Impact of Carbon Dioxide Removal Technologies on Deep Decarbonization: EMF 37 MARKAL–NETL Modeling Results

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Abstract

This paper examines the MARKAL-NETL modeling results for the Energy Modeling Forum study on Deep Decarbonization and High Electrification Scenarios for North America (EMF 37) with a specific focus on carbon dioxide removal (CDR) technologies and opportunities under different scenario guidelines, policies, and technological advancements.

The results demonstrate that CDR, such as bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and afforestation, are key technologies in deep decarbonization scenarios and account for 40–60 percent of avoided carbon dioxide (CO_2) emissions annually. From 2025 to 2050, cumulative CO_2 abatement by CDR technologies will range from 37 to 47 billion tons ($GtCO_2$), or more than 2 $GtCO_2$ annually by 2050. The potential scale of CDR and its impact depends on the advancement and costs of energy supply and demand technologies, end-use sector electrification, and availability and costs of CDR. Results show that the price of carbon is substantially lower when advanced technologies are available, particularly in the EMF 37 carbon management scenarios [1].

While BECCS deployment is likely to be constrained for environmental and/or political reasons, the results display relatively large-scale BECCS deployment. The study found that BECCS could make a substantial contribution to emissions reductions after 2035, and, in the medium term, CO_2 sequestration by BECCS will depend on CO_2 price; BECCS deployment starts at a carbon price of around $70/tCO_2$. Long-term CO_2 sequestration by BECCS increases in all scenarios, reaching the same annual level of ~890 $MtCO_2$ by 2050 in net-zero CO_2 scenarios. According to the modeling results, DAC acts as a true backstop technology at carbon prices of around $600/tCO_2$.

Keywords

EMF 37; MARKAL–NETL multi-regional energy model; deep decarbonization scenarios; carbon dioxide removal; bioenergy with carbon capture and storage; direct air capture

1. Introduction

The EMF 37 study on deep decarbonization and high electrification analyzed a set of illustrative policies to reach economy-wide net-zero carbon dioxide (CO_2) emissions in North America by mid-century; it achieved this through a modeling results analysis comprising 16 energy-economy models running a common set of scenarios [1]. Energy system models are diverse in their geographical landscape, modeling types and capabilities, sectoral coverage, available decarbonization technology options, and costs. An essential goal of modeling results via intercomparison with EMF 37 is to identify which insights are robust across all models and scenarios and which are sensitive to model-specific characteristics and assumptions.

The objectives of this paper are as follows: provide details on the MARKAL–NETL energy system model for the EMF 37 study; present MARKAL–NETL modeling results and decarbonization pathways for net-zero CO_2 emissions scenarios by 2050; and evaluate the magnitude of carbon dioxide removal (CDR) technologies for deep decarbonization.

The current debate over developing CDR technologies has been prompted by the comprehensive review of climate science by the Intergovernmental Panel on Climate Change (IPCC) [2]. According to current studies, CDR technologies, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC), are key technologies for deep decarbonization of the U.S. energy sector since some hard-to-abate CO_2 emissions from, for example, aviation and industrial processes remain a challenge and would need to be offset by CDR [3–4].

The CDR options have been investigated primarily using integrated assessment models and mainly at the global level [5–8]. In previous studies on CDR, DAC performs as a long-term mitigation measure, and it is mainly deployed in the distant future, and BECCS and land use, land use change, and forestry (LULUCF) are more cost-competitive [9–12]. The current literature on CDR technologies mainly addresses detailed technical and economic characteristics, factors limiting CDR deployments, and the risks associated with CDR deployed at scale. Our study addresses detailed CDR impact on long-term energy system in the U.S. and how the availability and cost of other mitigation technologies can impact CDR deployment.

The rest of the paper is organized as follows: Section 2 provides an overview of the MARKAL–NETL model; Section 3 looks at the results from six scenarios and provides insights into the similarities and differences across the scenarios; and Section 4 discusses the challenges regarding the questions raised and provides a summary and recommendations for future work.

2. Method: the MARKAL–NETL Model and EMF 37 Scenarios

MARKet Allocation (MARKAL) is an integrated energy systems modeling platform that analyzes energy, economic, and environmental matters to quantify the impacts of policy options on energy technology deployment and associated environmental feedback in the long term [13]. MARKAL does not contain a built-in database, so the modeler must enter input parameters, energy system technological characteristics, energy carrier types, energy service demands, etc. MARKAL–NETL is a modified version of the Environmental Protection Agency's (EPA) nine-region database of the U.S. energy system based on the nine U.S. census divisions (EPAUS9r) [14–16].

MARKAL–NETL is an optimized, bottom-up, linear programming energy system model that identifies the optimal fuel and technology mixes to achieve the lowest energy system cost while meeting energy service demands and constraints, which allows the U.S. energy system to be modeled for 2010–2075 in five-year increments. MARKAL–NETL computes an inter-temporal, partial equilibrium on energy markets, which means that the quantities and prices of the fuels and commodities are in equilibrium, and investments made in any given period are optimal over the time horizon as a whole. Each of the U.S. census regions in MARKAL–NETL is modeled as a distinct energy system with different regional costs, resource availability, existing capacity, and end-use demands, and regions are connected through a trade network.

MARKAL–NETL includes energy production, conversion, and final energy consumption modules. It is a demand-driven energy system model; therefore, end-use energy service demand is the same in all scenarios and consistent with the Annual Energy Outlook 2022 reference scenario [17]. In the reference scenario, the model must satisfy these energy service demands in each period by using the existing capacity or by deploying new capacity for end-use technologies. The model can also be run with some or all, demands assumed inelastic. In alternate scenarios, the prices of energy services could vary from the reference case prices; for example, a scenario causing the price of oil to rise would increase the cost of vehicle travel relative to the reference case and would also affect investment decisions. By design, the EMF 37 study focuses on the United States and includes only North America's energy trade flow. MARKAL–NETL does not incorporate important global dimensions of the natural gas trade beyond North America and does not include the export of liquefied natural gas.

The model includes the following existing policies as environmental constraints: the Cross-State Air Pollution Rule [18]; Mercury and Air Toxics Standards regulations [19]; state-level renewable portfolio standards, aggregated and represented in MARKAL–NETL at the regional level [20]; and the Corporate Average Fuel Economy standards for light-duty vehicles included in the transportation sector [21]. The U.S. government's Inflation Reduction Act of 2022 (IRA), designed to stimulate clean energy and carbon management, was not included in this study. The MARKAL–NETL modeling results on the impact of IRA energy systems have been provided separately in a multi-model analysis study [22].

CDR technologies in the model are presented via BECCS, DAC, and LULUCF. The MARKAL–NETL model does not include a LULUCF submodule; LULUCF is an exogenous sink with assumptions of 728 $MtCO_2$ in 2010 and 772 $MtCO_2$ in 2050. BECCS technology is presented in the model through biomass integrated gasification combined cycle (IGCC) plants with pre-combustion CO_2 capture. There are two modes of capturing CO_2 emissions within the model: (1) post-combustion capture, applicable to both coal steam and natural gas combustion turbines, and (2) pre-combustion capture. The CO_2 capture rate is assumed to be 90 percent for coal and biomass plants and 85 percent for natural gas combined cycle.

Though IGCC biomass with carbon capture and storage (CCS) employs a system design similar to advanced coal IGCC technology, BECCS deployment depends highly on biomass resource availability, which varies across regions, has lower energy density than coal, and has a higher feedstock cost per unit of energy produced. Biomass resources in MARKAL–NETL are organized into three categories: woody, herbaceous, and landfill gas from municipal solid waste. They are characterized by supply chains covering biomass for use in electricity and hydrogen production, in the industrial sector, ethanol from both cellulosic feedstocks and corn feedstocks, the blending of denatured ethanol and gasoline, and biodiesel. In each census region, different biomass feedstock supplies are made available to the model, including transportation for biomass and conversion technologies. Data for biomass supply were taken from [23], which includes feedstock supply estimates organized by forest biomass and wood waste resources, agricultural biomass and waste resources, and biomass energy crops. Each of the supply curves includes several steps that present the cost and upper bound for the given feedstock. It is important to mention that efforts to expand biomass supply can increase the demand for water, land, and fertilizer or have other ecosystem impacts [24–25]. Thus, the assumptions in the model regarding the technical aspects of biomass with CCS are considered realistic, but they could be unrealistic regarding the extent of bioenergy deployment as the results of the institutional and infrastructural barriers to the use of biomass energy feedstocks [26].

The CO_2 capture approaches in DAC technologies are more expensive than capture from fossil fuel or biomass power plants because CO_2 in the air is about 300 times more diluted than that from a power plant. Two groups of DAC technologies have been identified as the most promising from technical and economic perspectives—liquid solvent DAC and solid solvent DAC—and the solid solvent DAC technologies are still at the earlier research stage. Liquid solvent DAC technology clusters that are currently available include high-temperature DAC (natural gas), high-temperature DAC (fully electric), and low-temperature DAC (electric heat pump). Only high-temperature DAC (natural gas) was included in the current version of the model as the more economically attractive option [27]. All technical parameters and costs were taken from [27], with capital cost assumptions at the high end of the range. Table 1 provides additional information for CDR technology assumptions.

Table 1. Assumptions for CDR Technologies

Technology	Investment Costs*		Variable O&M*		Fixed O&M*		Fuel Use		Availability Factor
	First Year	2050	First Year	2050	First Year	2050	First Year	2050	
BECCS	4921 2018$10e6/GW ($445/tCO₂/year)	4921 $10e6/GW ($445/tCO₂/year)	1.99 $10e6/PJ	1.99 $10e6/PJ	132.68 $10e6/PJ	132.68 $10e6/PJ	2.42 PJ/MtCO₂	2.42 PJ/MtCO₂	0.85
BECCS Advanced	4921 $10e6/GW ($445/tCO₂/year)	2193 $10e6/GW ($199/tCO₂/year)	1.99 $10e6/PJ	1.62 $10e6/PJ	132.68 $10e6/PJ	114.51 $10e6/PJ	2.42 PJ/MtCO₂	2.42 PJ/MtCO₂	0.85
DAC	1255 $10e6/PJ ($1314/tCO₂/year)	1255 $10e6/PJ ($1314/tCO₂/year)	1.70 $10e6/PJ	1.70 $10e6/PJ	29.70 $10e6/PJ	29.70 $10e6/PJ	5.25 PJ/MtCO₂	5.25 PJ/MtCO₂	0.95
DAC Advanced	1255 $10e6/PJ ($1314/tCO₂/year)	1026 $10e6/PJ ($1075/tCO₂/year)	1.70 $10e6/PJ	1.70 $10e6/PJ	29.70 $10e6/PJ	29.70 $10e6/PJ	5.25 PJ/MtCO₂	5.25 PJ/MtCO₂	0.95

- All cost data are in 2018$USD.

BECCS and DAC technology deployments depend on the geological storage potential to safely trap CO_2. The cumulative CO_2 storage capacities in the MARKAL–NETL model are indicated by region, increase over time, and are based on U.S. Department of Energy estimations [28]. In addition, there is no carbon storage availability in New England [28]. We ran twenty EMF 37 scenarios using the MARKAL model but focused on reference scenarios and advanced scenarios to catch the impact of advanced technologies in different sectors on CDR deployment. Thus, this paper examines six of the EMF 37 scenarios, presented in Table 2.

Table 2. Scenarios and Scenario Definitions

EMF 37 Scenarios	Scenario Abbreviations	Scenario Definitions
Reference	Reference	No new climate policy after early 2022
Net-zero reference	Net Zero	U.S. energy system-wide net-zero CO_2 emissions defined as a linear CO_2 emissions reduction from 2020 to net-zero emissions by 2050; default assumptions for technology costs, complementary policies, and consumer preferences; CO_2 trade among census regions is allowed
Net-zero scenario with advanced technologies in the building sector	Net Zero BSG+	Includes optimistic assumptions regarding the potential for electrification and decarbonization in the building sector
Net-zero scenario with advanced technologies in the industrial sector	Net Zero ISG+	Includes optimistic assumptions regarding electrification, efficiency improvement, and decarbonization in the industrial sector
Net-zero scenario with advanced technologies in the transportation sector	Net Zero TSG+	Includes optimistic assumptions regarding technology cost and availability in the transportation sector
Net-zero scenario with advanced carbon management technologies	Net Zero CMSG+	Includes optimistic assumptions regarding the technology costs of all carbon management options (CCS, hydrogen, and DAC)
Net-zero scenario with advanced technologies in all sectors and carbon management technologies	Net Zero+	Includes optimistic assumptions regarding the potential for electrification and decarbonization in the building, industrial, and transportation sectors, and a decline in the technology costs of all carbon management options

The cap-and-trade approach[1] has been implemented for CO_2 constraints in deep decarbonization scenarios with CO_2 trade among census regions. Investment costs, operation and maintenance (O&M) costs, and heat rate technology assumptions in reference cases are the same as those for the start year and improved only

[1] The CO_2 cap-and-trade approach in MARKAL-NETL indicates national CO_2 upper limit and allows regions to sell or buy CO_2 allowances.

in scenarios involving advanced technologies. The next section presents results for one reference and five net-zero scenarios.

The following assumptions should be noted: (1) EMF 37 Net-Zero scenario run under the assumption that CCS technologies are unavailable shows infeasibility; (2) EMF 37 Net-Zero scenario that uses the assumption that DAC technologies are unavailable resulted in dummy technologies[2] in 2055–2075 and a high CO_2 price of approximately $9,000/t$CO_2$ in 2050; and (3) only three models of the EMF 37 Carbon Management Study Group—FARM, GCAM, and US-REGEN—were able to run scenarios under the assumption that CCS technologies are unavailable [29]. On the one hand, this is an indication of how strict CO_2 mitigation constraints are and how little time is available to make the transition, on the other hand, this is an indication of how important CO_2 sequestration technologies are in achieving the net-zero 2050 goal.

3. Results and Discussion

The U.S. energy system's CO_2 emissions (including industrial processes) in the reference scenario are projected to moderately decrease by 8 percent in 2050 from 2020 emissions (Figure 1). MARKAL–NETL projects gross CO_2 emissions greater than 3,148 MtCO_2 by 2050 in the reference scenario. In the net-zero scenarios, emissions from energy and industrial processes experience a maximum decline to around 1,800 MtCO_2 by 2050 in the Net Zero+ scenario and a minimum decline to around 2,600 MtCO_2 in the Net Zero CMSG+ scenario. Except for the Net Zero TSG+ and Net Zero+ scenarios, CO_2 emissions are projected to be greater than 2,000 MtCO_2. Positive CO_2 emissions reductions from 2020 to 2050 range from 40 percent to about 60 percent in the net-zero scenarios. Residual positive emissions are offset by large-scale deployment of negative emission technologies, especially DAC and BECCS.

Figure 2 shows residual CO_2 emissions and sectoral CO_2 emissions modeling results. There is no consistent definition of residual CO_2 emissions, but in the literature on energy systems modeling, "residual CO_2 emissions" is defined as emissions whose abatement remains uneconomical or technically infeasible under the assumptions of specific model and scenario constraints [30, 31]. The transportation and building sectors show the largest variation in residual CO_2 emissions between scenarios. Residual emissions in the net-zero scenarios for the transportation sector are larger than in other sectors for all scenarios, followed by those for the industry and building sectors. Residual CO_2 emissions positively correlate with DAC in all net-zero scenarios—lower DAC is associated with lower residual CO_2 emissions.

Results of the Net Zero+ scenario show reductions in gross emissions across the building, industry, and power sectors, as well as hydrogen production (with the largest reduction in the power sector) as compared to the reference scenario (the right stacked bar in Figure 2). Other net-zero scenario results demonstrate that in net-zero scenarios without advanced end-use sector technological assumptions, the transportation and/or building sectors' CO_2 emissions are 100–400 MtCO_2 higher than in the reference scenario. Industrial sector CO_2 emissions reductions are about the same in all scenarios due to a trade-off between sectoral CO_2 reductions and the cost of clean technologies for those reductions, primarily electrification.

[2] Dummy technologies in MARKAL are technologies with high variable O&M costs that are used only when the model cannot meet its demand with available technologies.

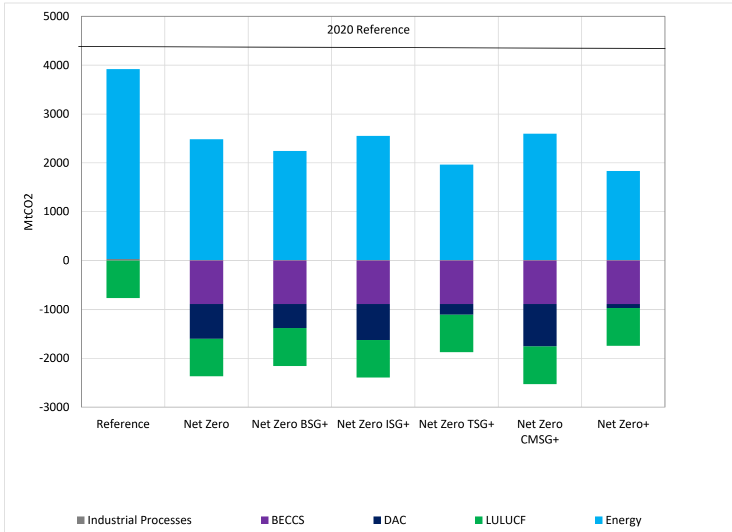


Figure 1. CO_2 emissions in 2050 for reference and net-zero scenarios; the stacked bars show 2050 reported CO_2 emissions, and the line shows gross 2020 energy and industrial process emissions from the reference scenario; industrial process emissions include only cement and limestone production emissions.

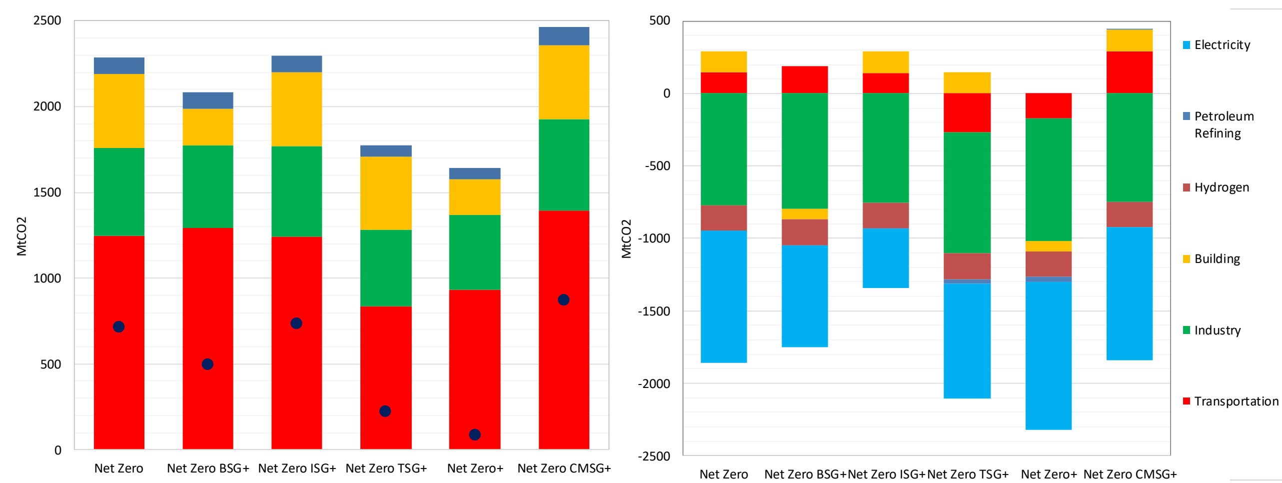
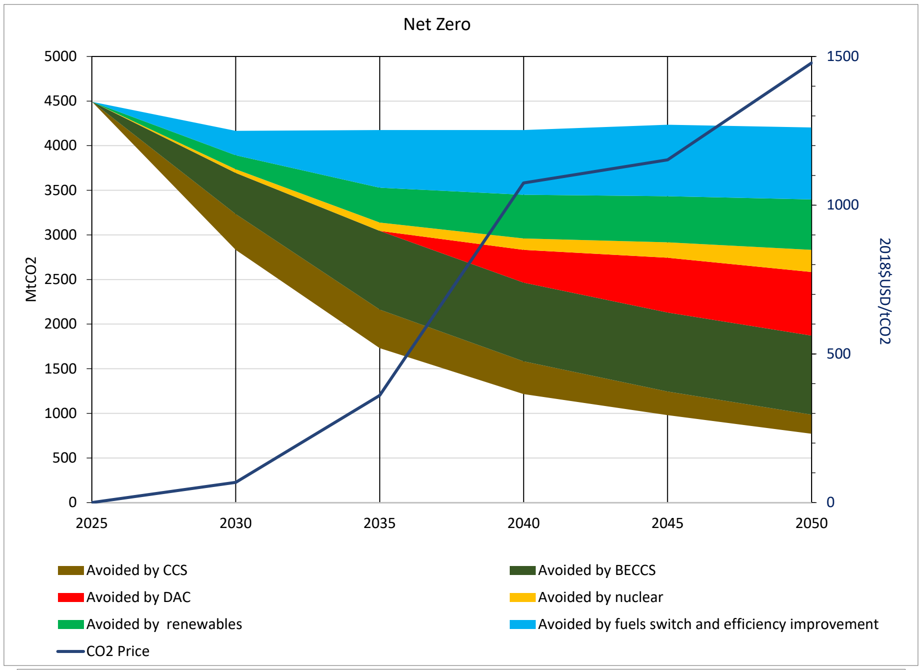


Figure 2. Sectoral CO_2 emissions for net-zero scenarios in 2050; the left stacked-bar graph shows residual sectoral emissions in the net-zero scenarios and DAC (dots) in 2050; the right stacked-bar graph shows the difference in sectoral emissions between the reference scenario and the net-zero scenarios.

In the MARKAL–NETL model, clean technologies in the building sector primarily include electrification and efficiency improvements (hydrogen was not included as a technological option in the building sector). Clean technologies in transportation include electrification, efficiency improvements, biofuels, and hydrogen. The modeling results show that decarbonization of the building and transportation sectors is more flexible than in the industry sector and depends on the costs of advanced clean technology and electricity.

In the industry sector, fossil fuels are currently the main source of energy and feedstock in the United States. Fossil fuels are particularly suitable for providing the high-temperature heat required by heavy industry production processes at a relatively low cost. In the MARKAL–NETL model, advanced clean technologies in the industrial sector include CCS, electrification, and efficiency improvements; however, hydrogen technologies are not presented in the industrial sub-module. Hydrogen and biomass-based technologies can reduce industrial CO_2 emissions; however, these technologies may not be compatible with various industrial production processes or may require different infrastructure. According to the modeling results, the industrial sector decarbonization level is inflexible and roughly the same in all scenarios, and it does not rely heavily on the availability of advanced technologies. The question remains whether it is difficult to decarbonize the industrial sector or difficult to model it. On the one hand, despite the urgent need to reduce CO_2 emissions, many studies show that the decarbonization of most high-emitting industries is not aligned with the net-zero CO_2 emissions goal [32], and one of the hard-to-decarbonize industries is the steel industry (including primary iron production). On the other hand, it is challenging to model material substitution, recycling, and dematerialization in the industrial sector into the future or to model related technologies that are unknown at present.

It is important to explore the relative contribution of reductions in CO_2 emissions by different technology clusters in more detail since future energy policies should leverage the projected technologies' successes. Figure 3– Figure 5 show technology contributions to reductions in CO_2 emissions in the net-zero scenarios compared to the reference scenario for 2025–2050. These figures do not include LULUCF, as it is an exogenous sink assumption that is identical in all scenarios.



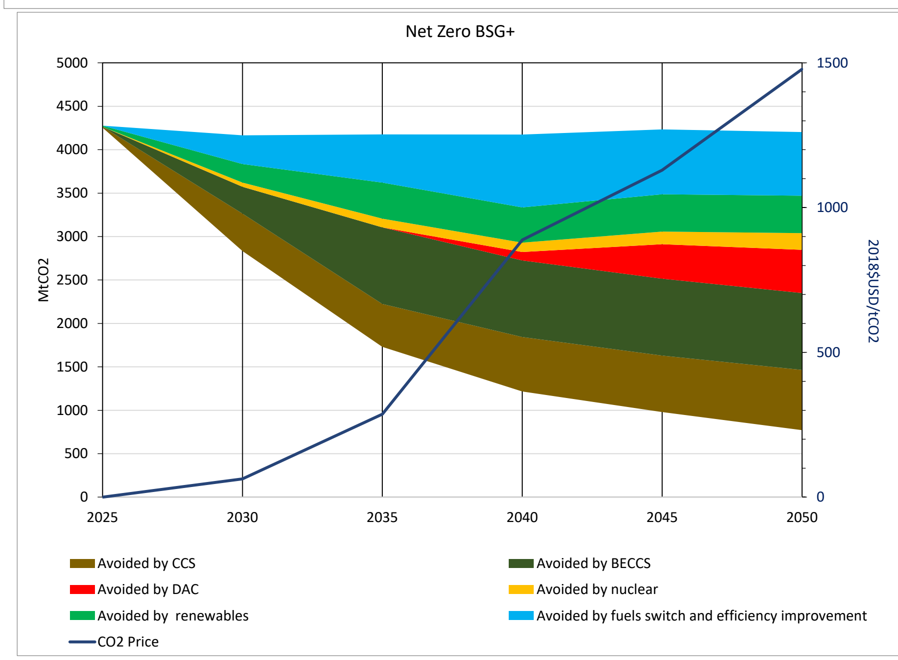


Figure 3. Contributions of CCS, BECCS, DAC, nuclear, renewables, and end-use fuels switching and efficiency improvements to CO_2 emissions reductions in the Net Zero scenario (top) and the Net Zero BSG+ scenario (bottom) in comparison to the reference scenario; lines show CO_2 emission prices in 2025–2050 (right axis values for each graph).

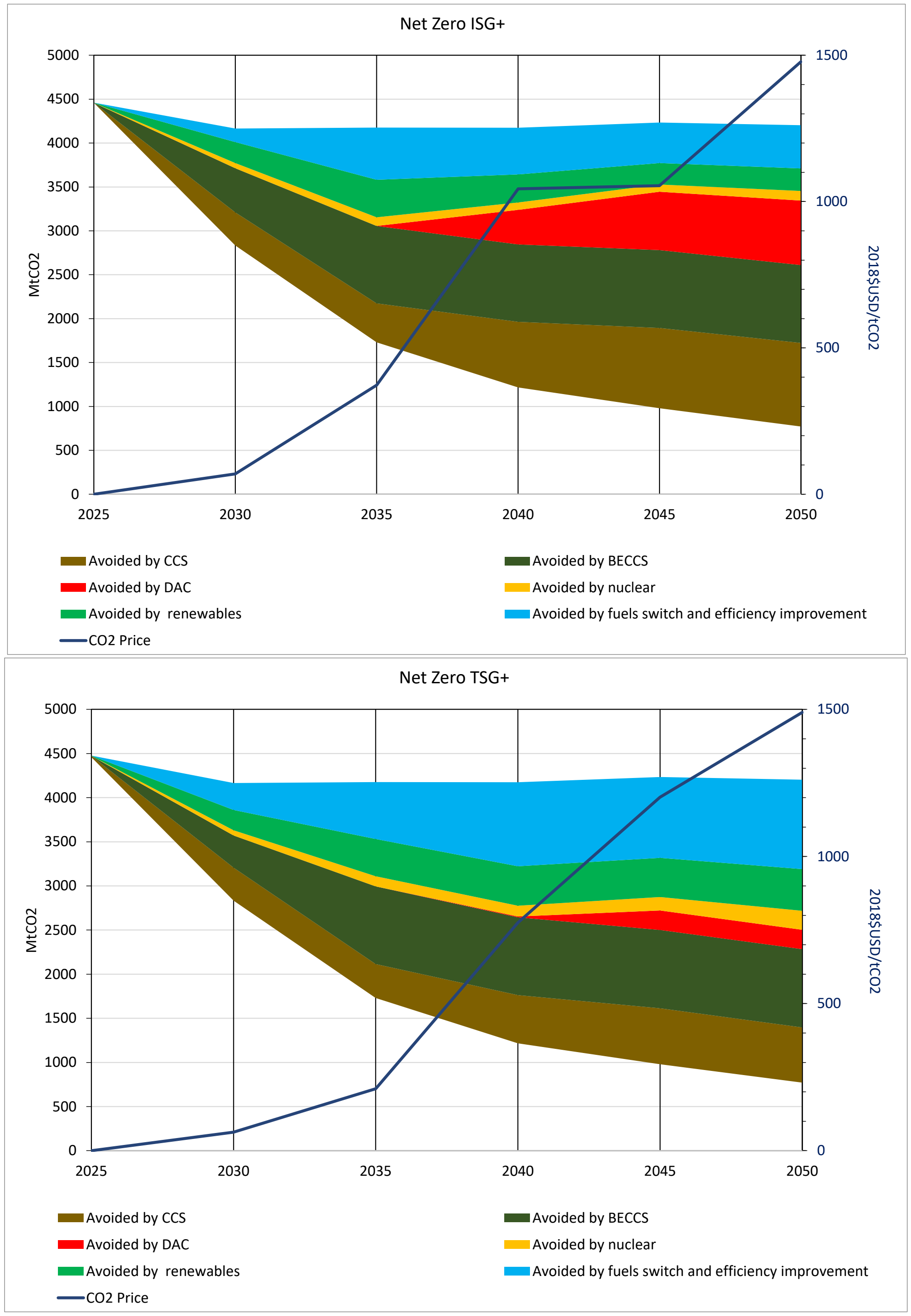
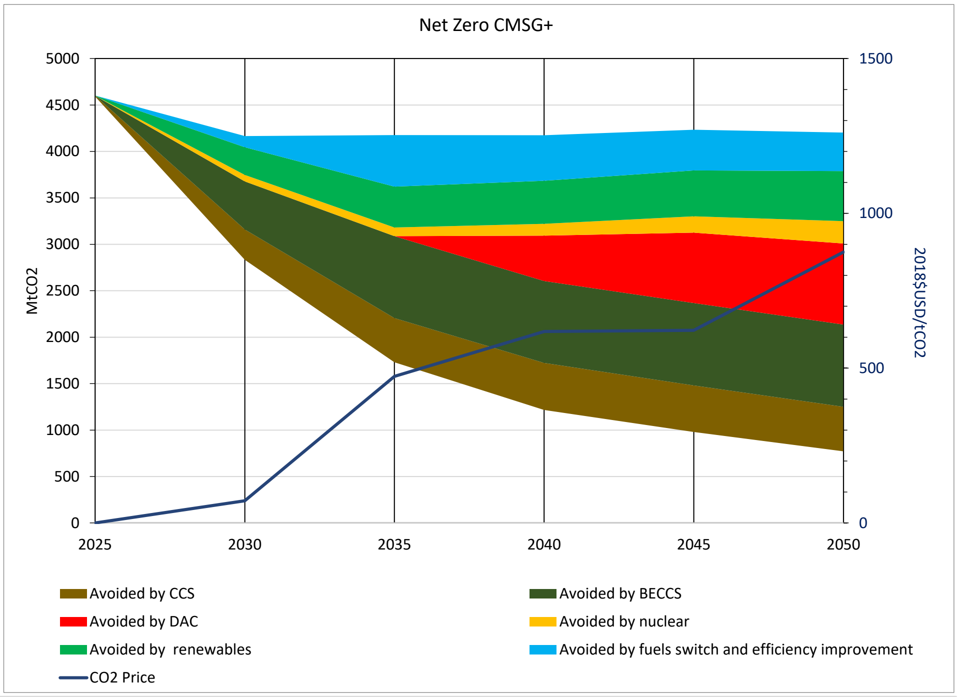


Figure 4. Contributions of CCS, BECCS, DAC, nuclear, renewables, and end-use fuels switching and efficiency improvements to CO_2 emissions reductions in the Net Zero TSG+ scenario (bottom) and the Net Zero ISG+ scenario (top) in comparison to the reference scenario; lines show the CO_2 emissions price in 2025–2050 (right axis values for each graph).



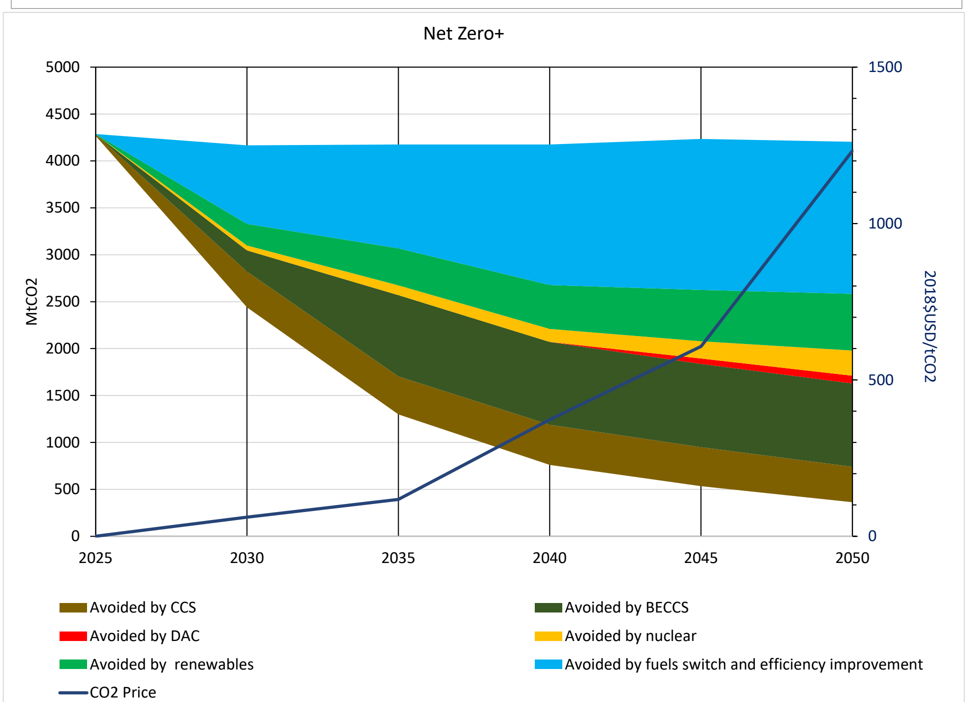


Figure 5. Contributions of CCS, BECCS, DAC, nuclear, renewables, and end-use fuels switching and efficiency improvements to CO_2 emissions reductions in the Net Zero CMSG+ scenario (top) and Net Zero+ scenario (bottom) in comparison to the reference scenario; lines show the CO_2 emissions price in 2025–2050 (right axis values for each graph).

In the short term, 36 percent of avoided CO_2 emissions will be via LULUCF and 11–25 percent will be via BECCS; therefore, CDR will be responsible for 50–60 percent of decarbonization by 2030 in all net-zero scenarios at a CO_2 price of \$60–70/tCO_2 (Figure 3–Figure 5). The next important decarbonization sources in the short term are fuel switching (e.g., shifts from coal to gas or from petroleum products to biofuels and electricity), efficiency gains, and CCS, and all are associated with 20–40 percent CO_2 reduction. By 2030, CO_2

emissions reductions due to renewables and nuclear deployments in the power generation sector will be roughly the same in all scenarios (approximately 250 $MtCO_2$ and 60 $MtCO_2$, respectively) and correspond to a 10–18 percent CO_2 reduction when combined.

In the EMF 37 study, the total use of CDR, including LULUCF, ranged from 1.2 GtCO2 (gTech) to 3.1 GtCO2 (FECM-15 NEMS) by 2050 [29]. According to the MARKAL-NETL model, CO_2 decarbonization through CDR will range from 1.7 GtCO2 (Net Zero+) to 2.5 GtCO2 (Net Zero CMSG+) by 2050. CO_2 decarbonization through CDR will range from 40 to 60 percent of CO_2 emissions reductions, with unchanged shares of BECCS and LULUCF (21 percent and 18 percent, respectively). Decarbonization through DAC technology fluctuates from 2 to 21 percent of total avoided CO_2 emissions and depends on net-zero scenario assumptions. The highest level of DAC deployment is in the Net Zero CMSG+ scenario (at a CO_2 price of \$875/tCO_2) and the lowest level is in the Net Zero+ scenario (at \$1,232/tCO_2). In the scenarios with end-use sector advanced technologies, the lowest level of CO_2 decarbonization by DAC is seen in Net Zero TSG+ (5 percent at a CO_2 price of \$1,490/tCO_2), and the highest is seen in the Net Zero ISG+ scenario (18 percent at \$1,478/tCO_2).

CO_2 emissions reductions through CCS technologies have a 5–23 percent range, with the lowest share in the Net Zero scenario and the highest share in the Net Zero ISG+ scenario. The contributions of fuel switching and efficiency gains in long-term decarbonization vary between 12 and 35 percent of CO_2 emissions reductions, while energy from nuclear and renewable sources is about 20 percent in all scenarios (excluding Net Zero ISG+, which has the highest level of CCS deployment). The average capture rate across the EMF 37 scenarios for fossil, bioenergy, and DAC is approximately 1.5 $GtCO_2$ in 2050—high values were roughly 2.6 $GtCO_2$ in 2050, and low rates were as little as about 0.4 $GtCO_2$ in 2050. The range of capture rate for CCS, BECS, and DAC across MARKAL-NETL scenarios is 1.3–2.6 $GtCO_2$ in 2050. FECM-NEMS and MARKAL-NETL had the highest cumulative capture of CO_2 among the three models. [29].

CO_2 prices in the Net-Zero scenarios are reported in the EMF 37 overview paper [1], with a range across models of approximately \$100 to \$1,500/tCO_2 in 2050, and exhibited considerable variation across models, and most models were within a range of \$400 to \$800/tCO_2. Nonetheless, the marginal cost of achieving net zero in 2050 was between two and 10 times higher without CCS and/or DACCS available (when CCS was not available, CO_2 prices ranged from \$1300 to \$2100/tCO_2) [29]. Figure 3 - Figure 5 show high CO_2 prices after 2035 (up to \$1,500/tCO_2). MARKAL-NETL has significantly higher carbon prices across all scenarios than the other models [29]; however, according to IPCC, CO_2 worldwide marginal abatement costs ranging from \$245/tCO_2 to \$13,000/tCO_2 would be needed to stabilize emissions below the 1.5 °C limit by 2050, which is between three to four times higher than for a 2 °C limit [33].

In the short term, by 2035, the total cumulative CO_2 abatement range is 29–32 $GtCO_2$ with a CDR share of 55–57 percent (Table 3). Beyond CDR, fuels switching and efficiency improvements (12–30 percent) and CCS (12–16 percent) play a significant role in total cumulative CO_2 abatement by 2035. The highest total cumulative CO_2 abatement (33 $GtCO_2$) is in Net Zero+ in comparison to 29 $GtCO_2$ in all other scenarios, which is mainly due to the higher level of CO_2 emissions through fuel switching and efficiency improvements (9.7 $GtCO_2$ in 2035).

Table 3. Cumulative CO_2 Abatement in 2025–2050 by Technology Group in 2035 and 2050 in $GtCO_2$

Technology Group	Net Zero		Net Zero BSG+		Net Zero ISG+		Net Zero TSG+		Net Zero CMSG+		Net Zero+	
	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050
LULUCF	9.76	19.70	9.76	19.70	9.76	19.70	9.76	19.70	9.76	19.70	9.76	19.70
BECCS	6.71	18.21	5.96	17.46	6.93	18.43	6.23	17.73	7.00	18.50	5.45	16.95
DAC	0.00	7.03	0.00	3.96	0.00	7.50	0.00	1.81	0.00	8.85	0.00	0.53
CDR Total	16.47	44.95	15.71	41.12	16.68	45.63	15.98	39.24	16.76	47.06	15.21	37.19
CCS	4.2	8.0	4.7	13.1	4.1	15.3	3.8	11.6	4.0	10.5	4.0	9.3
Nuclear	0.7	2.9	0.7	2.6	0.8	1.9	0.9	2.9	0.8	3.1	0.8	3.2
Renewables	2.7	9.5	3.2	8.7	3.3	6.9	3.3	9.1	3.7	10.1	3.1	10.0
Fuels switching and efficiency improvements	4.6	14.66	4.43	14.57	3.75	10.20	4.75	17.1	3.4	9.3	9.7	30.1
Total	28.65	79.96	28.72	80.03	28.66	79.97	28.71	80.02	28.69	80.00	32.82	89.87

By 2050, the cumulative CO_2 abatement range is 80–90 $GtCO_2$ with a CDR share of 41–59 percent. Fuels switching and efficiency improvements (12–30 percent of total cumulative CO_2 abatement) and CCS (10–20 percent of total cumulative CO_2 abatement) are more important than abatement from nuclear and renewables combined. The highest total cumulative CO_2 abatement (90 $GtCO_2$) is in Net Zero+ in comparison to 80 $GtCO_2$ in all other scenarios.

Cumulative captured CO_2 emissions through 2050 across models and scenarios ranged up to 42 $GtCO_2$ [29]. According to our results, cumulative captured CO_2 emissions of 27–41 $GtCO_2$ do not challenge existing storage resources, though matching capture sites and storage sites could be challenging, and more work to explore the implications of better representations of CO_2 storage capacity and reservoir fill rates at the sub-regional levels is needed.

4. Conclusion

U.S. mitigation of energy system pathways to reach net-zero CO_2 emissions by 2050 will include demand-side measures and improvements in efficiency and a transition to fossil fuels with CCS, BECCS, renewables and nuclear, and, in the long term, to DAC. The results show that in the MARKAL–NETL model, CDR technologies could substantially contribute to emission reductions in 2030–2050 under climate stabilization goals.

The combination of bioenergy and carbon dioxide sequestration creates an opportunity for net negative CO_2 emissions, and the most common pathway in the Net Zero scenario is BECCS [29]. Sequestration using BECCS varies widely across EMF 37 models (up to 1 $GtCO_2$ in 2050), and in MARKAL-NETL modeling results it is 0.9 $GtCO_2$ in all Net Zero scenarios by 2050. After 2035, DAC acts as a true backstop technology for the majority of deep decarbonization scenarios since (1) decarbonization rates through other CDR technologies have limits in the long term (i.e., BECCS has resource constraints and LULUCF is limited and exogenous); (2) energy service demand is exogenous in the MARKAL–NETL model (i.e., unchanged in all scenarios), and DAC does not produce energy but consumes it; and (3) the capital cost of DAC technology is assumed at a relatively high level at S1,255 10e6/PJ ($1,314/$tCO_2$). In comparison, BECCS has a capital cost of $4,921/kW ($445/tCO_2), and while available by 2030 in the model, DAC deployments start at the earliest by 2040.

In the EMF 37 study, some models rely on DAC for sequestration (up to 2.2 $GtCO_2$), and others use a combination of BECCS and DAC, and the marginal cost associated with net-zero CO_2 emissions exhibited considerable variation across models [29]. However, the literature shows low agreement in DAC cost estimates, and, according to the results of this study, a lower DAC capital cost increases its deployment and, for the most part, decreases investments in fuel-switching and efficiency improvements. A scenario with DAC as the only available CDR option was not run, but a net-zero scenario run without DAC resulted in dummy technologies in 2055–2075 and a CO_2 price of approximately $9,000/t$CO_2$ in 2050. Still, it is crucial that policies consider DAC as a complement to drastic CO_2 emission reductions while establishing supporting policies for clean technology deployment in energy end-use sectors.

Several caveats regarding this model and the results should be mentioned. The scenario projections are not predictions but only possible future pathways based on specific modeling assumptions. An assumption on terrestrial carbon sink of up to 800 MtCO_2 is highly uncertain [34]. Furthermore, behavioral changes are not captured in the model, and exploring the impact of those changes on the results could be an avenue for future work. An analysis of the cost of various DAC technologies and multiple sources of energy usage by DAC would be a fruitful area for future analysis. Also, water constraints were not included in this analysis, but the dependence of the U.S. energy sector on water and its scarcity or abundance will affect modeling results on the construction of new power plants and DAC in different regions. For example, efforts to expand biomass supply can increase the demand for water, land, and fertilizer, or have other ecosystem impacts. Thus, the assumptions regarding the technical aspects of biomass with CCS are considered to be realistic but could be unrealistic regarding the extent of bioenergy deployment. The spatial distribution of CDR technologies deployment that depends on considerable regional variation, such as biomass availability and suitable geologic CO_2 storage sites, was not presented in this study and is an area of forthcoming analysis.

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