As depicted in Fig. 1, these technologies can potentially deploy across a wide spectrum of applications enabling emissions mitigation ranging from reduced emissions to zero emissions and even negative emissions (CDR). The effect of these three technologies on emissions is outlined in Table 1.

PSCCS can be deployed across a broad array of applications throughout the economy. In power generation, PSCCS can be deployed in combination with both fossil fuel and bioenergy use, and can be deployed either as part of new capacity installations or retrofitted to existing facilities. PSCCS, when used in combination with bioenergy (BECCS), either for power generation, biofuel refining, hydrogen production, or to provide industrial energy services, can deliver CDR services since bioenergy feedstocks sequester $CO_2$ through photosynthesis as they grow.

Hydrogen is a carbon-free energy carrier that can be produced using a range of technologies. Currently, the most common method for producing hydrogen is steam reforming of methane ($CH_4$), although $H_2$ can be obtained from any hydrocarbon feedstock including coal, oil, or bioenergy. Using bioenergy with PSCCS to produce $H_2$ provides carbon-free energy and CDR. $H_2$ can also be produced without any $CO_2$ emissions by using electrolysis to separate $H_2$ from oxygen in water. Nuclear power can be used to thermally dissociate hydrogen and oxygen from water. $H_2$ can be produced either at large central stations and moved via pipeline to point of use or produced near the point of use to reduce infrastructure requirements for transporting and storing $H_2$.

Once obtained, $H_2$ can either be combusted in industrial applications (and potentially in buildings) or used in fuel cells to provide electricity and heat. Fuel cells could potentially deploy in any part of the energy system, such as for transportation including land-based passenger and freight modes, ships, and aircraft; larger fuel cells could be deployed in buildings and industry for combined heat and power applications. Hydrogen can also be used as a fuel for turbines or fuel cells to produce electricity and balance load in response to fluctuations in variable renewable energy generation across diurnal and seasonal cycles.

In addition to capturing $CO_2$ before it is emitted, it is also possible to directly remove $CO_2$ from the atmosphere . A variety of DACCS CDR technologies have been created that enable direct scrubbing of $CO_2$ from ambient air [5,6]. There are several different designs under development with variations using different energy sources with any fossil-based emissions also captured by the process. DACCS is most cost-effective when built at or near the $CO_2$ storage site.

Once captured, $CO_2$ must be disposed at a permanent storage site. In general, three options have been considered for CO2 disposition: storage in geologic formations [7,8], ocean storage [9,10], or recycled fuels [11–13]. Geologic storage is by far the most common disposal assumption in models participating in this study. The potential for deep ocean carbon storage is considered in only two of the CMSG models (GCAM and GCAM-USA); this is a potentially vast carbon sink but entails significant technological, environmental, measurement and verification, and institutional uncertainties [14]. Since geologic storage capacity is relatively abundant in the United States, deep ocean storage is a less important option in the U.S. compared to other regions with more little or no geologic storage potential. The use of $CO_2$ as a feedstock for fuels has generated recent interest and could serve as a mechanism for creating high-energy-density fuels if geologic $CO_2$ disposal and/or limits on bioenergy were to constrain energy systems. Only one of the models included in this study (US-REGEN) considered $CO_2$ utilization (via synthetic fuel production); this represents an important research frontier. The representation of $CO_2$ transport and storage in Carbon Management Study Group models is presented in Supplementary Table 1.

## 2. Methods

### 2.1. Experimental scenario design

To examine the role of these technology sets in U.S. deep-decarbonization pathways, the CMSG explored a set of eight numerical experiments that include and build upon two core EMF 37 scenarios (highlighted in blue in Table 2). Each of the scenarios in this paper reflect a long-term decarbonization target of net-zero $CO_2$ emissions in the U.S. by 2050. Note that this paper does not explore the Net Zero+ scenario described in Browning et al. [15] in order to limit the number of scenarios presented, and because Browning et al. [15] already explored the Net Zero+ scenario (and the associated interactions between advanced carbon management technologies and advanced buildings, industry, and transportation technologies) in considerable detail.

Each of the unique CMSG scenarios explores a technology sensitivity intended to better understand the potential roles of PSCCS, H2, and/or DACCS.

**Net Zero (NZ Ref)** is a core EMF 37 scenario. It assumes that policies (usually represented in the model as a price on $CO_2$ emissions) are put in place to reduce net U.S. $CO_2$ emissions to zero by 2050. Note that this scenario differs from the stated U.S. long-term strategy goal that seeks to reduce net greenhouse gas (GHG) emissions to zero in 2050; the core EMF 37 and CMSG scenarios reduce only $CO_2$ emissions to zero by 2050. Each model uses its own reference technology assumptions. Specifically, modeling teams assume that reference versions of PSCCS, $H_2$, and DACCS technologies are available in their models. (Note that fossil fuel prices, and technology costs more broadly, were not explicitly harmonized across models. See, for example, Supplementary Figure 1 for a plot

[w] Throughout this study we use CCS to refer to all forms of CCS (PSCCS and DACCS).

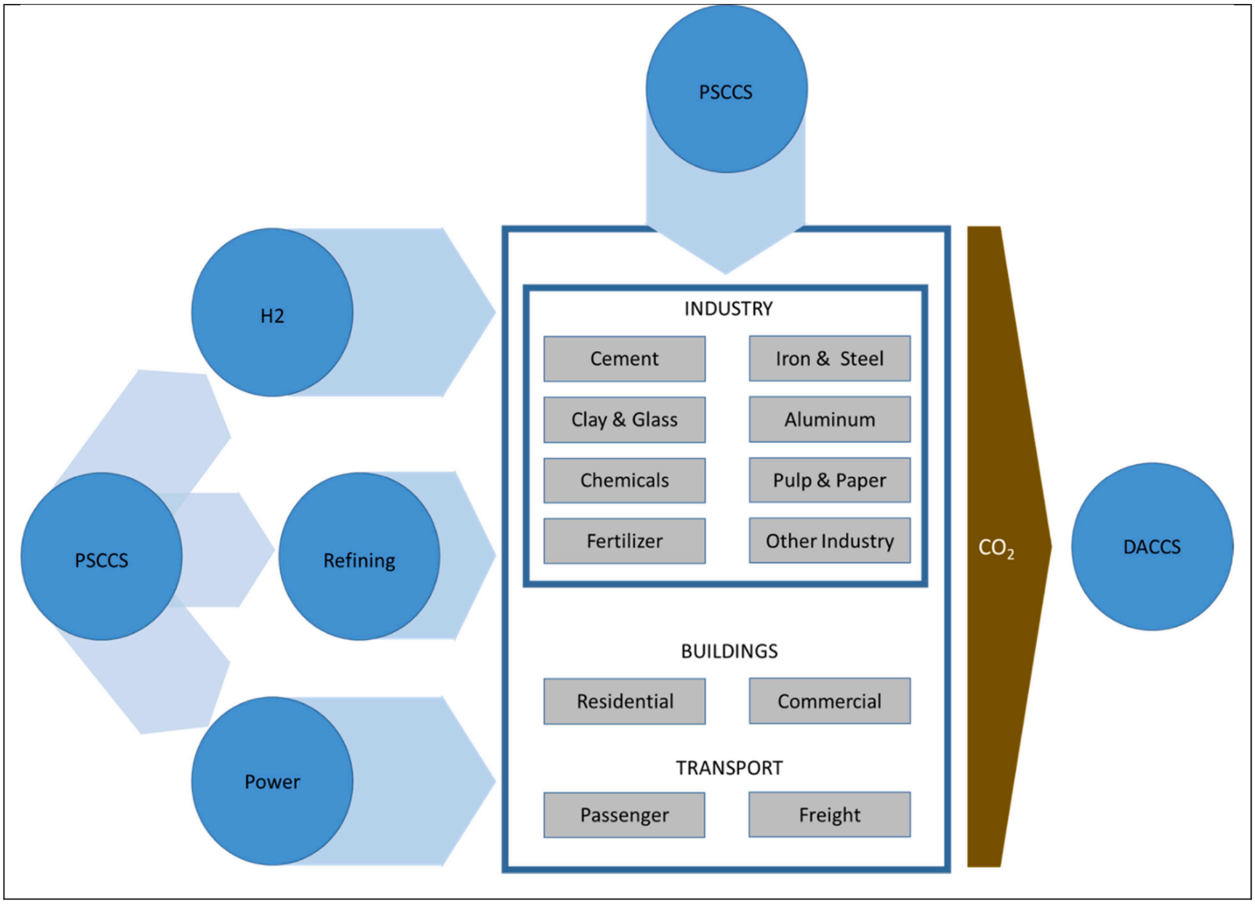


**Fig. 1. Carbon Management Study Group Technologies and Their Role in Emissions Mitigation.** Point source CCS can be deployed in several energy transformation sectors (e.g., electricity generation, refining, hydrogen production). These energy carriers are used to provide energy services in the industry, buildings, and transportation end-use sectors. Point source CCS is possible for some industrial sectors. Direct Air Capture can be used to offset harder-to-abate emissions from these end-use sectors.

of fossil fuel prices across models). Models were allowed to assume that a constant 800 Mt $CO_2$ per year are removed from the atmosphere by the U.S. land sink, in line with average historical U.S. terrestrial carbon removals [16]. Models that simulate land-use change emissions endogenously reported their endogenous land-use change emissions in place of the default 800 Mt $CO_2$ per year assumption.

Three additional scenarios explore the impact of rapid development of our CMSG technologies. **Adv CCS** is the same as **NZ Ref** except that reference PSCCS technology characteristics are replaced by assumptions consistent with potential technology advances that might materialize with substantial investments in technology improvements, including advances in both $CO_2$ capture and storage. It is up to the modeling team to implement technology advances that they envision. The benefit of those assumed technology advances can be inferred by contrasting **NZ Ref** and **Adv CCS**. Similarly, **Adv DAC** is identical to **NZ Ref** except for advanced DACCS cost and performance assumptions; **Adv $H_2$** explores technology advances related to the production, transport, storage, and utilization of hydrogen. **Adv CMSG** represents the combination of **Adv CCS, Adv DAC**, and **Adv $H_2$** and explores the potential benefit of advances across all the CMSG technologies. By contrasting **Adv CMSG** with our other CMSG scenarios we can observe non-linear synergies or competition that might emerge from a broad technology advance.

Finally, three scenarios explore the impact of CMSG technologies being unavailable to support decarbonization. **No CCS** is a scenario that differs from the **NZ Ref** scenario in that models are not allowed to utilize either PSCCS or DACCS technologies in achieving net-zero emissions in 2050. The benefit of having $CO_2$ capture technologies available is revealed by contrasting the **NZ Ref** and **No CCS** sensitivities. Similarly, **No DAC** is the same as **NZ Ref** except that DACCS is assumed to be unavailable. By contrasting **No DAC** and **NZ Ref** the benefit of having DACCS can be inferred. Similarly, by contrasting **No CCS** with **No DAC**, we can isolate the unique contribution of PSCCS technology without concurrent DACCS technology availability. **No New $H_2$** is the same as **NZ Ref** except that $H_2$ technology use is limited to its role in the Reference scenario [15]. Note that the **No CCS, No DAC**, and **No New $H_2$** scenarios have been undertaken for comparison purposes only; this is not intended to be seen as expressing uncertainty with regards to the potential availability of such technologies.

Note that while bioenergy is not explicitly a focus of the CMSG scenario design, it nonetheless plays an important role across the CMSG scenarios. The EMF 37 reporting conventions assume that bioenergy is carbon neutral and assign zero $CO_2$ emissions when bioenergy is transformed or consumed. That is, the carbon contained in the bioenergy brought to market was sequestered from the atmosphere and thus, when that carbon is re-released to the atmosphere in the production of energy, there is no net change in atmospheric $CO_2$ (for a more detailed discussion, see [17]). In other words, the EMF 37 emissions reporting treats the production and release of the carbon is simultaneous rather than explicitly tracking uptake and release. This convention does not consider indirect carbon release associated with bioenergy production, such as emissions from expansion of bioenergy cropland or conventional cropland into more carbon dense land types or changes in soil carbon retention. Models with full representations of the terrestrial system (e.g., GCAM and GCAM-USA) capture these indirect emissions explicitly within their land sector. Other models use a variety of approaches to account for these emissions or limit bioenergy supply to levels expected

**Table 1**
Impact on emissions mitigation of CCS (PSCCS and DACCS) and $H_2$.

| | Low—$CO_2$ emissions | Zero $CO_2$ emissions | Net $CO_2$ Removal |
|---|---|---|---|
| PSCCS | Used with large point emissions sources in industry and power to remove $CO_2$ from the exhaust stream. Since carbon capture processes are <100 % efficient, some residual $CO_2$ reaches the atmosphere. PSCCS can be deployed to either existing plant and equipment (retrofit) or new construction. Once captured, $CO_2$ must be prevented from reaching the atmosphere by transport and storage to appropriate geologic formations. | Occurs when bioenergy is co-fired with a fossil fuel and PSCCS. | Used in combination with biofuels, bioenergy with PSCCS, or BECCS, is a net negative $CO_2$ emitting energy source. |
| $H_2$ | When methane ($CH_4$) or other hydrocarbons are used as the feedstock for $H_2$, PSCCS can be used to reduce net $CO_2$ emissions associated with $H_2$ production. | $H_2$ produced using either electrolysis using non-$CO_2$ sources or thermal dissociation of water. | If biomass is used as a feedstock in combination with PSCCS, $H_2$ production may be a CDR pathway. |
| DACCS | | | DACCS is direct air carbon capture and storage. It is a special case of CCS. DACCS directly removes $CO_2$ from the atmosphere while also capturing $CO_2$ emissions from its energy source. |

NOTE: This table provides a simplified, heuristic summary of potential emissions profiles of the carbon management technologies explored in this study. It does not reflect a full life-cycle accounting of the technologies' emissions footprint, and intentionally excludes embodied emissions, upstream emissions (except for $CO_2$ sequestered in bioenergy feedstocks), and non-$CO_2$ GHG emissions.

**Table 2**
CMSG Scenario summary.

| Scenario | Net Zero $CO_2$ Goal | Technology Includes | | |
|---|---|---|---|---|
| NZ Ref (Net Zero Ref) | 2050 | Ref PSCCS | Ref $H_2$ | Ref DACCS |
| Adv CCS | 2050 | **Adv PSCCS** | Ref $H_2$ | Ref DACCS |
| Adv DAC | 2050 | Ref PSCCS | Ref $H_2$ | **Adv DACCS** |
| Adv $H_2$ | 2050 | Ref PSCCS | **Adv $H_2$** | Ref DACCS |
| Adv CMSG | 2050 | **Adv PSCCS** | **Adv $H_2$** | **Adv DACCS** |
| No CCS | 2050 | **No PSCCS** | Ref $H_2$ | **No DACCS** |
| No DAC | 2050 | Ref PSCCS | Ref $H_2$ | **No DACCS** |
| No New $H_2$ | 2050 | Ref PSCCS | **No New $H_2$** | Ref DACCS |

to minimize indirect land-use change emissions (Supplementary Table 2).

### 2.2. Modeling frameworks

Eight of the EMF 37 modeling teams directly participated in the CMSG. Participating modeling teams defined the CMSG scenario design, tested early scenario design drafts, and identified key output variables to ensure were included in the EMF37 database. The CMSG modeling teams were:

- AnyMOD
- The National Energy Modeling System modified by OnLocation for use by the DOE Office of Fossil Energy and Carbon Management (FECM-NEMS)
- The EPA version of the TIMES Model (EPA-TIMES)
- Future Agricultural Resources Model (FARM)
- The Global Change Analysis Model (GCAM)
- The Global Change Analysis Model-USA (GCAM-USA)
- NETL's MARKet Allocation Model (MARKAL)
- The U.S. Regional Economy, GHG and Energy Model (US-REGEN)

Models include detailed structural models such as FECM-NEMS, computable general equilibrium models such as FARM, optimization models like MARKAL, and models with global coverage such as GCAM. In addition to the models participating in the study group, six additional models participating in EMF-37 ran one or more of the CMSG scenarios.[x] If a modeling team ran a CMSG scenario, we reported their results in Figs. 2–11 along with the results from the CMSG teams. A short summary of the primary characteristics of all models can be found in the EMF 37 Overview paper ([15]; Table 2). Technical representations and assumptions for the eight models participating in the CMSG are summarized in Supplementary Table 1.

All CMSG modeling teams ran at least one of the CMSG scenarios. However, not all teams ran all CMSG scenarios. In some (but not all) cases, teams did not produce a scenario because it was infeasible in their modeling framework. Table 3 shows CMSG participating modeling teams and scenarios contributed to the CMSG database.

## 3. Results

The model experiments outlined above generated a wealth of information about potential pathways to reaching net-zero CO2 emissions in the United States under different conditions of carbon management technology cost and availability. Here, we present select finding from these scenarios, divided into three major sections: (1) The Role of PSCCS and DACCS; (2) Energy System Impacts of Carbon Management Technologies; and (3) The Role of Hydrogen.

Broadly, the numerical experiments conducted by the CMSG team support several key findings. First, all models were able to meet the net-zero U.S. $CO_2$ goal in 2050 (NZ-2050) when all reference versions of technologies were available. All models deployed some form of CDR in meeting NZ-2050. There were three major types of CDR deployed: terrestrial carbon storage, BECCS, and DACCS.

All teams took advantage of some amount of terrestrial carbon storage. The default assumption, used throughout the EMF37 study, for models without an endogenous land-use sector was 800 $MtCO_2$/year of terrestrial carbon storage, meaning that if fossil fuel and industrial emissions were reduced to 800 $MtCO_2$/year in 2050, the model was deemed to have met the NZ-2050 goal. Of the 13 teams running CMSG scenarios, seven used this assumption, while the other six models calculated terrestrial carbon storage endogenously. GCAM and GCAM-USA simulated similar levels of carbon dioxide removal but with varying contributions from the terrestrial system, BECCS, and DACCS; these differences are discussed in Supplementary Note 2.

When PSCCS and DACCS were both available, (**NZ Ref**), one or both of BECCS and DACCS deployed in all CMSG model runs. DACCS was particularly important for several of the modeling teams, as shown in Fig. 2. Total use of CDR, including terrestrial carbon storage, ranged

[x] The six other models whose results we report here are ADAGE, EPS, gTech, NATEM, TEMOA, and USREP-ReEDS.

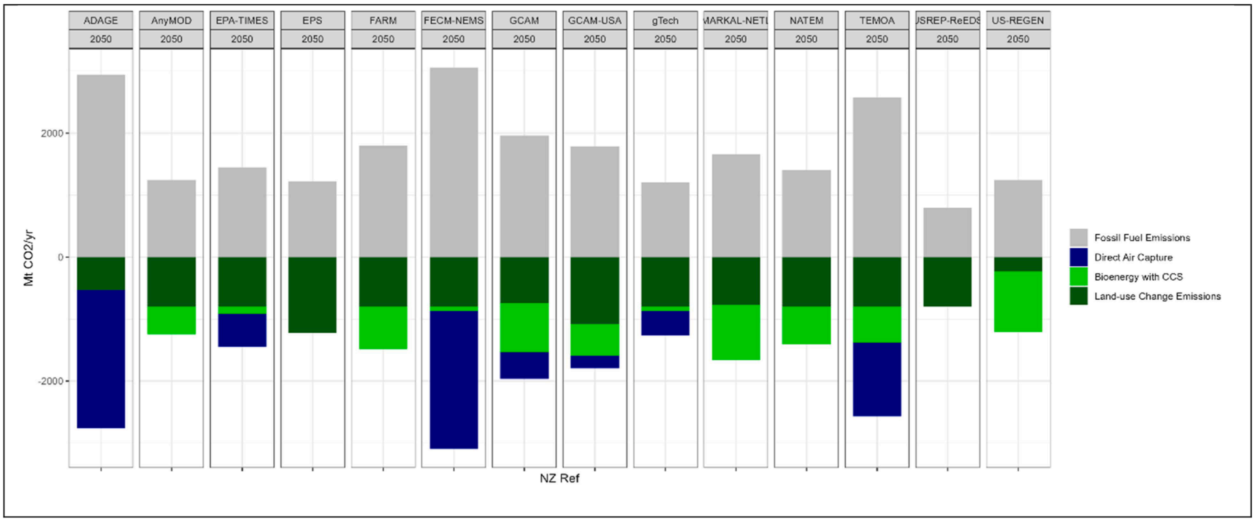


**Fig. 2.** Use of CDR to meet U.S. NZ-2050 Goal with reference technology assumptions by model.

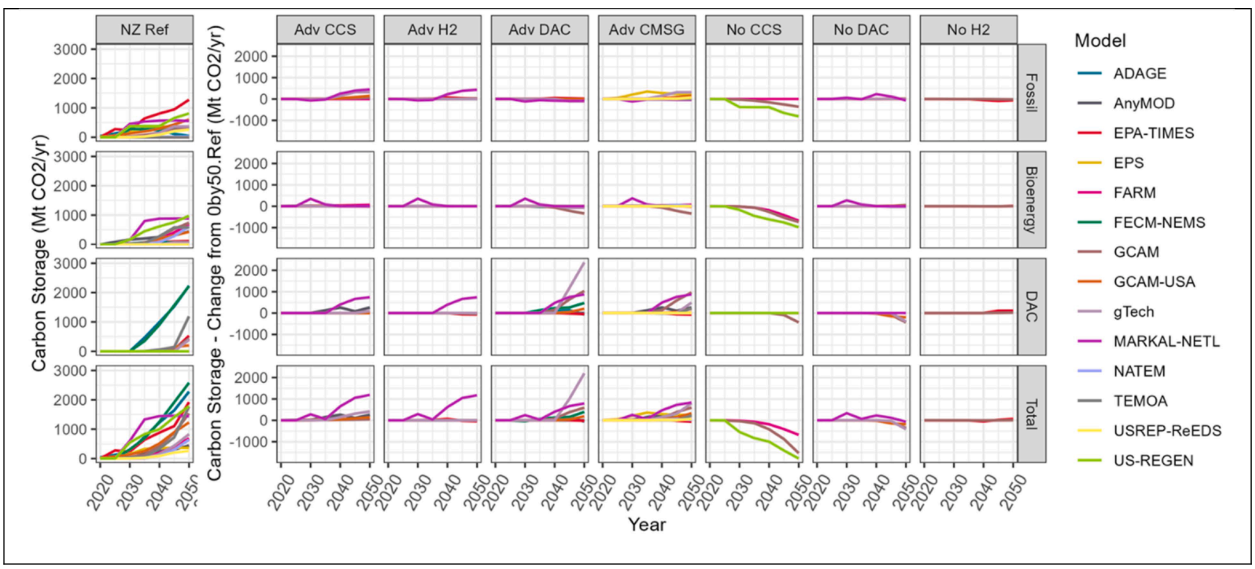


**Fig. 3.** $CO_2$ Capture rates by fuel and DACCS.

from 3091 $MtCO_2$/year (FECM-NEMS) to 1207 $MtCO_2$/year (US-REGEN). When DACCS was unavailable (**No DACCS),** CMSG models that solved reduced their fossil fuel and industrial emissions relative to **NZ Ref**, and/or expanded use of BECCS to make up for the lack of DACCS $CO_2$ removals.

FARM, GCAM, and US-REGEN were the only models that reported results for the **No CCS** sensitivity, which is more restrictive than no DACCS. This is an indication of how stringent the emissions mitigation constraint is and how little time is available to make the transition without some mechanism to remove carbon from fossil fuel and industrial sources and/or the atmosphere. This is also an indication of how important CCS, in some form, is in achieving the net-zero 2050 goal. While FARM, GCAM, and US-REGEN were able to achieve the goal without PSCCS or DACCS, they required an average carbon price of approximately \$1700/$tCO_2$ in 2050, in contrast to \$425/$tCO_2$ when PSCCS and DACCS were available.

### *3.1. The role of PSCCS and DACCS*

Fig. 3 shows $CO_2$ capture rates for seven scenarios in relation to **NZ Ref** (net-zero with reference technology). By comparing across these scenarios, we can see how the role of PSCCS and DACCS change with technology availability and performance. Technology availability is a precondition for $CO_2$ capture.

Comparing **No DAC** with **NZ Ref** shows that for models with a response, adding the reference technology version of DACCS increases overall $CO_2$ capture, but reduces BECCS and point-source fossil fuel $CO_2$ capture. In addition, improving DACCS technology performance, **Adv DAC**, further increases DACCS deployment and overall $CO_2$ capture, but further reduces the role of BECCS and fossil fuel $CO_2$ capture. There are relatively small differences between **Adv DAC** (advanced DACCS) and **Adv CMSG** (All-Advanced Technologies) indicating that the big difference between **NZ Ref** and **Adv CMSG** is the improvement in DACCS technology.

Against a background of reference technology availability assumptions (**NZ Ref**), the average capture rate for fossil, bioenergy and DACCS is approximately 1.3 $GtCO_2$/year in 2050. Models varied significantly in aggregate non-terrestrial capture rates. High values were roughly 2.6 $GtCO_2$/year in 2050, and low rates were as little as about 0.3 $GtCO_2$/year in 2050. Not all $CO_2$ capture is carbon dioxide removal. Only $CO_2$ captured either from the air (DACCS) or from the use of bioenergy (BECCS) constitute CDR. CDR rates ranged between 0 and 2.3 $GtCO_2$/

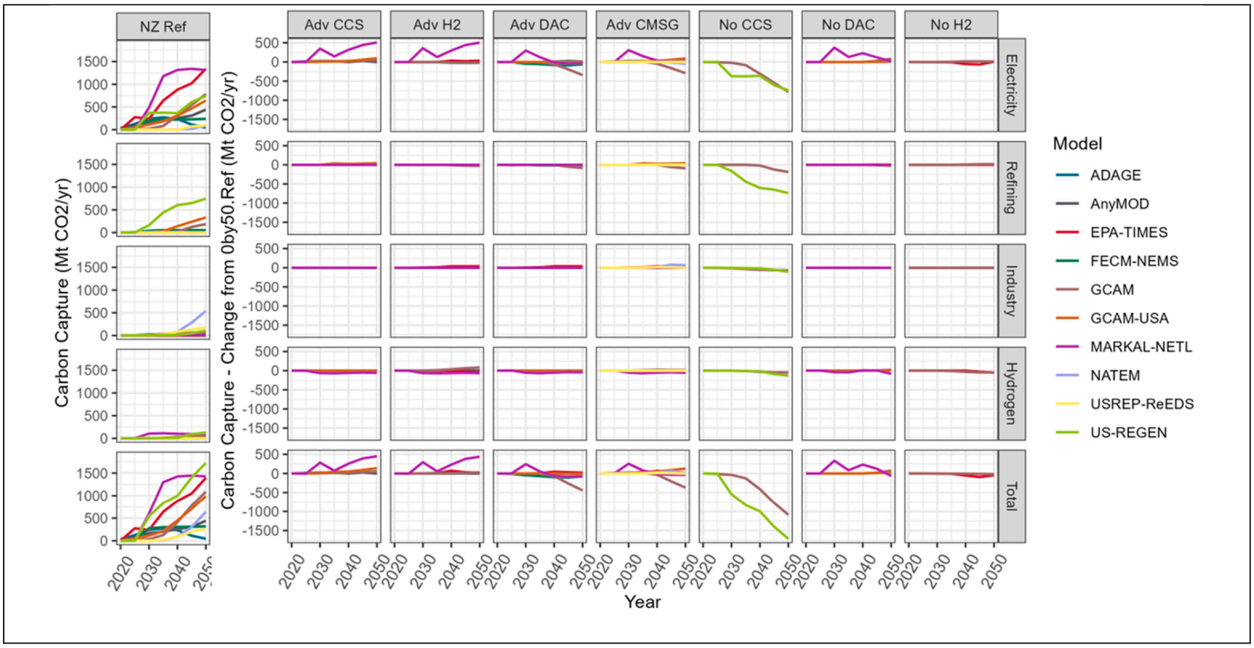


**Fig. 4.** $CO_2$ Capture by sector to 2050 by model.

year in 2050.

When both forms of CCS are available, $CO_2$ is captured in the power sector, refining sector, and other industrial sectors (Fig. 4). While any large point source could potentially capture $CO_2$, $CO_2$ capture is dominated by power production in the EMF-37 CMSG scenarios. We note that not all models reported $CO_2$ capture by sector. For models that did report $CO_2$ capture by sector, the electricity sector accounted for 8–100 % (median = 93 %) of captured carbon in 2050 across scenarios in which CCS was available. The electricity sector accounted for less than half of total point source carbon capture (excluding DACCS) in only three model-scenario combinations (NATEM **NZ Ref**; NATEM **Adv CMSG**; US-REGEN **NZ Ref**).

This study did not explicitly explore the role of carbon utilization (as opposed to carbon storage). Only one team reported carbon utilization outcomes; US-REGEN reported carbon utilization via synthetic fuel production in the **No CCS** case. Representing carbon utilization is an important opportunity for future model development.

Between 2021 and 2050, substantial amounts of $CO_2$ are captured by several of the CMSG participating models (Fig. 5). ADAGE, FECM-NEMS and MARKAL-NETL had the highest cumulative capture of $CO_2$ among the models. MARKAL-NETL captured 28.5 $GtCO_2$ between 2021 and 2050 in **NZ Ref** and >42 $GtCO_2$ in the **Adv CCS** case. While these cumulative capture totals are substantial, potential storage sites, particularly in deep saline formations, have orders of magnitude larger capacity for $CO_2$ storage. NETL [18] estimates that potentially between 2379 $GtCO_2$ and 21,633 $GtCO_2$ could be stored cumulatively.

Carbon prices associated with CMSG scenarios are show in Fig. 6.[y] Carbon prices represent the marginal cost of achieving net-zero $CO_2$ emissions. In many models and scenarios where DACCS is available, DACCS operates as a “backstop” technology setting this marginal cost; in the **NZ Ref** scenario, several models do not deploy DACCS even though it is available, suggesting that the marginal technology is BECCS or terrestrial carbon removal and marginal $CO_2$ abatement costs fall below the cost of DACCS. In **NZ Ref**, carbon prices generally rise until this “backstop” is hit. Carbon prices in 2050 ranged from \$165- \$706/$tCO_2$ across most models in the **NZ Ref** scenario, except for MARKAL-NETL, which had significantly higher carbon prices across all scenarios than the other models. The **Adv CCS** scenario, which focused on improvements in PSCCS technology alone (excluding DACCS), had little impact on carbon prices, as the carbon price was largely set by the cost of deploying DACCS. The same is true for **Adv $H_2$** (advanced $H_2$), and **No New $H_2$** due to limited $H_2$ use. Improvements in DACCS technology (**Adv DAC** and **Adv CMSG**) on the other hand, reduced the marginal cost of achieving net-zero for most models. Note that the price ranges in Fig. 6 do not reflect the fact that several models find constrained scenarios (e.g., **No DAC, No CCS**) to be infeasible (see Table 3) are not counted in the range or average, which may mean that costs associated with stringent emissions under these conditions are underestimated [19].

### 3.2. Energy system impacts of carbon management technologies

The energy system and the role of electricity are affected by the state of carbon management technologies. In this section of the paper, we explore how CMSG models describe the energy system and its evolution across the seven CMSG scenarios. Fig. 7 shows direct fossil fuel and industrial $CO_2$ emissions for the U.S. economy disaggregated into seven end-use and energy transformation sectors. Absolute/gross $CO_2$ emissions levels for the core EMF 37 net-zero scenario are shown in the far-left column of the figure. Net changes in $CO_2$ emissions are shown for the 7 CMSG scenarios.

Six modeling teams – AnyMOD, FARM, GCAM, GCAM-USA, gTech, and MARKAL-NETL – ran the **Adv CCS** sensitivity. Some models, including AnyMOD, FARM, gTech, and MARKAL-NETL, showed increased fossil fuel and industry emissions by 2050, which are counterbalanced by a shift toward DACCS (AnyMOD, gTech, and MARKAL-NETL) or BECCS (FARM). GCAM and GCAM-USA showed relatively little difference in fossil fuel and industrial $CO_2$ emissions in the **Adv CCS** case, compared with **NZ Ref**.

Five models – AnyMOD, EPA-TIMES, GCAM, gTech, MARKAL-NETL – explored an **Adv $H_2$** technology sensitivity. MARKAL-NETL reported significantly greater fossil fuel and industrial emissions (in industry and electricity, respectively). AnyMOD, EPA-TIMES, GCAM, and gTech reported changes that were relatively modest in comparison.

Eight models – ADAGE, AnyMOD, EPA-TIMES, FECM-NEMS, GCAM,

[y] Models calculate CO2 prices either as either shadow price on the scenario’s $CO_2$ emissions constraint, or by iterating across a carbon price tax schedule until the target emissions level is achieved.

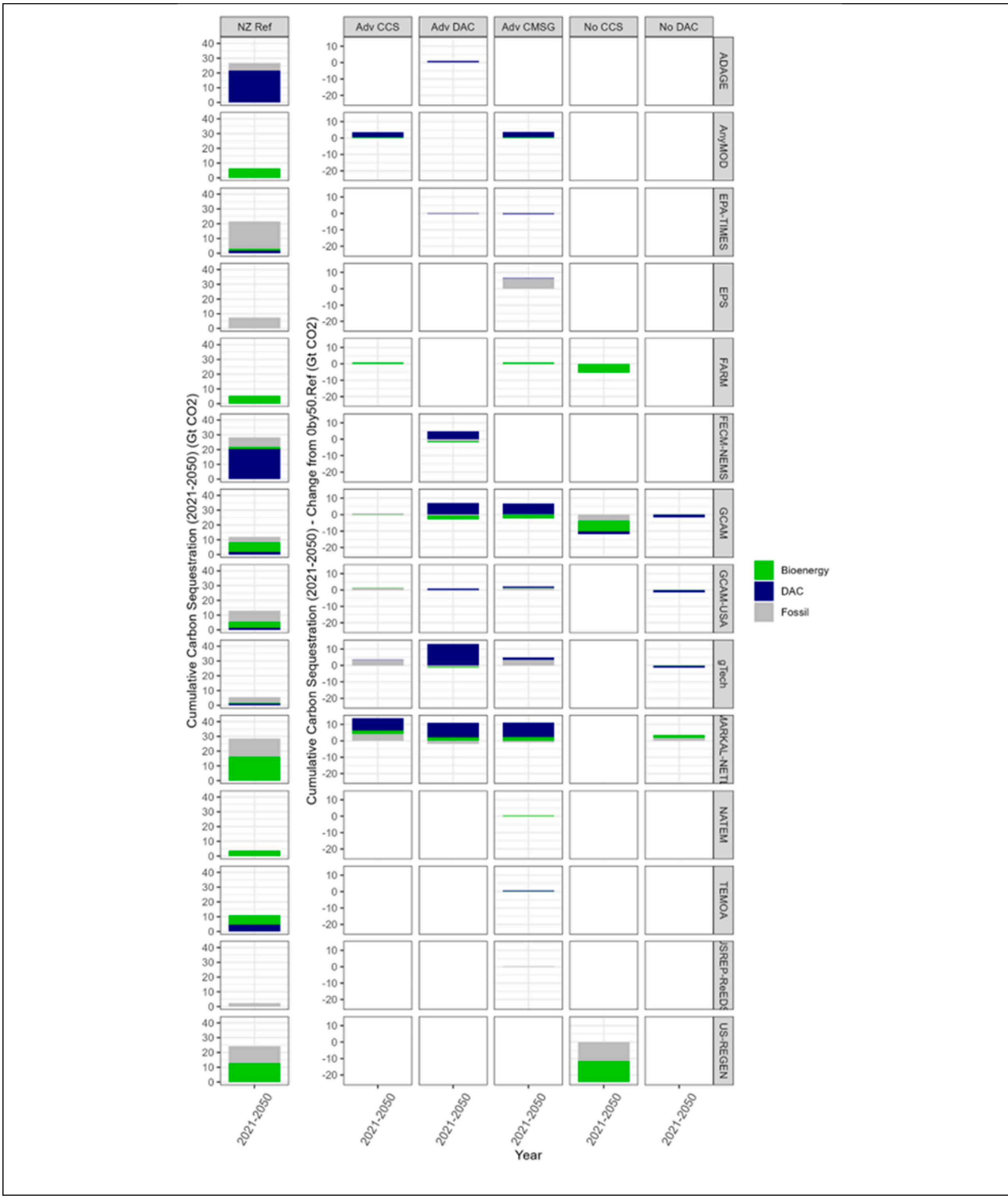


**Fig. 5.** Cumulative $CO_2$ capture 2021–2050.

GCAM USA, gTech, MARKAL-NETL – performed the **Adv DAC** technology scenario. By 2050, all models except EPA-TIMES showed increased emissions from fossil fuel and industrial activities, with negative emissions from DACCS offsetting higher cost mitigation opportunities. gTech results change the most in response to the **Adv DAC** scenario, with large increases in industry emissions (>1 GT $CO_2$ higher in the **Adv DAC** scenario, relative to **NZ Ref**) and more modest increases in emissions from electricity and transportation. Besides gTech, GCAM and FECM-NEMS also show significant (> 100 MT $CO_2$) increases in emissions from electricity generation; GCAM, FECM-NEMS, and MARKAL-NETL show significant (> 100 MT $CO_2$) increases in transportation emissions. In GCAM, the increased electricity emissions are driven partially by the increased demand for electricity used in direct air capture, as well as lower reliance on BECCS (Fig. 5), much of which occurs in the power sector. Changes in building, industry (excluding gTech), and non-electricity energy transformation sectors were smaller across models.

The **All-In** scenario with advanced PSCCS, $H_2$, and DACCS

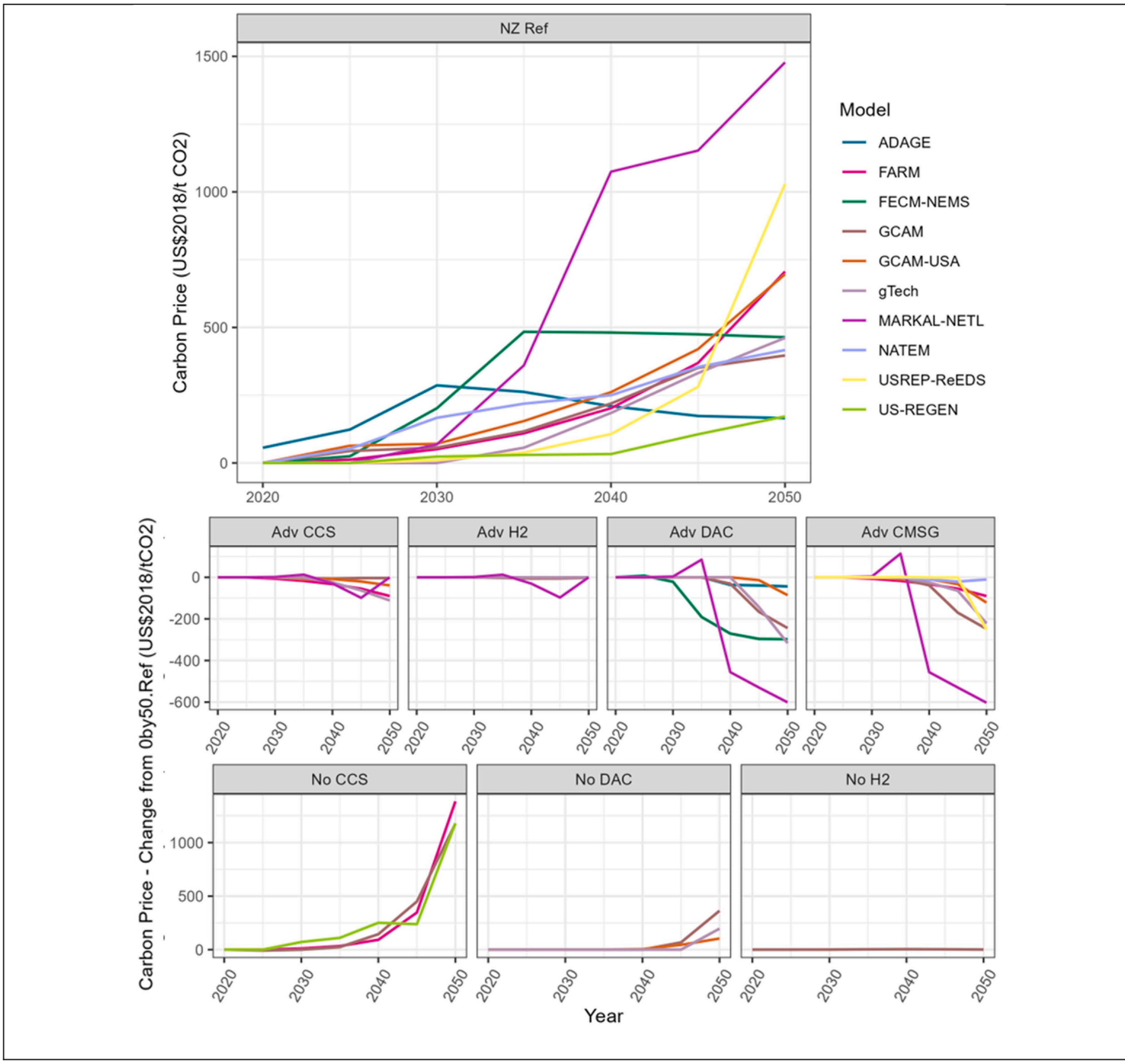


**Fig. 6.** Carbon Price by CMSG Scenario, 2021–2050. The plot presents modeled carbon prices for the **NZ Ref** scenario and changes in carbon price from the **NZ Ref** scenario for all other scenarios. For scenarios other than **NZ Ref**, positive values indicate an increase in carbon price for that scenario relative to **NZ Ref**, and negative values indicate a decrease in carbon price relative to **NZ Ref**.

technology assumptions, was run by ten models. Results were generally similar to the **Adv DAC** scenario, which is intuitive given the relatively smaller impact of the **Adv CCS** and **Adv $H_2$** technology sensitivities. MARKAL-NETL demonstrated the largest changes in the **All-In** scenario, with large increases in emissions from industry (>600 MT $CO_2$ difference) and transportation ~100 MT $CO_2$ difference). FARM and gTech had emission increases of greater than 300 MT $CO_2$ in the electricity sector. Industry and electricity saw the largest increase in emissions across most models. Transportation had the largest increase in MARKAL-NETL; GCAM and gTech also had large (>100 MT $CO_2$) increases in transportation emissions.

Three modeling teams – FARM, GCAM, and US-REGEN – reported results for the **No CCS** scenario. Direct emissions of $CO_2$ were reduced in the **No CCS** case since residual emissions from fossil fuels can only be balanced by removals from the land system. The three models largely agreed about the magnitude of direct $CO_2$ emission reductions, with reductions ranging from 960 – 990 MT $CO_2$ in 2050. Some of the larger reductions occurred in the transportation (36–48 % of reductions in 2050) and industry (14–28 % of reductions in 2050) sectors. FARM simulated significant electric power sector reductions (35 % of total reductions in 2050) but little additional building sector mitigation (buildings are largely decarbonized by 2050 in FARM's **NZ Ref** scenario). US-REGEN found the opposite – small reductions in electric power emissions but increased mitigation in buildings (28 % of total reductions in 2050) – while GCAM saw more balanced reductions between electric power (12 % of total reductions in 2050) and buildings (17 %).

Four modeling teams – GCAM, GCAM-USA, gTech, and MARKAL-NETL – reported results for the **No DAC** scenario. In general, the changes in emissions were smaller in scale but similar in distribution across sectors to the **No CCS** scenario. The one exception to the scale finding is the MARKAL-NETL results which were of similar scale to those reported for the **No CCS** sensitivity.

Only two models – EPA-TIMES and GCAM – ran the **No New $H_2$**scenario. This scenario was intended to examine the consequences of losing the ability to deploy $H_2$ in hard-to-abate applications. As might be expected, both models reported increased fossil fuel and $CO_2$ emission when $H_2$ availability as constrained. However, because $H_2$ deployment

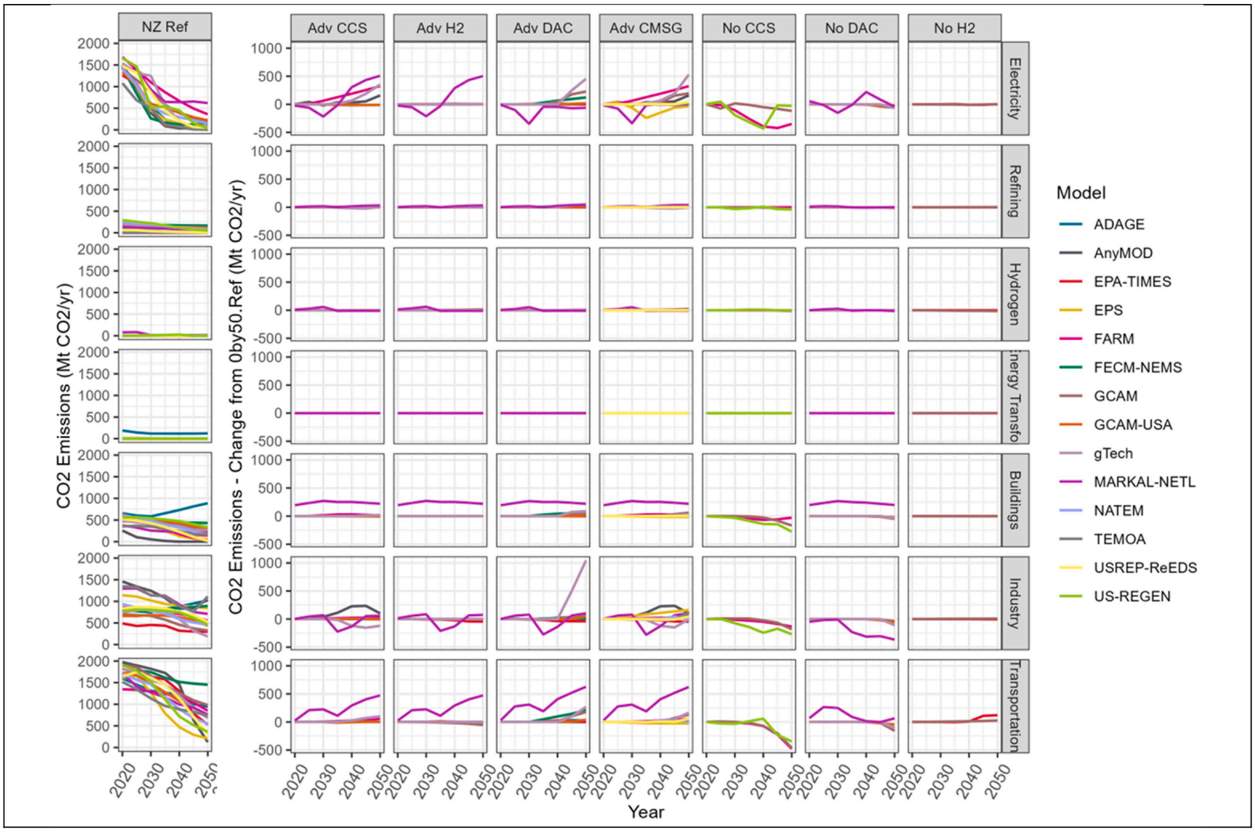


**Fig. 7.** Fossil fuel and industrial $CO_2$ emissions by sector.

was generally limited in the in the **NZ Ref** scenario (Section 3.3), constraining $H_2$ didn't lead to major differences in emissions outcomes.

Fig. 8 shows the impact of our CMSG sensitivities on aggregate energy demands and energy system composition. We aggregate results to 7 energy carriers: oil, liquid biofuels, gas, bioenergy (solid), electricity, hydrogen, and other (e.g., coal, heat, synthetic fuels). Where reported, the **No CCS** scenario had the largest impact on final energy outcomes. In 2050, all models show reduced oil use (7.5–9.6 EJ less than **NZ Ref**) and increased electricity consumption (4.0–5.9 EJ more). GCAM and US-REGEN also reported significant reductions in natural gas use (8.0–11.5 EJ lower than **NZ Ref** in 2050); FARM, which had the lowest natural gas final energy consumption across all models in the **NZ Ref** case in 2050, observed much smaller reductions in gas consumption (1.2 EJ difference in 2050). Qualitatively similar, but smaller in magnitude, results are reported by the four models which ran the **No DAC** sensitivity: GCAM, GCAM-USA, gTech, and MARKAL-NETL.

Most models showed relatively little change in the **Adv CCS** sensitivity. With **Adv DAC** assumptions, models that exhibit significant increases in DAC deployment (gTech, GCAM, MARKAL-NETL) display increased gas (in part to power DACCS units) and oil consumption.

The two models that ran the **No New $H_2$** sensitivity, GCAM and EPA-TIMES, saw increases in electricity and oil use that offset decreased $H_2$ use. Some models (AnyMOD, gTech, and MARKAL-NETL) show little additional $H_2$ produced in the advanced $H_2$ technology sensitivity (**Adv H2**), while others (EPA-TIMES, GCAM) show modest increases ($>$ 1 EJ/year in 2050). This increased hydrogen consumption displaces electricity and oil consumption in EPA-TIMES and GCAM; GCAM also simulates some reductions in final energy from gas and biomass liquids.

Eleven models reported results for the all-advanced technologies sensitivity (**Adv CMSG**). The responses were similar in direction but smaller in magnitude compared to the **Adv DAC** sensitivity, since the Adv CMSG scenario tended to entail both greater negative emissions but also greater direct mitigation in the electricity sectors (and other sectors that leverage PSCCS) and greater use of hydrogen.

Whereas Fig. 8 showed the sensitivity of the final energy consumption to different CMSG sensitivity experiments, Fig. 9 takes another perspective on the energy system. Fig. 9 shows total primary energy, which also reflects energy used in energy transformation sectors like electricity generation, refining, and hydrogen production. Fig. 9 thereby allows us to observe the use of PSCCS in conjunction with oil, gas, coal, and bioenergy. Note that primary energy is measured here using 3.6 MJ per kWh for wind and solar energy.

All three models that ran the **No CCS** sensitivity – FARM, GCAM, and US-REGEN – increased wind and solar use when CCS was unavailable. US-REGEN also significantly increased nuclear energy use; GCAM used less biomass overall but increased use of bioenergy without PSCCS. All models reduced use of fossil fuels with and without PSCCS. Results for the **No DAC** scenario were similar in direction but much smaller in magnitude than those for **No CCS**.

The **Adv CCS** case generally resulted in small increases in fossil fuel use with PSCCS and minor reductions in solar, wind, and fossil fuels without PSCCS. The availability of advanced DACCS (**Adv DAC**) resulted in small decreases in wind and solar use and larger increases in fossil fuel use (with and without PSCCS).

Finally, making new hydrogen production unavailable made a relatively small difference in primary energy outcomes, with GCAM using slightly more oil and biomass in the **No New $H_2$** case to offset the energy provided by hydrogen, as well as less gas, wind, and solar. These trends are reversed in the case with advanced hydrogen technologies (**Adv $H_2$**).

### *3.3. The role of hydrogen*

Fig. 10 presents the impact of the CMSG sensitivity experiments on hydrogen production. $H_2$ production varies little outside of the **Adv $H_2$**, **Adv CMSG**, and **No New $H_2$** cases, except for US-REGEN's **No CCS** scenario, which entails significantly higher hydrogen production

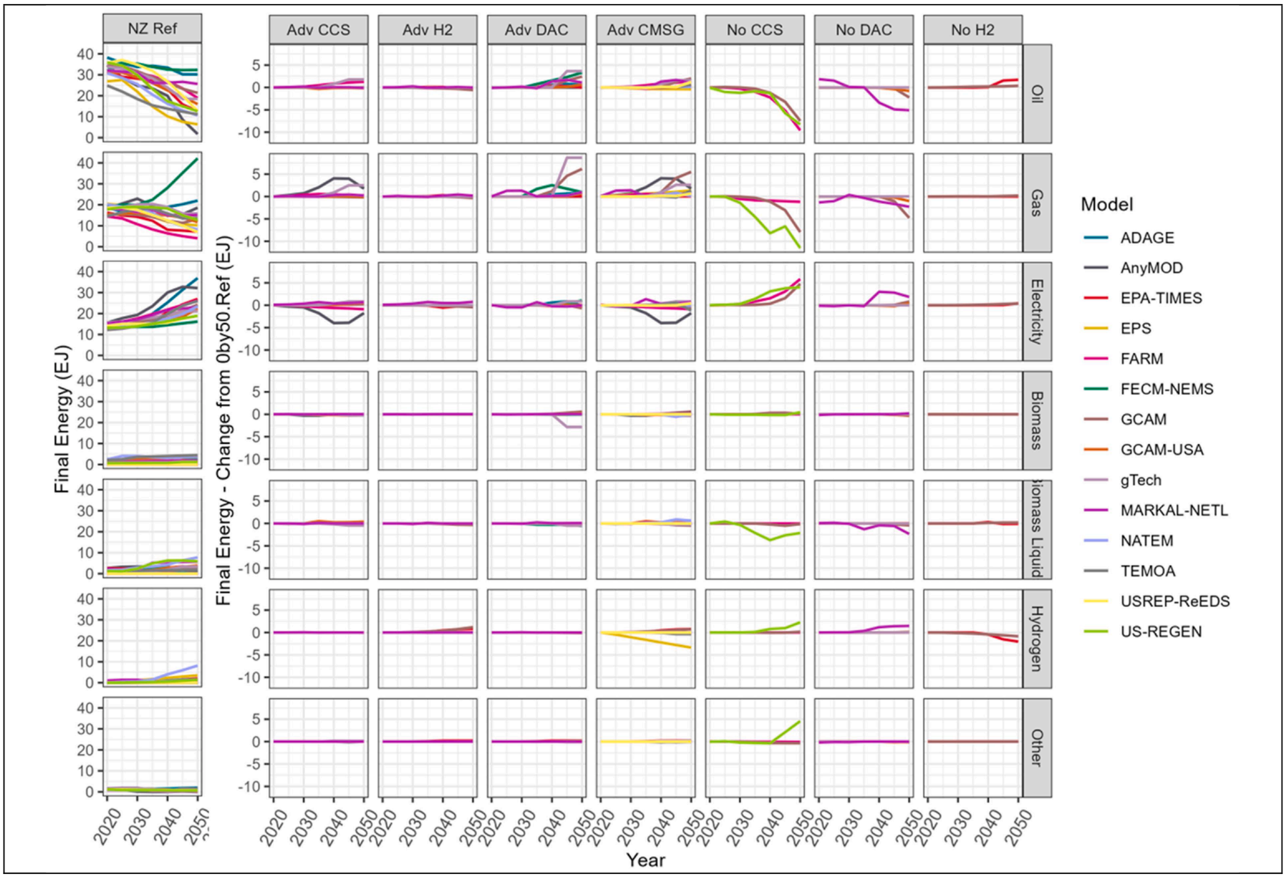


**Fig. 8.** Final energy by fuel.

(primarily from electrolysis). With **Adv $H_2$ technologies**, EPA-TIMES, GCAM, and MARKAL-NETL produce more $H_2$; EPA-TIMES and MARKAL-NETL's production increase comes primarily from electrolysis, while GCAM's increased production comes from a mix of natural gas with PSCCS, bioenergy with PSCCS, and electricity. Trends are similar but slightly smaller in the **Adv CMSG** case.

Supplementary Figure 3 compares CCS deployment (including fossil CCS, BECCS, and DACCS) and hydrogen deployment in 2050 to explore a possible relationship or tradeoff between the two technologies. One immediate observation is that the scenario with the largest hydrogen deployment is one of the few **No CCS** scenarios, suggesting that hydrogen may be more valuable when CCS is limited. CCS and hydrogen deployment vary across modeling frameworks, but we do observe a negative relationship between CCS and hydrogen deployment (e.g., more CCS deployment leads to less reliance on hydrogen, and vise-versa) between scenarios generated by the same model for some frameworks (e.g., EPS, TEMOA, US-REGEN), but not all.

Fig. 11 presents hydrogen consumption by sector and changes associated with our CMSG sensitivity scenarios. Magnitudes in Fig. 11 are smaller than those in Fig. 10 due to transmission and delivery losses. In the **No CCS** case, US-REGEN increases its $H_2$ consumption primarily for use in synthetic fuel production, with smaller amounts used in industry and transportation. GCAM reported only minor changes in $H_2$ use in the **No CCS** case, compared with **NZ Ref.**

When advanced $H_2$ technology was available (**Adv $H_2$**), EPA-TIMES and GCAM reported the most significant increases in hydrogen consumption in the transportation sector, with GCAM also simulating a smaller increase in industry. Similar, but smaller, changes were reported for the **Adv CMSG** scenario.

## 4. Discussion

The CMSG generated unique insights that added to the broader set of findings from the EMF 37 study. Many of the CMSG scenarios challenged modeling teams. Indeed, some of the CMSG scenarios proved computationally infeasible for many models. For example, the challenge of limiting U.S. $CO_2$ emissions to net-zero in 2050 without PSCCS and/or DACCS proved impossible or prohibitively costly for many of the participating models. Carbon dioxide removal played a role in all scenarios that achieved net-zero $CO_2$ emissions. Significant model development occurred during the study, but work remains to be done to enable all modeling teams to faithfully represent energy system behavior, especially in the context of scenarios with limited technological availability.

Not all models have detailed industrial sectors with the option to deploy PSCCS. One sector in particular, refining, has the potential for significant PSCCS deployment. The refining sector processes fuels, including both fossil fuels and bioenergy, and increases the hydrogen to carbon ratio. This creates the opportunity to capture $CO_2$ created in the refining process. Where models have disaggregated industrial sector representations that go beyond refining, they report $CO_2$ capture, but not on the same scale as for the power sector. Another manufacturing sector with significant potential for the application of PSCCS is cement. Several models broke out PSCCS capture for cement from aggregate industry.

While sufficient cumulative $CO_2$ storage potential exists to support the levels of carbon capture and storage deployed across the scenarios in this study, building, permitting, storing [20], and monitoring $CO_2$ at gigaton scales requires the development of institutional capacity. Because most models in this study operate at coarse geographic resolutions, the $CO_2$ transportation costs they include may not capture

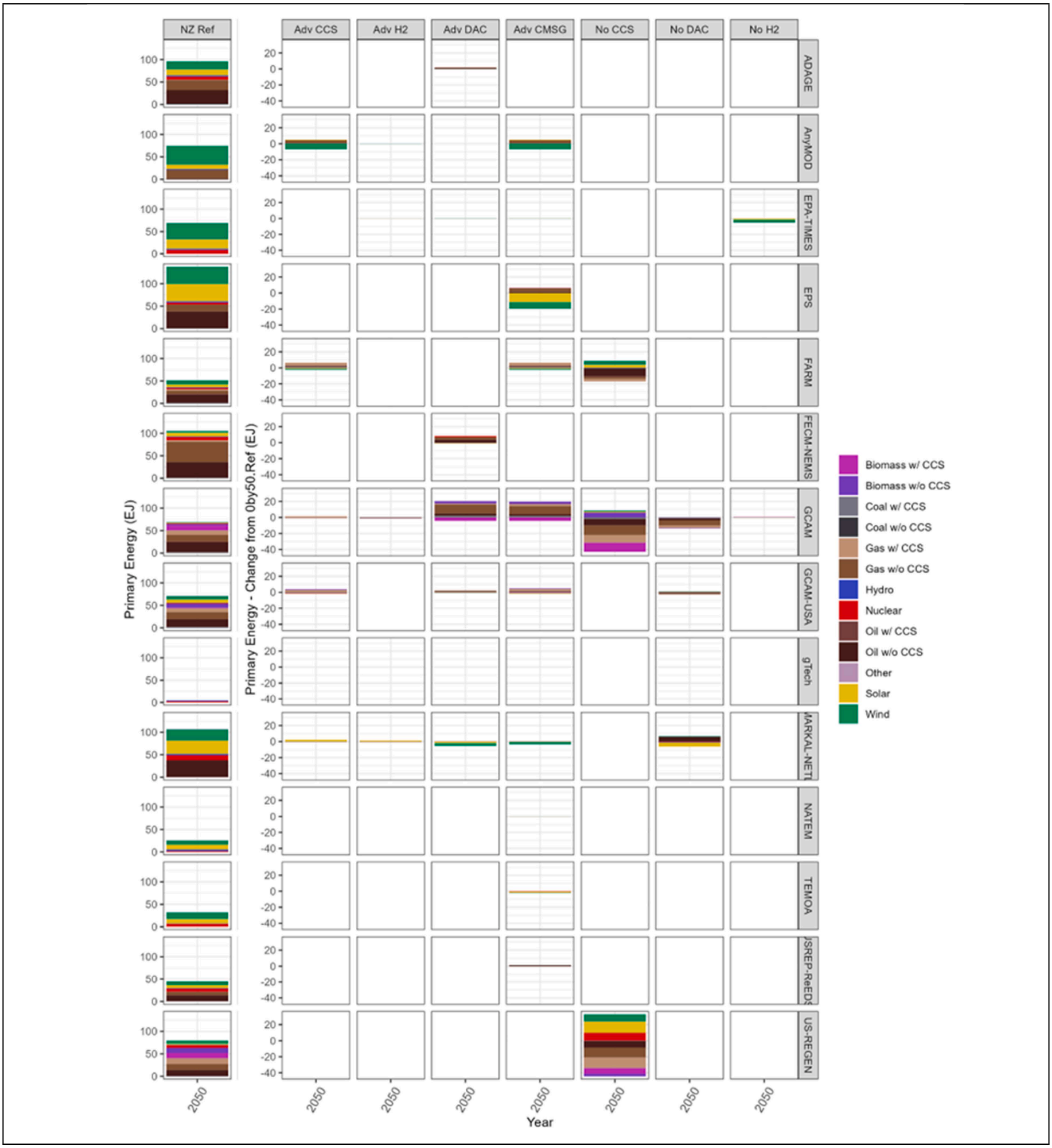


**Fig. 9.** Primary energy by fuel.

situation-specific factors that would influence $CO_2$ transportation mode (e.g., pipeline, rail, or ship). Future studies leveraging more spatially resolved, bottom-up analysis of $CO_2$ sources, sinks, and associated implications for $CO_2$ transportation infrastructure requirements could enhance our understanding of the opportunities, challenges, and costs of $CO_2$ transportation and storage, and is an important area for future research.

As one might imagine, carbon prices were higher when technologies were unavailable and lower when advanced versions of technologies were available. Carbon prices were particularly sensitive to the availability to PSCCS and DACCS technologies. In fact, carbon prices tended to be closely linked to the cost of PSCCS and DACCS. When neither were available, carbon prices could climb into thousands of dollars per ton of $CO_2$ to reach net-zero U.S. emissions in 2050. The availability of advanced versions of PSCCS and DACCS lowered prices compared to the scenario with reference technology assumptions.

The CMSG scenarios that explored model sensitivities to $H_2$ technologies were illuminating. Many models either did not include detailed $H_2$ technology options or technology options that were only partially represented. The modeling community would benefit from further model enhancements related to hydrogen production and use. The models that reported results for the CMSG $H_2$ sensitivities showed mixed results. Few models produced results in which $H_2$ became the dominant energy carrier rivaling electricity. However, some models found that $H_2$ could play an important role in either industrial or transport emissions mitigation.

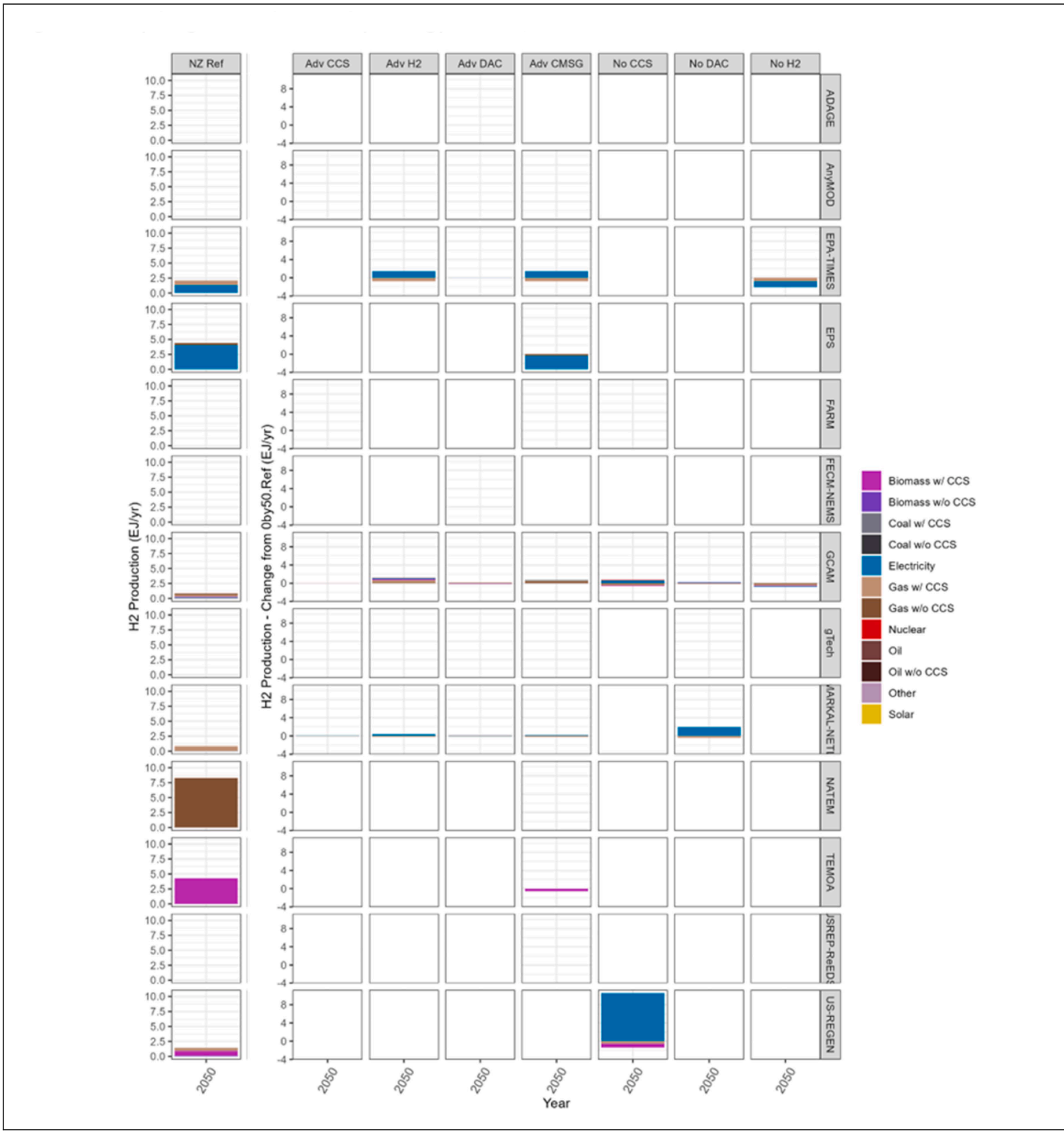


**Fig. 10.** Hydrogen production by energy source, 2021–2050.

## Data repository

The EMF37 study used the IAMC reporting format (Excel spreadsheet) with submissions uploaded to the IIASA scenario database (https://data.ece.iiasa.ac.at/emf37-internal/). The repository compiles all the results into a single data base.

## CRediT authorship contribution statement

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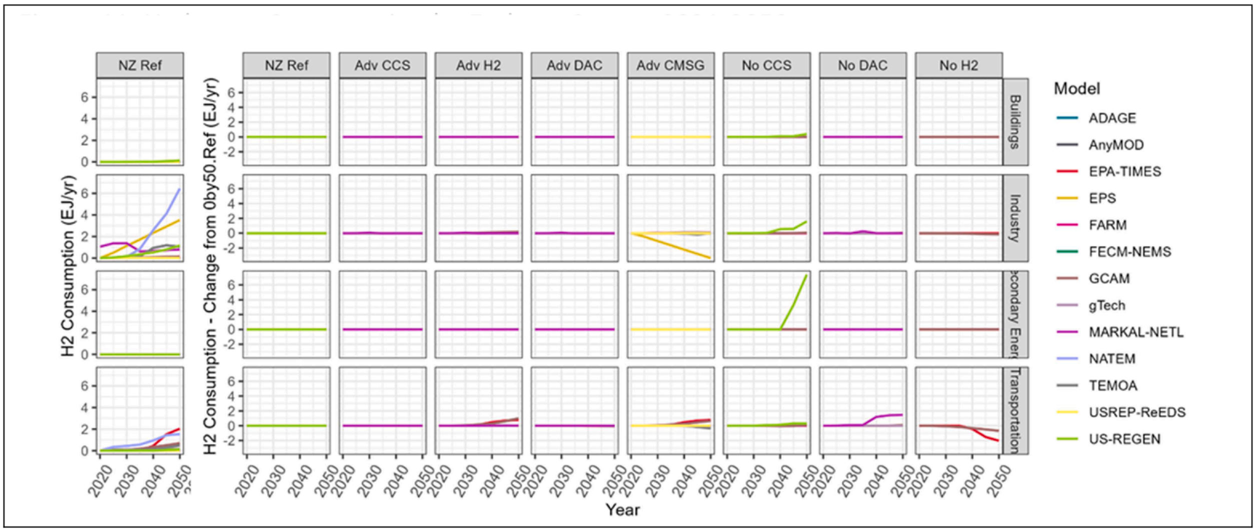


**Fig. 11.** Hydrogen consumption by End-use sector, 2021–2050.

**Table 3**
Modeling teams and scenario contributions to the CMSG.

| Scenario | Net Zero Goal | ADAGE | AnyMOD | EPS | FECM-NEMS | FARM | GCAM | GCAM-USA | gTech | MARKAL | NATEM | TEMOA | EPA-TIMES | US-REGEN | USREP-ReEDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref | BAU | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| NZ Ref | 2050 | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| No CCS | 2050 | | X | | X | * | * | | | | | | | * | |
| Adv PSCCS | 2050 | | * | | | * | * | * | * | * | | | | | |
| Adv $H_2$ | 2050 | | * | | | | * | | * | * | | | * | | |
| Adv DACCS | 2050 | * | * | | * | | * | * | * | * | | | * | | |
| Adv CMSG | 2050 | | * | * | | * | * | * | * | * | * | * | * | | * |
| No DACCS | 2050 | | | | X | | * | * | * | * | | | | | |
| No New $H_2$ | 2050 | | | | | | * | | | | | | * | | |

*Model ran corresponding scenario
X: Model attempted to run corresponding scenario, but it was unable to solve.

**Frances Wood:** Writing – review & editing, Investigation. **Sha Yu:** . **Mei Yuan:** Writing – review & editing, Investigation.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jae Edmonds reports financial support was provided by US Department of Energy. Matthew Binsted, Ellie Lochner, Jae Edmonds, Jay Fuhrman, Gokul Iyer, Page Kyle, Haewon McJeon, Sha Yu, Francisco De La Chesnaye, Amogh Prabhu, Frances Wood and Sharon Showalter reports financial support was provided by US Department of Energy. Luis Sarmiento reports financial support was provided by European Research Council. Kowan O'Keefe reports financial support was provided by Pierre Elliott Trudeau Foundation. Kowan O'Keefe reports financial support was provided by Government of Canada Social Sciences and Humanities Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements and disclaimer

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Matthew Binsted, Ellie Lochner, Jae Edmonds, Jay Fuhrman, Gokul Iyer, Page Kyle, Haewon McJeon, and Sha Yu acknowledge support from the U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM).

Luis Sarmiento acknowledges that this publication has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (N2020 grant agreement No 853487–2D4D) and the European Climate and Energy Modelling Forum ECEMF (H2020 grant agreement No 101022622).

Nadejda Victor acknowledges support by the United States Department of Energy, National Energy Technology Laboratory, in part, through a site support contract.

Francisco De La Chesnaye, Amogh Prabhu, Frances Wood and Sharon Showalter wish to acknowledge research support from the U.S. Department of Energy's Office of Fossil Energy and Carbon Management.

Kowan T. V. O'Keefe was partly supported by funding from the Pierre Elliott Trudeau Foundation and the Social Sciences and Humanities Research Council.

Ron Sands wishes to acknowledge that his contribution to this paper was supported by the U.S. Department of Agriculture, Economic Research Service.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100154.

## References

[1] Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104.

[2] Jae Edmonds, Tom Wilson, Marshall Wise, John Weyant, Electrification of the economy and $CO_2$ emissions mitigation, Environ. Econ. Policy Stud. 7 (3) (2006) 175–203.

[3] Clarke, Leon E., Allen A. Fawcett, John P. Weyant, James McFarland, Vaibhav Chaturvedi, and Yuyu Zhou. "Technology and US emissions reductions goals: Results of the EMF 24 modeling exercise." Energy J. 35, no. Special Issue (2014).

[4] Melaina, M., C.S. Lenox, M. Browning, D.L. McCollum, O. Bahn, S. Ou., Energy and climate change, modeling hydrogen markets: Energy system model development status and decarbonization scenario results, 2024.

[5] Elmar Kriegler, Ottmar Edenhofer, Lena Reuster, Gunnar Luderer, David Klein, Is atmospheric carbon dioxide removal a game changer for climate change mitigation? Clim. Change 118 (2013) 45–57.

[6] Gokul Iyer, Leon Clarke, Jae Edmonds, Allen Fawcett, Jay Fuhrman, Haewon McJeon, Stephanie Waldhoff, The role of carbon dioxide removal in net-zero emissions pledges, Energy Clim. Chang. 2 (2021) 100043.

[7] Temitope Ajayi, Jorge Salgado Gomes, Achinta Bera, A review of CO 2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, Pet. Sci. 16 (2019) 1028–1063.

[8] Kelemen, Peter, Sally M. Benson, Hélène Pilorgé, Peter Psarras, and Jennifer Wilcox. "An overview of the status and challenges of CO2 storage in minerals and geological formations." *Front. Clim.* 1 (2019): 9.

[9] Zheng Junjie, Zheng Rong Chong, M.Fahed Qureshi, Praveen Linga, Carbon dioxide sequestration via gas hydrates: A potential pathway toward decarbonization, ENERG. FUEL. 34 (9) (2020) 10529–10546.

[10] Albanese, Anthony S., and Meyer Steinberg. "Environmental control technology for atmospheric carbon dioxide." Energy 5, no. 7 (1980): 641–664.

[11] M.N. Anwar, A. Fayyaz, N.F. Sohail, M.F. Khokhar, M. Baqar, A. Yasar, K. Rasool, et al., CO2 utilization: Turning greenhouse gas into fuels and valuable products, J. Environ. Manage. 260 (2020) 110059.

[12] G. Zang, P. Sun, A.A. Elgowainy, A. Bafana, M. Wang, Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process, Journal of CO2 Utilization 46 (2021) 101459. Apr 1.

[13] Luyi Xu, Yang Xiu, Fangyuan Liu, Yuwei Liang, Shengjie Wang, Research progress in conversion of CO2 to valuable fuels, Molecules. 25 (16) (2020) 3653.

[14] N. Hilmi, M. Sutherland, S. Farahmand, G. Haraldsson, E. van Doorn, E. Ernst, M. S. Wisz, A. Claudel Rusin, L.G. Elsler, L.A. Levin, Deep sea nature-based solutions to climate change, Front. Clim. 5 (2023) 1169665, https://doi.org/10.3389/fclim.2023.1169665.

[15] Browning, Morgan, James McFarland, John Bistline, Gale Boyd, Matteo Muratori, Matthew Binsted, Chioke Harris, Trieu Mai, Geoff Blanford, Jae Edmonds, Allen A. Fawcett, Ozge Kaplan, John Weyant. "Net-zero CO2 by 2050 scenarios for the United States in the energy modeling forum 37 study." Energy Clim. Chang. 4 (2023) 100104. https://doi.org/10.1016/j.egycc.2023.100104.

[16] EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021, U.S. Environmental Protection Agency (2023). EPA 430-R-23-002, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

[17] C. Green, K.A. Byrne, Biomass: Impact on Carbon Cycle and Greenhouse Gas Emissions, in: C.J. Cleveland (Ed.), Encyclopedia of Energy, Elsevier, 2004, pp. 223–236, https://doi.org/10.1016/B0-12-176480-X/00418-6, 2004ISBN 9780121764807.

[18] NETL (National Energy Technology Laboratory). 2015. "Carbon Storage Atlas – Fifth Edition (Atlas V)." DOE/NETL-2015/1709. https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf. Paris Agreement (2015). ≤https://unfccc.int/resource/docs/convkp/conveng.pdf≥.

[19] M. Tavoni, R.S.J. Tol, Counting only the hits? The risk of underestimating the costs of stringent climate policy, Clim. Change 100 (2010) 769–778, https://doi.org/10.1007/s10584-010-9867-9.

[20] Steven T. Anderson, Jahediesfanjani Hossein, Estimating the pressure-limited dynamic capacity and costs of basin-scale CO2 storage in a saline formation, Int. J. Greenhouse Gas Control 88 (2019) 156–167.