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Bioenergy pathways within United States net-zero CO_2 emissions scenarios in the Energy Modeling Forum 37 study

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A B S T R A C T

The Energy Modeling Forum 37 study is organized around carbon dioxide (CO_2) mitigation scenarios reaching net-zero CO_2 emissions by 2050 in the United States. This paper summarizes the potential contribution of bioenergy use in the electric power, transportation, industrial, and buildings sectors toward meeting that target based on model results. Thirteen modeling teams reported bioenergy consumption in the Reference and Net Zero scenarios. Consumption of bioenergy increased over time in the Reference scenario, from an average across models of 3.2 exajoules (EJ) in 2020 to 3.8 EJ in 2050. Average bioenergy consumption in 2050 increased further to 7.3 EJ in the Net Zero scenario. All scenarios that reach net-zero emissions required some form of carbon dioxide removal to offset emissions that are difficult to reduce. Carbon dioxide removal using bioenergy with CO_2 capture and storage (BECCS) varies widely across models, up to 1000 Mt CO_2 in 2050. Some models rely instead on direct air carbon capture and storage (DACCS), up to 2200 Mt CO_2, and others use a combination of BECCS and DACCS. Model results show a strong inverse relationship between the amounts of BECCS and DACCS deployed. All modeling teams assumed a carbon sink from land use, land use change, and forestry, further offsetting a portion of emissions from fossil fuels and industry that are expensive to eliminate. Bioenergy consumption in 2050 decreased by an average of 1.5 EJ across eight models in a Net Zero+ scenario relative to the Net Zero scenario, due in part to a lower equilibrium carbon price resulting from optimistic cost assumptions for all energy technologies.

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1. Introduction

The Stanford Energy Modeling Forum (EMF) is a prominent model intercomparison project that provides policy-relevant analysis of energy and environmental issues such as energy security, energy efficiency, and climate change mitigation. This paper examines the role of bioenergy across models participating in the EMF 37 study on net-zero CO_2 by 2050 scenarios for the United States. Related prior studies include U.S. Technology and Climate Policy Strategies (EMF 24), Global Technology and Climate Policy Strategies (EMF 27), and Bioenergy and Land Use (EMF 33). Three papers from EMF 33 explored global options for future bioenergy demand [1], biomass supply [2], and bioenergy technologies [3] in long-run climate change mitigation.

The EMF 37 study specifically explores pathways to achieve economy-wide net-zero CO_2 emissions by mid-century in North America. Greenhouse gas emissions targets are based on CO_2 only, and are achieved either from reduced emissions, geologic storage, or increased terrestrial storage.[1] An EMF 37 overview paper has been published [5], but the study also includes papers from four study groups: carbon management [6], transportation, industry [7], and buildings. Additional cross-cutting papers focus on individual technologies and topics including the electricity sector [8], hydrogen [9], bioenergy (this paper), household distributional outcomes [10], air quality benefits [11], and policy implications of net-zero emissions [12].[2]

The largest sources of U.S. bioenergy today are wood in industry and residential buildings, and corn-ethanol in transportation. Other sources include municipal solid waste, biodiesel, and renewable diesel [13]. The fastest growing biofuel is renewable diesel, a drop-in fuel for existing diesel engines.[3] A key driver is the U.S. Renewable Fuel Standard which requires replacement of a portion of petroleum-based transportation fuels by bioenergy. In addition, the California Low Carbon Fuel Standard has a goal of reducing the carbon intensity of transportation fuels by at least 20 percent by 2030 [14]. Bioenergy feedstocks and their primary applications include wood in residential space heat, wood residues consumed by industry, municipal solid waste used in electric power generation, corn used to produce ethanol for transportation, and oil seeds used in biodiesel and renewable diesel production. In many cases, bioenergy feedstocks compete for land with other forestry and agricultural products, and some feedstocks compete directly for land with food production.

When combusted, bioenergy feedstocks emit CO_2 that was recently removed from the atmosphere by plants. Potential future uses of biomass include bioenergy with carbon dioxide capture and storage (BECCS), where the primary purpose is the generation of clean or carbon-negative energy, and fuels for hard-to-abate activities in the transportation sector: sustainable aviation fuel (SAF) and marine fuels [15]. Bioenergy use as a chemical feedstock is another possible role for biomass but one that is not yet reflected in many of the participating models. Production of a dedicated energy crop (e.g., switchgrass) for BECCS implies trade-offs such as competition for agricultural land and indirect land use change [16]. However, continuing increases in agricultural productivity could limit the need for expansion of agriculture into natural lands [17].

Many EMF 37 models rely on bioenergy to meet a 2050 net-zero CO_2 emissions target in the United States, especially in transportation and for carbon dioxide removal. We provide an overview across models of economy-wide bioenergy consumption, how bioenergy is allocated to energy sectors, and the contribution of biomass to carbon sequestration.

We address the following questions. How do models use bioenergy over time in a reference scenario versus a deep decarbonization scenario? Which sectors provide the greatest opportunity for bioenergy demand? What is the role of BECCS in meeting a net-zero CO_2 target? What are the implications for land use in a net-zero CO_2 scenario?

2. Study design

EMF 37 is organized around a Reference scenario and mitigation scenarios reaching net-zero CO_2 emissions by 2050. The emission reduction scenarios are specified with a linear emissions reduction path from 2020 reference emissions to net-zero CO_2 emissions by 2050. While the emissions pathways were specified as CO_2 only, modelers also applied the resulting carbon price or shadow price on carbon to non-CO_2 greenhouse gases or adopted a common assumption about land use contributions.[4] Modelers were encouraged to use a baseline calibrated to the U.S. Energy Information Administration's Annual Energy Outlook (AEO) 2022 [18]. Key drivers in AEO 2022 include projections to 2050 of U.S. population, gross domestic product, and the cost of electricity generation for solar, wind, and natural gas.

2.1. Reference scenario

The Reference scenario assumes no new federal or sub-national climate policies and no tax on CO_2 emissions. As in EIA's Annual Energy Outlook 2022, modelers were encouraged to include existing federal incentives for energy technologies as well as state policies (e.g., Renewable Portfolio Standards [19], California's Global Warming Solutions Act of 2006 [14]). The Inflation Reduction Act of 2022 was not included in the Reference scenario.[5] Modeling teams reported components of energy consumption and CO_2 emissions from 2020 through 2050 by year or five-year intervals depending on model resolution.

2.2. Net Zero scenario

The Net Zero decarbonization pathway is defined by a linear emissions reduction from 2020 to zero by 2050. The target includes CO_2 emissions from fossil fuel combustion and industrial processes. Non-CO_2 greenhouse gas emissions are excluded from the Net Zero emissions target. For models that do not estimate a carbon sink from land use, land use change, and forestry (LULUCF), a constant sink of 800 Mt CO_2 per year is assumed in the Net Zero scenario. This translates to a maximum reduction of fossil fuel and industrial CO_2 emissions of 87 percent in 2050, relative to emissions in 2020, with the 800 Mt CO_2 sink offsetting the remaining 13 percent of emissions. For models that can calculate their own LULUCF emissions, indirect land use change emissions from expanded bioenergy production should be reported as part of LULUCF emissions.

Estimates of historical LULUCF sequestration are published annually by the U.S. Environmental Protection Agency (EPA) [20,21]. A key feature of the estimates is a gradual decline of this sink between 1990 and 2022. Further, the time series of estimates was significantly revised upward between the 2023 and 2024 EPA inventories: the estimated sink for 2021 increased from 754 Mt CO_2 to 911 Mt CO_2 with the revision

[1] Emissions targets in this study are broadly consistent with the U.S. Global Change Research Program climate literacy guide [4]: "Limiting global warming requires net-zero carbon dioxide emissions globally: where emissions fall to zero, or remaining emissions are balanced by removal of carbon from the atmosphere. To keep warming well below 2 °C (3.6°F), global carbon dioxide emissions would need to reach net zero around 2050, along with substantial reductions of emissions of all greenhouse gases."

[2] The EMF 37 special collection consists of 19 papers, including other special topics.

[3] We use the term biofuel to refer to liquid forms of bioenergy, especially for transportation.

[4] The study included an optional net-zero all greenhouse gas by 2050 sensitivity scenario.

[5] This study was started before the Inflation Reduction Act (IRA) of 2022 was passed and therefore the Reference, Net Zero, and Net Zero+ scenarios do not reflect the various IRA tax credits and programs designed to incentivize various low-emitting technologies including biofuels.

between inventories.

Carbon dioxide removal technologies such as BECCS, direct air carbon capture and storage (DACCS), and natural carbon sinks from LULUCF were used by modeling teams to enable net-zero emissions by 2050. A carbon pricing policy was the primary economic incentive for emissions reduction and sequestration technologies. Each modelling team used their own default assumptions for technology costs in the Net Zero scenario.

2.3. Net Zero+ scenario

The cost of reaching net-zero CO_2 emissions depends on the availability of advanced technologies and the pace of cost reduction in key energy technologies such as solar, wind, and battery storage among others. The Net Zero+ scenario uses the same linear emissions reduction pathway as the Net Zero scenario, but with optimistic assumptions regarding the potential for electrification and decarbonization across the buildings, industry, transportation, electricity, and carbon management sectors. A wider set of technology options can alter the cost trajectory of reaching net-zero emissions by 2050. For electricity generation in the Net Zero+ scenario, advances in CCS technologies lower the cost of carbon capture and the cost of biomass energy with CCS. For transportation, rapid cost reductions for biofuel technologies improve competitiveness with fossil-fueled vehicles, although greater adoption of electric vehicles may reduce liquid fuel consumption.

The EMF 37 overview paper and supplemental materials [5] provide a comprehensive description of assumptions for the Reference, Net Zero, and Net Zero+ scenarios. All modelling teams participating in EMF 37 were encouraged to submit energy use, emissions, and economic results for all scenarios; however, not all scenarios and variables were submitted by all participants.

Table 1 lists sixteen models that report bioenergy consumption for the United States in the Reference scenario. Model characteristics vary from single-sector models (Scout, TEMPO) to coverage of all major energy sectors, such as electricity generation, industry, buildings, and transportation (AnyMOD, ENERGY 2020, EPA-TIMES, EPS, FECM-NEMS, MARKAL-NETL, NATEM, Temoa, US-REGEN) to coverage of energy and agriculture (GCAM, GCAM-USA) to economy-wide general equilibrium (ADAGE, FARM, gTech). Thirteen models reported results for the Net Zero scenario; eight models reported results for the Net Zero+ scenario. Use of CCS outside of electricity generation is limited: three models (GCAM, US-REGEN, and TEMOA) report using CCS with hydrogen production; two models (GCAM and US-REGEN) use CCS with biomass liquids production; and no model reports using CCS with biogas production.

3. Historical bioenergy accounting

The U.S. Energy Information Administration (EIA) reports historical U.S. bioenergy consumption in the Monthly Energy Review [13]. Models participating in EMF 37 rely on historical data for base-year calibration and the simulated trend from base year to present. Base years vary by model, but all models report energy consumption for 2020 as a point of comparison. Biofuels in transportation and wood as an energy source in industry are a challenge for model calibration. Total U.S. bioenergy consumption reported by EIA for 2020 was 4.8 exajoules (EJ).

Table 1
Models reporting bioenergy in the EMF 37 Reference scenario.

Model	Institution	Sectors	Spatial units	Bioenergy pathways	Reference
ADAGE	RTI International	Economy-wide (CGE)	U.S. + 7 other world regions	Wood, residues (crop and forest), energy crops, grain and cellulosic ethanol, bio-based diesel	[22,23]
AnyMOD	TU Berlin, ETH Zürich	Buildings, Industry, Transportation, Electric power	Federal states for the U.S., Mexico, and Canada	Wood, energy crops, corn ethanol	[24]
ENERGY 2020	Systematic Solutions, Inc.	Buildings, Industry, Transportation, Electric power	U.S. states, Canadian provinces, Mexico	Wood, energy crops, corn ethanol	[25]
EPA-TIMES	U.S. EPA	Buildings, Industry, Transportation, Electric power	9 U.S. regions	Wood, waste, residues, energy crops, corn ethanol, SAF	[26]
EPS	Energy Innovation	Economy-wide	U.S. (single region)	Wood, waste, energy crops, corn ethanol, bio-based diesel, SAF	[27]
FARM	USDA Economic Research Service	Economy-wide (CGE)	U.S., Canada + 11 other world regions	Wood, waste, energy crops, corn and cellulosic ethanol	[28]
FECM-NEMS	OnLocation, Inc.	Buildings, Industry, Transportation, Electric power	9 Census regions for demand, 25 electricity, 8 refinery regions	Limited BECCS (co-firing with coal for power generation), corn (with and without CCS) and cellulosic ethanol, biodiesel, renewable diesel, wood, waste	[29]
GCAM	PNNL	Buildings, Industry, Transportation, Electric power, Land use, Water, H_2, Macroeconomy	U.S., Canada, Mexico, + 29 other world regions	Wood, wood pellets, waste, residues, energy crops, corn and cellulosic ethanol, bio-based diesel, biogas, SAF, bio-H_2	[30]
GCAM-USA	PNNL and University of Maryland	Buildings, Industry, Transportation, Electric power, Land use	50 U.S. states + 31 other world regions	Wood, waste, residues, energy crops, corn and cellulosic ethanol, bio-based diesel, biogas, SAF	[31]
gTech	Navius Research Inc., Simon Fraser University	Economy-wide (CGE)	Canadian provinces + CA, OR, WA & rest of U.S.	Wood, waste, biogas, grain and cellulosic ethanol, biodiesel, renewable diesel	[32]
MARKAL-NETL	NETL	Buildings, Industry, Transportation, Electric power	9 U.S. regions	Wood, waste (biogas), energy crops, corn and cellulosic ethanol, bio-H_2	[33]
NATEM	ESMIA	Buildings, Industry, Transportation, Electric power	Canadian provinces + *U. S.* + Mexico	Wood, waste, residues, energy crops, corn ethanol, SAF	[34]
Scout	LBNL/NREL	Buildings	22 U.S. regions	Wood	[35]
Temoa	North Carolina State University	Buildings, Industry, Transportation, Electric power	9 U.S. regions	Wood, energy crops, corn ethanol, bio-H_2	[36]
TEMPO	NREL	Transportation	Urban, suburban, second city, small town, rural	Corn ethanol, bio-based diesel, SAF	[37]
US-REGEN	EPRI	Buildings, Industry, Transportation, Electric power	16 U.S. regions	Wood, residues, energy crops, corn and cellulosic ethanol, bio-based diesel, SAF, bio-H_2	[38]

Institutions: Research Triangle Institute (RTI); U.S. Environmental Protection Agency (EPA); U.S. Department of Agriculture, Economic Research Service (USDA ERS); Pacific Northwest National Laboratory (PNNL); National Energy Technology Laboratory (NETL); Lawrence Berkeley National Laboratory (LBNL); National Renewable Energy Laboratory (NREL); Electric Power Research Institute (EPRI). SAF = sustainable aviation fuels.

Bioenergy consumption is reported in the Monthly Energy Review by energy sector: transportation, industry, electricity generation, and buildings. Energy accounting is complex, especially for production of corn-ethanol and wood use in industry. There are interactions between energy sectors when bioenergy is an input to one sector, transformed into a different energy carrier, and consumed in another energy sector. For example, bioenergy can be used to generate electricity consumed elsewhere. EIA conducts regular surveys to collect statistically representative data on energy consumption by energy sector: Manufacturing Energy Consumption Survey [39], Commercial Building Energy Consumption Survey [40], and Residential Energy Consumption Survey [41].

Bioenergy consumption in four energy demand sectors from 2000 through 2024 is displayed in Fig. 1. There are significant energy losses in the conversion of shelled corn, animal fats, vegetable oils, and recycled grease feedstocks to ethanol, biodiesel, and renewable diesel. These losses appear as an industrial energy input in the “losses and co-products” time series. These losses appear in EIA bioenergy accounting but do not appear in energy balance tables used for calibration of energy-economy models. If the “losses and co-products” component is excluded, then total bioenergy consumption across sectors in 2020 (the year for comparison with model output) was 4009 petajoules (PJ), with 2068 PJ as wood energy, 464 PJ as waste energy, and 1478 PJ as liquid biofuels. Models vary in their ability to match this adjusted total and its components. Three models (FECM-NEMS, GCAM, NATEM) closely match the adjusted total.

Ethanol is a special case because it is produced in the industrial sector but consumed mostly in transportation. Ethanol production is a multi-input and multi-output technology with energy and non-energy outputs [42] that is difficult to fully capture in an energy-economy model. Inputs include shelled corn, natural gas, and electricity. Economically useful ethanol co-products include distillers’ grains (animal feed), corn oil, and a high-purity stream of CO_2 for carbonated beverages and potentially available for geologic storage. Approximately 62 percent of gross heat content of shelled corn ends up in ethanol [18]. The remainder are energy losses and energy embodied in co-products, which are assigned by EIA to the industrial sector as bioenergy input.

The largest biofuel inputs to **transportation** are ethanol, biodiesel, and renewable diesel. With incentives from the U.S. Renewable Fuel Standard, consumption of ethanol has remained stable from 2010 through 2023, except for a decline during 2020 when liquid fuel consumption dropped substantially due to impacts of the COVID-19 pandemic on transportation demand. Consumption of biodiesel has been relatively stable, but consumption of renewable diesel is rising rapidly [43]. While biodiesel and renewable diesel are derived from similar feedstocks, different production processes make these fuels distinct [44]. Biodiesel is produced through a chemical reaction, transesterification, and is typically blended with petroleum-based diesel fuel in concentrations of 2 to 20 percent biodiesel. Renewable diesel fuel is produced through a different process (hydrogenated vegetable oils) and can be used at concentrations up to 100 % in diesel engines without modification [13]. The largest feedstocks for renewable diesel in 2022 were yellow grease (waste fats and oils), soybean oil, corn oil, and beef tallow, but there are many other sources. Soybean oil was the largest source for biodiesel. Nearly all renewable diesel in the U.S. is consumed in California, with incentives from the state’s Low Carbon Fuel Standard [45]. Renewable diesel can provide a pathway to rapidly decarbonize heavy trucking and rail, provided environmental impacts from its production are minimized [46].

Industrial bioenergy consumption is dominated by wood and wood-derived fuels. The largest components are byproducts of paper production (e.g., black liquor), wood residues, and byproducts from mill processing (e.g., sawdust and shavings). Waste feedstocks include municipal solid waste from biogenic sources, landfill gas, and agricultural byproducts [13].

At present, bioenergy consumption for **electricity generation** is smallest of the four energy sectors. Bioenergy consumption is split nearly equally between wood and waste. Wood can be burned directly to generate electricity or wood chips can be burned with coal. Types of waste feedstock are the same as the industrial sector. Bioenergy consumption in the electricity sector has the potential to contribute to negative emissions processes, when linked with carbon capture and storage.

Bioenergy consumption in **buildings** is dominated by wood consumption (cord wood or wood pellets) for residential space heating. In 2020, wood consumption in buildings consisted of 364 PJ in residential buildings and 77 PJ in commercial buildings. Smaller amounts of waste (40 PJ) and ethanol (28 PJ) were consumed in commercial buildings [13].

4. Results

We first examine bioenergy consumption for each model, how bioenergy is divided among energy sectors, and how consumption changes over time and across scenarios. Three scenarios are reported in Fig. 2: Reference, Net Zero, and Net Zero+. In the Net Zero scenario, net CO_2 emissions in the U.S. are reduced to zero by 2050. Fig. 2 includes final bioenergy consumption for transportation, industry, and buildings. Bioenergy consumption for electric power is primary energy. In the Net Zero+ scenario, advanced energy technologies are available in each energy sector to reduce the cost of reaching net-zero CO_2 emissions. CO_2 prices in the Net Zero scenario are reported in the EMF 37 overview paper [5], with a range across models of approximately \$100 to \$1500 per t CO_2 in 2050.[6] However, most models were within a range of \$400 to \$800 per t CO_2. The overview paper also reported CO_2 prices for six models in the Net Zero+ scenario; prices were lower in the Net Zero+ scenario relative to the Net Zero scenario for the six models.

Reference scenario bioenergy consumption is displayed in the top row of panels in Fig. 2, for years 2020, 2035, and 2050. Three of the sixteen models focus on the use of bioenergy in a single energy sector, reporting results for the Reference scenario only: ENERGY2020 reports bioenergy consumption for electric power, Scout reports for buildings, and TEMPO reports for transportation. The general trend across other models is increasing bioenergy consumption over time. Average bioenergy consumption across thirteen models is 3.2 EJ in 2020, increasing to 3.8 EJ in 2050. In contrast, bioenergy declines over time in ADAGE because renewable technologies (solar and wind in electricity generation), advanced vehicle technologies (battery, fuel cell) continue to become cheaper and expand quickly to replace fossil, bioenergy, and conventional gasoline-ethanol vehicles even in the reference scenario.

Reported U.S. bioenergy consumption varies across models, including 2020, for many reasons. Each model contains a stylized representation of the energy system and a unique emphasis on a part of the energy-economy-agriculture system. Further, some models account for bioenergy consumption differently, depending on whether it is transformed to another energy form, or consumed as final demand. The first column in the 2020 panel reports the EIA 2020 benchmark, less the “losses and co-products” category for industrial biomass that represents biorefinery use of biomass energy to make final products. Three models (FECM-NEMS, GCAM, NATEM) are closely calibrated to this benchmark biomass total of 4.0 EJ in 2020.

The middle row of panels in Fig. 2 contains results for thirteen models that ran the Net Zero scenario. Average bioenergy consumption in 2050 is 7.3 EJ with wide variation across models. Some models report large increases in bioenergy consumption for electric power relative to the Reference scenario; other models report increases in biofuels for transportation. Industrial bioenergy consumption increases significantly in a few models, while bioenergy consumption in buildings is stable across scenarios and over time.

[6] All currency units are 2018 US\$

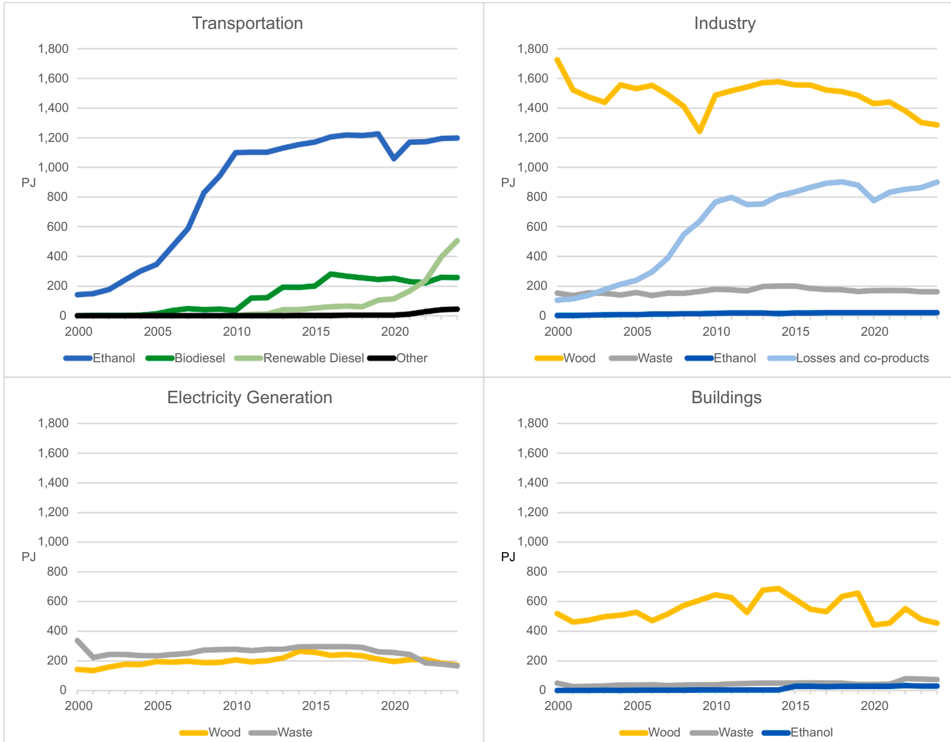

Fig. 1. Historical bioenergy consumption by energy sector (petajoules). Biodiesel is produced through transesterification of animal fats, oilseed crops, and recycled grease feedstocks. Renewable diesel fuel is produced from the same feedstocks through hydro-processing and is considered a drop-in replacement to petroleum-based diesel fuel. Losses and co-products from the production of ethanol are calculated as fuel ethanol feedstock plus denaturant (petroleum added to ethanol to make it undrinkable) minus fuel ethanol production. Wood as an industrial energy input is primarily wood residues, byproducts from mill processing, and byproducts from the paper production process (including black liquor). Wood use in buildings is primarily for residential space heating. Waste energy for electricity generation includes municipal solid waste from biogenic sources, landfill gas, sludge waste, agricultural byproducts, and other biomass.
Source: EIA Monthly Energy Review, May 2025.

Eight models reported bioenergy consumption in the Net Zero+ scenario. Bioenergy consumption in 2050 decreased by an average of 1.5 EJ across these models in the Net Zero+ scenario relative the Net Zero scenario, due in part to a lower equilibrium carbon price resulting from optimistic cost assumptions for all energy technologies.

Sector-specific models (e.g., Scout) contain detailed representations of energy technologies and capital investment decisions but might not be able to simulate the impact of carbon price in a Net Zero scenario. Partial-equilibrium economic models (e.g., GCAM-USA) can simulate energy consumption across energy sectors and geographic regions within the U.S., but usually not at the level of detail in a sector-specific model (e.g., TEMPO). Some models are computable general equilibrium with coverage of energy and non-energy sectors, and a carbon price applied to land emissions (e.g., ADAGE). Some models are global (e.g., ADAGE, FARM, GCAM), with greater input data requirements and representation of international trade. Global models usually represent the U.S. as a single region, lacking subnational detail.

Each model and associated output reflects decisions in model development about what questions can be addressed, coverage of energy and non-energy sectors, parameterization of energy technologies, and the economics of technology choice. The EMF 37 reporting template contains 1700 variables to cover a wide range of technology options and special features across participating models. The challenge for the modeler is to allocate time across model development, scenario coverage, and formatting model output for the reporting template. There are cases where a model can simulate a specific variable, but it was not reported due to time constraints. Lastly, models may have different boundaries between energy sectors than historical data reported by EIA (e.g., between commercial buildings and industry).

The next four figures break out bioenergy consumption by energy sector in the Reference and Net Zero scenarios. Each figure also includes consumption of other fuels for context.[7] There is a general increase in bioenergy consumption over time in both scenarios along with a decrease in fossil fuel consumption. The EIA 2020 benchmark is shown in the 2020 panel in each figure.

4.1. *Electric power*

In this section, we compare the amount of biomass to fossil fuels in the Reference and Net Zero scenarios. Biomass in the form of municipal solid waste and wood waste is an input to electricity generation, although in small amounts relative to fossil fuels in 2020 (Fig. 3). This amount increases over time in the Reference scenario in a few of the models (AnyMOD, FARM, GCAM). Most models report that coal declines as an input to electricity generation in the Reference scenario, while natural gas increases in 2035 but may increase or decrease in 2050 depending on competition with solar and wind.

In the Net Zero scenario, coal declines relative to the Reference scenario, with very little coal remaining as an input to electricity generation by 2050. Natural gas plus oil also declines relative to the Reference scenario but remains a significant input to electricity generation in 2050, with an average of 5.9 EJ across nine models. Average bioenergy input to electricity generation was 3.5 EJ, with a wide range across models from none in ADAGE to 9.1 EJ in FARM.

Except for ADAGE, all models in Fig. 3 use biomass with CCS to generate electricity in the Net Zero scenario by 2050. Several models

[7] For electric power, energy inputs for nuclear, hydro, wind, and solar are not shown to maintain a scale where biomass is visible.

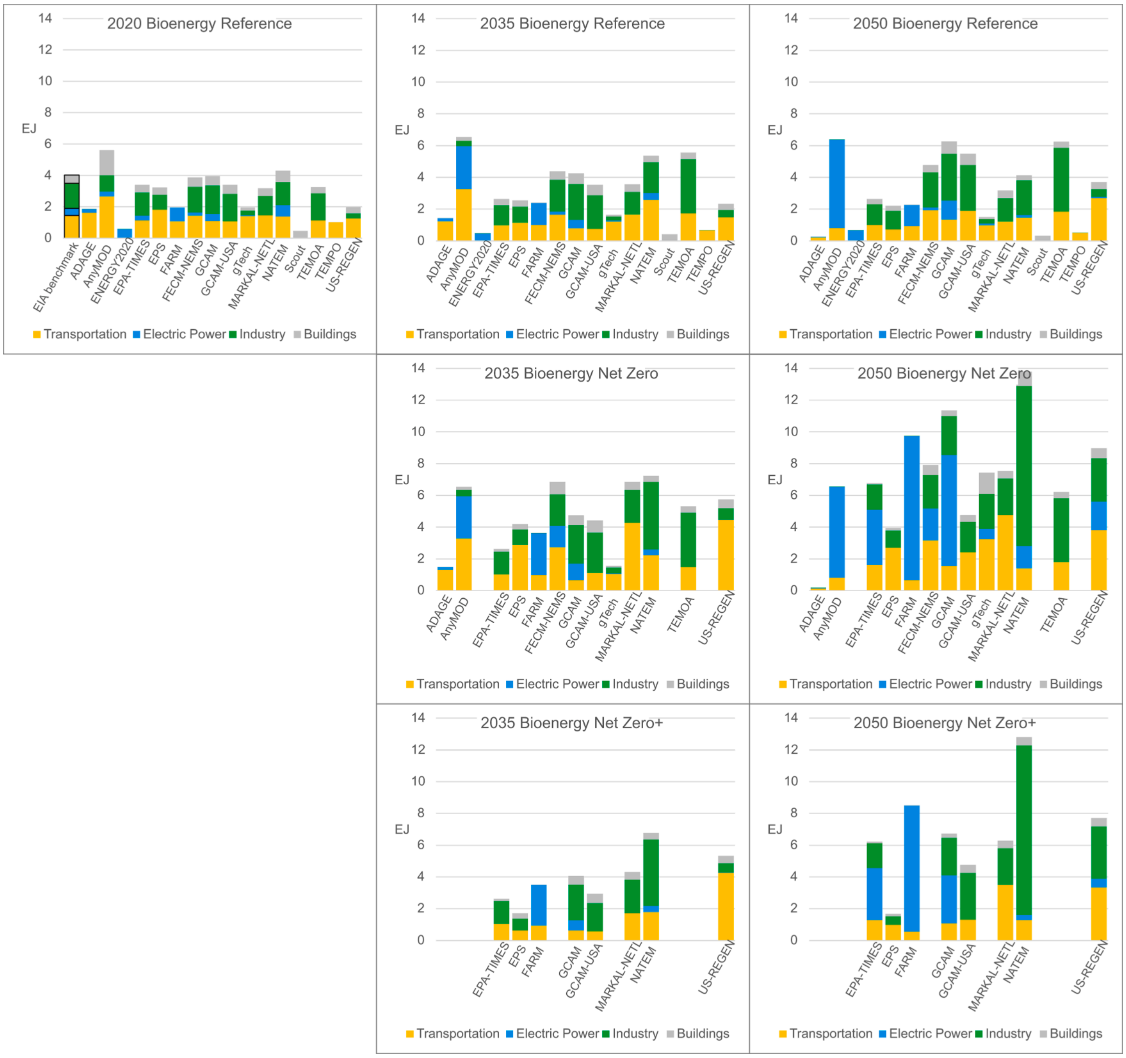

Fig. 2. Model projections of bioenergy consumption by energy sector (exajoules). Models are included if bioenergy consumption is reported in the Reference scenario. Bioenergy consumption for transportation, industry, and buildings is final energy. Consumption for electricity generation is primary bioenergy. The EIA benchmark in the top left panel excludes the "losses and co-products" component of industrial bioenergy consumption. Three of the sixteen models focus on bioenergy in a single energy sector, with results for the Reference scenario only (ENERGY2020, Scout, TEMPO). Thirteen models report results for the Net Zero scenario and eight models report Net Zero+.

with low amounts of BECCS use large amounts of DACCS to reach net-zero CO_2 emissions (ADAGE, FECM-NEMS, gTech).

Biomass feedstocks include forest and agricultural residues, perennial grasses, and short-rotation woody crops. Instead of calculating biomass supply endogenously, US-REGEN uses biomass supply curves from a U.S. agricultural and forestry model (FASOM-GHG) with subnational variation in land productivity [47]. Residues are used at the low end of the supply curve, but large-scale biomass supply requires dedicated energy crops that compete directly with land for food crops or pasture. Other models vary in the number of options for biomass supply, from a stylized perennial grass (e.g., FARM) to a range of residue and energy crop options (e.g., GCAM).

4.2. Transportation

Three major fuel types dominate energy use in transportation: oil products, biofuels, and electricity. The mix of fuels varies over time and across scenarios (Fig. 4). The general trend is for electricity to gradually replace some oil in the Reference scenario, but more so in the Net Zero scenario. Note that electric motors have a much higher efficiency of converting energy input to mechanical energy. Therefore, one EJ of electricity can displace more than one EJ of oil or biofuels in ground transportation. Some models also represent elastic demands or the option of switching transportation modes. In GCAM, GCAM-USA, and gTech for example, a carbon tax would result in changes in vehicle technologies, a shift of people across transportation modes (car sizes, buses, planes), and a decrease in passenger travel demand. Other models might not capture all of these. None of the models completely decarbonize transportation by 2050 in the Net Zero scenario.

Because traditional biofuels, such as corn ethanol and biodiesel, are usually blended with oil products, their use decreases with increasing electrification and decreasing reliance on liquid fuels. Newer bio-based technologies, such as Fischer-Tropsch (FT), pyrolysis, and renewable diesel can fully replace liquids as drop-in fuels. FT with CCS provides negative emissions, as does BECCS in power, but may not be represented in many models. Emissions reductions can also be achieved through CCS retrofits on existing corn ethanol plants.

Models vary widely in variables reported for biofuels in transportation: some reported only a biofuels total, while others reported a breakdown by transportation mode and freight vs. passenger. Two models reported significant amounts of SAF in 2050 in the Net Zero scenario: 1.2 EJ in EPA-TIMES and 1.6 EJ in EPS. The large increase in

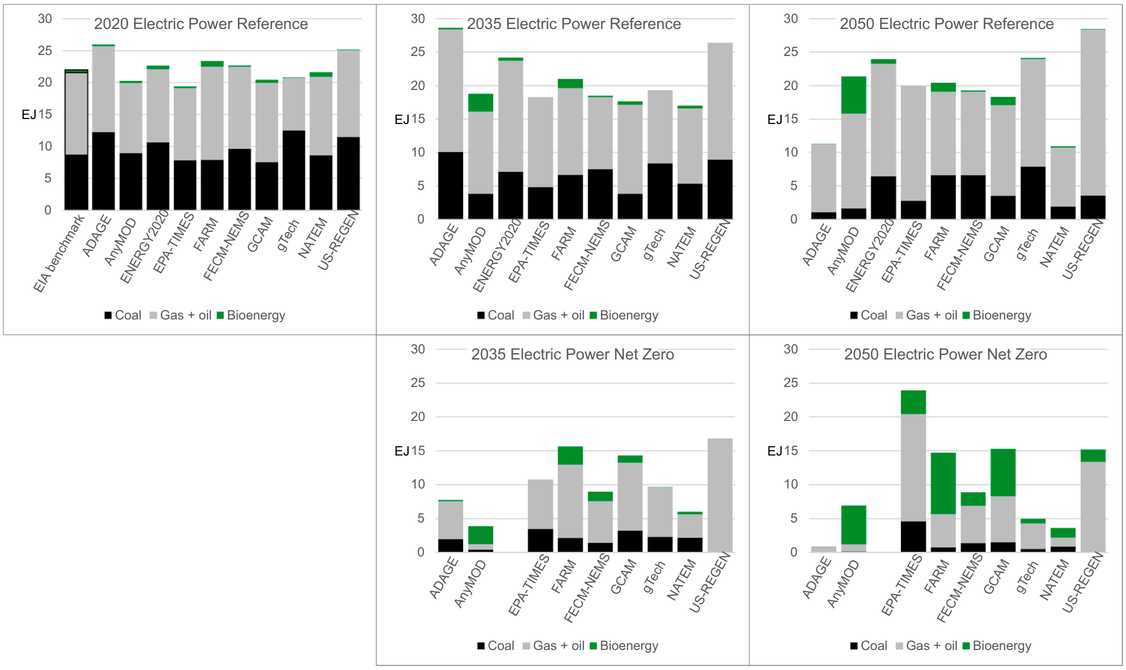

Fig. 3. Model projections of fossil and bioenergy consumption (exajoules) in **electric power**. Ten models report results for the Reference scenario, nine models for the Net Zero scenario. By 2050 in the Net Zero scenario, CCS is used for 91 percent of coal consumption, 83 percent of natural gas consumption, and 87 percent of biomass consumption (as an average across models). Energy inputs for nuclear, hydro, wind, and solar are not shown to maintain a scale where biomass is visible.

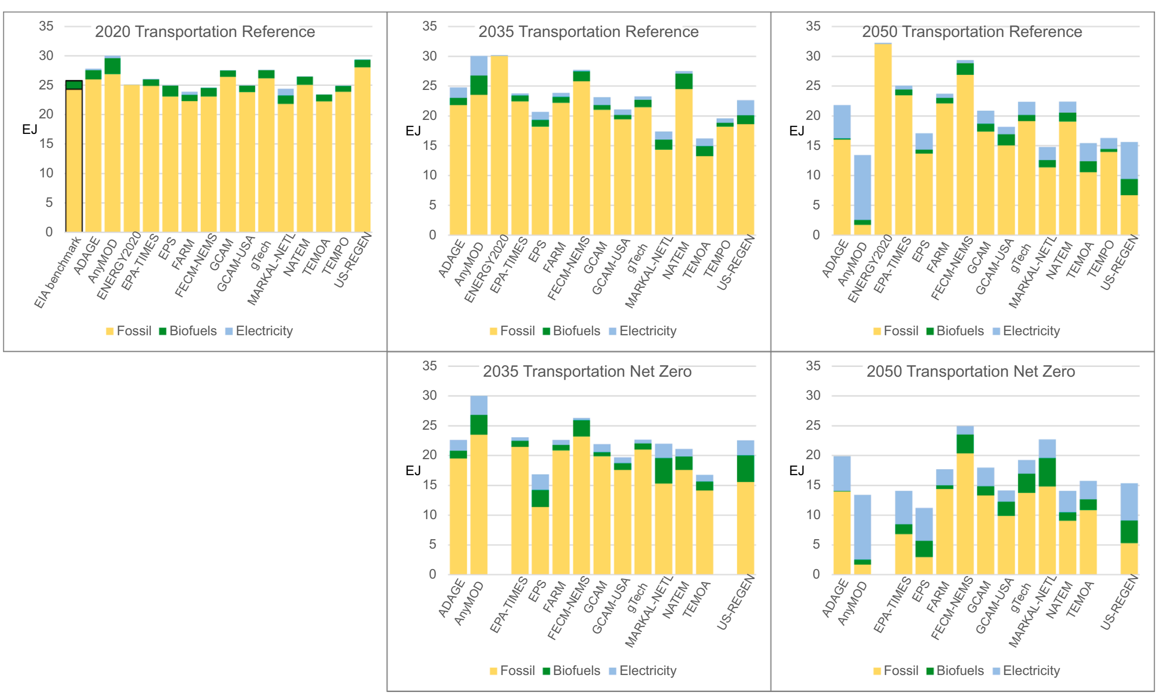

Fig. 4. Model projections of energy consumption for **transportation** by fuel (exajoules). Fifteen models reported energy consumption in the Reference scenario; thirteen models reported results in the Net Zero scenario. Electricity input to transportation is reported as captured energy (heat content of electricity). Two models reported small amounts of biogas in 2050 in the Net Zero scenario: gTech (0.08 EJ) and NATEM (0.15 EJ).

gTech biofuels is due to an increase of biomass liquids of 1.8 EJ for freight transport in 2050 relative to the Reference scenario. MARKAL-NETL reported an overall increase in transportation biomass liquids of 3.6 EJ. US-REGEN reported an increase of biomass liquids from 2020 to 2050 in the Reference scenario (1.5 EJ) and a further increase of 1.1 EJ in the Net Zero scenario, with increases spread over all modes of transportation.

4.3. Industry

As with transportation, none of the models could eliminate industrial consumption of fossil energy by 2050 in the Net Zero scenario (Fig. 5). Industrial bioenergy consumption increases over time in the Reference scenario, from an average of 1.0 EJ in 2020 to 1.4 EJ in 2050. Average consumption of bioenergy increased further in 2050 to 2.3 EJ in 2050 in the Net Zero scenario.

Average electricity consumption also increased across models, from 3.5 EJ in 2020 to 6.1 EJ in 2050 in the Net Zero scenario. Consumption of fossil fuels decreased over time in the Net Zero scenario, from 16.3 EJ in 2020 to 14.3 EJ in 2050.

Although not shown in Fig. 5, some models reported small amounts of biomass with CCS to produce hydrogen for industry in the Net Zero scenario (GCAM, Temoa, US-REGEN) [7]. Other pathways for hydrogen production in EMF 37 include electrolysis, natural gas with CCS, and coal with CCS.

In most models, there is little or no increase in biomass used in industry by 2050 in the Net Zero scenario. There are some exceptions: the NATEM model has a large increase in solid biomass combined with CCS in several industries; US-REGEN has an increase in biomass liquids for cement and food processing.

4.4. Buildings

Bioenergy consumption in residential and commercial buildings is small compared to total building energy consumption and remains so through 2050 in the Reference and Net Zero scenarios (Fig. 6). Historical bioenergy consumption in buildings is mostly wood for space heat, but some models allow for blending of biogas with the natural gas supply to partially decarbonize space and water heating technologies fueled by natural gas. For example, GCAM includes biogas as an option within natural gas supply. However, biogas accounts for a very small fraction (<1 percent) of gas supply in 2050 in the Net Zero scenario. This is mainly because GCAM does not include CCS with biogas and most bioenergy is in combination with CCS.

Relative to other energy sectors, there is little change in bioenergy consumption in buildings between the Reference and Net Zero scenarios. The major trends in buildings are gradually increasing electrification and corresponding declines in consumption of natural gas and oil.

4.5. Primary bioenergy

Some losses are expected in the transformation of one type of bioenergy to another as in the production of biomass liquids or biogas. Losses also occur in the use of bioenergy to produce hydrogen, which does not appear in earlier figures. These losses are shown in Fig. 7 as the difference between primary energy and bioenergy consumption reported earlier in Fig. 2.

A few models report large differences between primary and final energy, especially in the production of biomass liquids. For example, the US-REGEN model reports biomass liquid production of 7.2 EJ using 17.2 primary EJ of biomass, a difference of 10 EJ. The GCAM model reports biomass liquid production of 2.5 EJ using 4.8 EJ of primary biomass. Transformation losses also occur in the production of biogas and hydrogen.

4.6. Carbon sequestration

Much of the bioenergy input to electricity generation in the Net Zero scenario is combined with CO_2 capture and storage (CCS) to provide negative emissions. Some models rely only on BECCS for negative emissions, but others deploy a mix of BECCS and DACCS in 2050 in the Net Zero scenario. The relative role of BECCS in total carbon sequestration is shown in Fig. 8. Equilibrium models use a carbon price incentive for emission reductions relative to their reference scenario. Optimization models find a solution that meets the CO_2 emissions constraint, then report the shadow price of carbon. By study design, the carbon price in 2020 is zero and CCS is not used without a carbon price. There is some use of biomass in electric power in the Reference scenario, but none combined with CCS.

The combination of bioenergy and carbon dioxide sequestration creates an opportunity for net negative carbon dioxide emissions [48]. The most common pathway for offsetting residual emissions in the Net Zero scenario is BECCS. Carbon dioxide removal using BECCS varies widely across EMF 37 models, up to 1000 Mt CO_2 in 2050. In many models, BECCS primarily occurs in the power sector, but a few have significant BECCS for biofuels and one (NATEM) includes significant BECCS deployment in industry. Instead of BECCS, some models rely on DACCS for sequestration, up to 2200 Mt CO_2, and others use a combination of BECCS and DACCS. However, given the highly uncertain costs

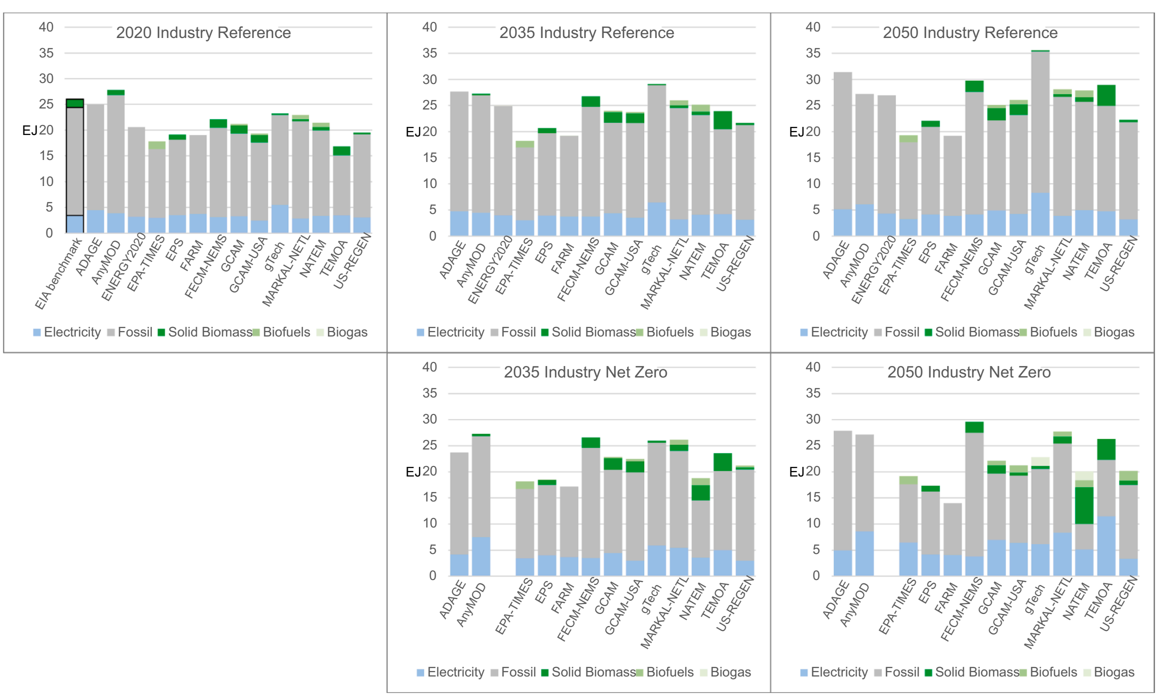

Fig. 5. Model projections of **industrial** energy consumption by fuel (exajoules). Fourteen models reported energy consumption in the Reference scenario; thirteen models reported results in the Net Zero scenario. Electricity input to industry is reported as captured energy (heat content of electricity).

Fig. 6. Model projections of energy consumption in **residential and commercial buildings** by fuel (exajoules). Fifteen models reported energy consumption in the Reference scenario; thirteen models reported results in the Net Zero scenario. Electricity input is reported as captured energy (heat content of electricity). In the Net Zero scenario in 2050, gTech reported 1.18 EJ of biogas, NATEM reported 0.76 EJ of biogas, and US-REGEN reported 0.26 EJ of bioliquid. Smaller amounts were reported by GCAM (bioliquid), GCAM-USA (bioliquid), and US-REGEN (biogas).

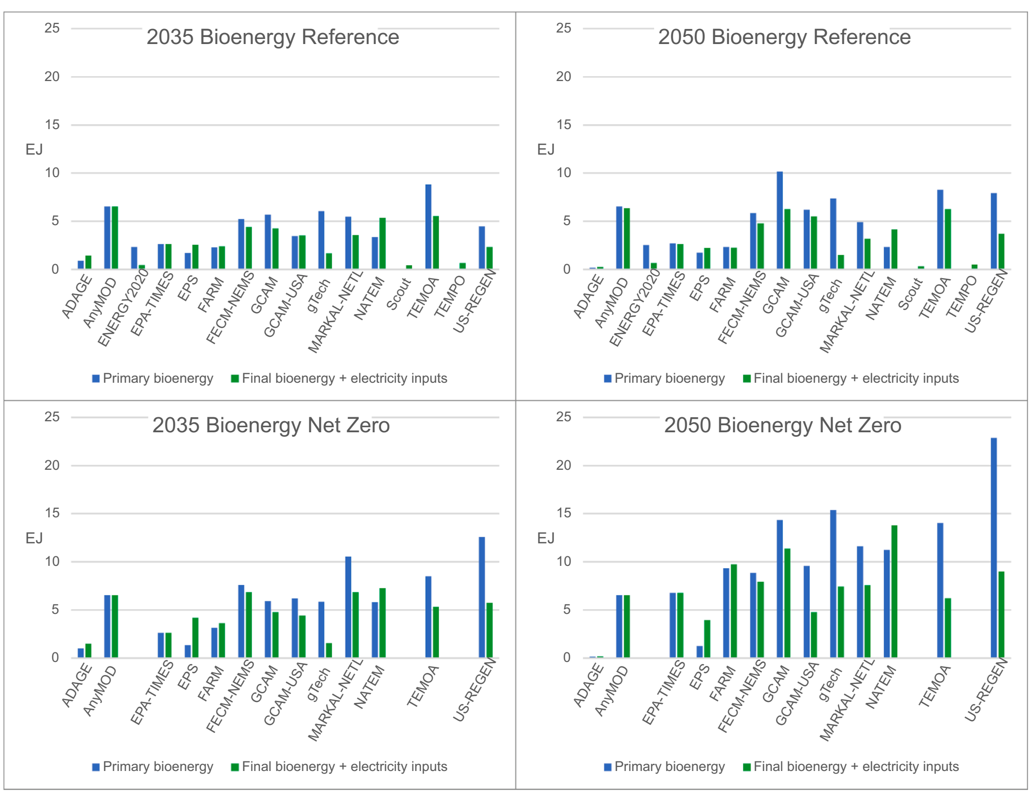

Fig. 7. Model projections of primary bioenergy compared to final bioenergy consumption plus inputs to electricity generation (sum of energy sectors in Fig. 2). The difference represents transformation losses from primary to consumed energy.

and scalability of DACCS facilities, BECCS is potentially an important use of biomass in a decarbonized future.

By 2050 in the Net Zero scenario, three major trends appear. First, there is a significant increase in biofuel consumption in transportation, especially for transportation modes that are difficult to electrify. Second, BECCS becomes very large in the electricity sector in some of the models. Third, for models with limited use of BECCS to achieve net-zero CO_2 emissions in 2050, DACCS provides additional carbon sequestration. For

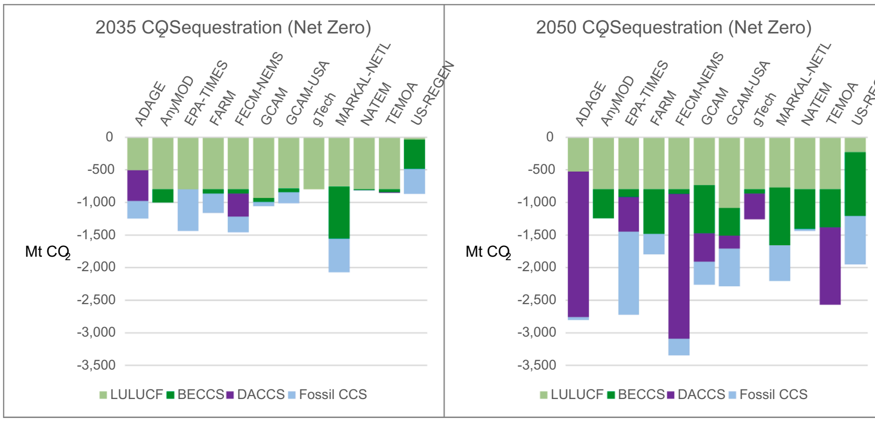

Fig. 8. Model projections of carbon dioxide sequestration (Mt CO_2 per year) in the Net Zero scenario. Carbon dioxide sequestration is zero in 2020 in the Net Zero scenario (except for LULUCF). The negative emissions technologies are bioenergy with CCS (BECCS) and direct air capture with storage (DACCS).

example, dedicated biomass with CCS is not included in FECM-NEMS but rather only biomass co-firing in coal plants. The ADAGE model has no representation of BECCS but instead relies on DACCS for carbon dioxide removal along with cleaner power generation and electrification.

5. Discussion

Biomass contributes to the attainment of net-zero CO_2 emissions targets in two major ways. First, through reductions in fossil fuel use by substituting bioelectricity, biogas, wood for heat, and biofuels for transportation. Second, by capturing carbon from the atmosphere that can be later stored geologically. For residual CO_2 emissions, EMF 37 models rely on several forms of carbon sequestration: bioenergy-fueled CCS paired with point-source emissions, DACCS, and land-based sequestration. For EMF 37 models, the cost and availability of DACCS is the primary determinant of the quantity of DACCS deployed, and indirectly the amount of biomass available for BECCS. Some models rely heavily on DACCS as a backstop technology, while DACCS might not be available or may be too expensive relative to other mitigation options to deploy in other models.

Models reported up to 1000 Mt CO_2 removed from the atmosphere annually through BECCS by 2050 in the Net Zero scenario. Biomass requirements can be approximated by first noting that dry switchgrass is approximately 47 percent carbon [49] which implies 1.72 t CO_2 emitted per ton of switchgrass combusted. At 90 percent CO_2 capture, at least 650 Mt biomass is required if switchgrass were used exclusively to remove 1000 Mt CO_2. This is within the range of estimates in the U.S. Department of Energy Billion-Ton Report [50] for dedicated energy crops, including herbaceous and woody energy crops, with a market incentive of \$130 per dry (short) ton of biomass. The Billion-Ton Report also estimates land requirements at 60 to 70 million acres (24 to 28 million hectares) for dedicated energy crops. For comparison, the four largest U.S. crops in 2017 in terms of area harvested were corn (90.8 M acres), soybeans (90.1 M acres), hay (56.9 M acres), and wheat (38.8 M acres) [51].

Wood and corn-ethanol dominate current uses of bioenergy in the United States. Industry is the largest consumer of wood for energy (using wood residue) followed by buildings (heating) and electricity generation. Ethanol from corn is blended into motor gasoline but the ethanol industry also produces marketable co-products: animal feed, corn oil, and a high-purity CO_2 stream of 45 Mt CO_2 per year [52]. The remaining carbon dioxide can be captured and transported to an area favorable for geologic sequestration [53]. Emerging biofuels include renewable diesel, SAF, and more advanced technologies using woody biomass feedstocks, such as FT (with and without CCS), pyrolysis, and cellulosic ethanol.

The greatest deployment of BECCS across models is in electric power generation, but some models provide examples of BECCS in other sectors. Three models report CCS used with biomass in hydrogen production for industry (GCAM, Temoa, US-REGEN). In the GCAM model, nearly all combustion and fuel transformations have the option to employ CCS. The NATEM model reports a large increase in solid biomass combined with CCS in several industries. FECM-NEMS uses CCS with corn-ethanol production.

From model results, the electricity generation and transportation sectors provide the greatest opportunities for expanded consumption of bioenergy. The range of biomass used across models for electricity generation in 2050 in the Net Zero scenario is 0.0 to 9.1 EJ, with a strong inverse relationship to the amount of DACCS used by models. The range of biofuel consumption for transportation in 2050 is 0.1 to 4.8 EJ, with larger levels corresponding to models with greater numbers of biofuel pathways and modes of transportation.

Key uncertainties for the future role of bioenergy include competition between BECCS and DACCS for large-scale carbon dioxide removal, the cost-competitiveness of advanced biofuels, the pace of electrification of ground transportation, and the demand for renewable diesel and SAF feedstocks. The main limitation of this study is the incomplete representation of bioenergy in key energy conversion sectors (e.g., liquids, natural gas, hydrogen) and complex industrial sectors (e.g., chemicals). This points out the need for model enhancements in these areas.

CRediT authorship contribution statement

Ronald D. Sands: Writing – original draft, Formal analysis, Conceptualization. **Liz Wachs:** Writing – original draft, Conceptualization. **Patrick Lamers:** Writing – original draft, Conceptualization. **Olivier Bahn:** Formal analysis. **Robert H. Beach:** Formal analysis. **Matthew Binsted:** Formal analysis. **Geoffrey Blanford:** Formal analysis. **Yongxia Cai:** Formal analysis. **Francisco De La Chesnaye:** Formal analysis. **James A. Edmonds:** Conceptualization. **Leonard Göke:** Formal analysis. **Chioke Harris:** Formal analysis. **Christopher Hoehne:** Formal analysis. **Gyungwon J. Kim:** Formal analysis. **Page Kyle:** Formal analysis. **Haewon McJeon:** Formal analysis. **Robbie Orvis:** Formal analysis. **Sharon Showalter:** Formal analysis. **Aditya Sinha:** Formal analysis. **Emma Starke:** Formal analysis. **Kathleen Vaillancourt:** Formal analysis. **Nadejda Victor:** Formal analysis. **Peter Volkmar:** Formal analysis. **John Weyant:** Conceptualization. **Frances Wood:** Formal analysis.

Declaration of competing interest

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

Geoff Blanford and John Weyant are editors for the special issue for which this manuscript is being submitted. 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.

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Supplementary materials

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