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SUPPORTING MATERIAL
Designs for Net-Zero Energy Systems: Meta-Analysis of U.S. Economy-Wide Decarbonization Studies

This document provides supporting information regarding the underlying methodology and data for the “Designs for Net-Zero Energy Systems: Meta-Analysis of U.S. Economy-Wide Decarbonization Studies” report.

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Metrics of Comparison and Base-Year Data

We compared the model-year 2050 results of the five evaluated studies across 12 metrics: primary energy, final energy,[1] buildings, industry, transportation, electricity generation capacity, electricity generation, hydrogen production, pipeline gas consumption, liquid fuel consumption, greenhouse gas emissions, and costs.

We leveraged centralized U.S. databases for most base year data. We obtained energy data from the U.S. Energy Information Administration (EIA)’s Annual/Monthly Energy Review (AER/MER) for the year 2022 whenever possible. Hydrogen production data was adapted from 2020 base-year data in the LCRI report. We assumed all pipeline gas in 2022 to be natural gas, then extracted the natural gas quantity for 2022 from EIA’s Natural Gas Consumption by End Use dataset.[2,3] We computed the energy-equivalent amount of liquid fuels used in 2022 by summing the respective amounts in the end-uses. Since GHG emissions data for 2022 was not yet available, we obtained data for 2021 from EPA’s Inventory of U.S. Greenhouse Gas Emissions and Sinks.[4]

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[1] Final energy was calculated by summing the energy consumed by the three end-uses: transportation, industry, buildings.
[2] U.S. Natural Gas Consumption by End Use (eia.gov)
[3] Heat Content of Natural Gas Delivered to Consumers (eia.gov)
[4] Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 – Main Report (epa.gov)

Metric	Definition	Meta-NZ Unit	Base Year Data
Primary Energy	Energy resources consumed at the source to supply all sectors	Exajoules (EJ)	AER 2022 Table 1.3
Final Energy	Energy resources consumed at the point of end use (transportation, industry, buildings)	Exajoules (EJ)	AER 2022 Tables 2.2-2.5
Transportation	Energy resources consumed in the transportation sector	Exajoules (EJ)	AER 2022 Table 2.5
Industry	Energy resources consumed in the industrial sector	Exajoules (EJ)	AER 2022 Table 2.4
Buildings	Energy resources consumed in the buildings sector	Exajoules (EJ)	AER 2022 Tables 2.2-2.3
Electricity Generation Capacity	Maximum power output from each source	Gigawatts (GW)	AER 2022 Table 7.7a
Electricity Generation	Total electrical energy generated from each source	Exajoules (EJ)	AER 2022 Table 7.2a
Hydrogen Production	Energy-equivalent amount of hydrogen produced by each pathway	Exajoules (EJ)	LCRI 2022
Pipeline Gas Consumption	Energy-equivalent amount of each type of gaseous fuel delivered through pipelines	Exajoules (EJ)	EIA 2023
Liquid Fuel Consumption	Energy-equivalent amount of each type of liquid fuel delivered	Exajoules (EJ)	AER 2022 Tables 2.2-2.5
Greenhouse Gas Emissions	Mass of positive, abated, and negative GHG emissions from all sources	Giga tonnes of carbon dioxide equivalent ($GtCO_{2e}$)	EPA 2023
Costs	Relative costs of net-zero scenarios as a percentage increase of that study's BAU scenario cost	Percentage (%)	N/A

Emissions Data

Studies differed in the greenhouse gases considered when solving for net-zero emissions. LCRI and OEO considered carbon dioxide only, whereas Princeton, EER, and DA considered non-CO_2 greenhouse gas emissions as well. The latter studies incorporated both the existing land sink and incremental growth of the land sink as part of the total negative emissions flows from the atmosphere. The LCRI study incorporated the incremental land sink only, whereas the OEO study did not incorporate the land sink. Studies also differed in how they categorized their emissions. LCRI, Princeton, DA, and EER reported emissions by source, whereas OEO reported emissions by sector only. These characteristics are summarized below.

Emissions	LCRI	OEO	Princeton	EER	DA
Gases	CO_2 Only	CO_2 Only	CO_2 and non-CO_2 GHGs	CO_2 and non-CO_2 GHGs	CO_2 and non-CO_2 GHGs
Land Sink	Incremental land sink only	Not included	Existing and incremental land sink	Existing and incremental land sink	Existing and incremental land sink
Categorization	By source	By sector	By source	By source	By source

The three studies leveraging the EnergyPATHWAYS model—EER, Princeton, and DA—had subtle differences in their non-CO_2 GHG and land sink calculations. The DA study assumed a fixed land sink contributing -0.85 $GtCO_2$/year and fixed non-CO_2 GHG emissions of 0.85 $GtCO_{2e}$/year across all scenarios. The magnitude of the land sink was thus equal to that of the non-CO_2 GHG emissions, such that the DA study effectively solved for net-zero CO_2 emissions under the condition of zero land sink. The Princeton study used the same fixed -0.85 $GtCO_2$/year value for land sink as DA but computed a higher fixed value of 1.02 $GtCO_{2e}$/year for non-CO_2 GHG emissions across scenarios. Adding land sink and non-CO_2 emissions gives an interim balance of +0.17 $GtCO_{2e}$/year. So, the Princeton study effectively solved for a way to reach -0.17 $GtCO_2$/year of CO_2 emissions. The EER ADP2022 study, unlike DA and Princeton, did not assume fixed values for land sink or non-CO_2 emissions. Both elements are included in the net-zero modeling solve for the study. So, the magnitudes of land sink and non-CO_2 emissions vary across scenarios.

Studies differed in their representations of ‘positive’ and ‘negative’ emissions. LCRI and OEO counted only the unabated component of fossil fuel emissions as positive emissions. Bioenergy with carbon capture and sequestration (BECCS) and direct air carbon capture with sequestration (DACCS) are counted as negative emissions. The EER, Princeton, and DA studies used a different reporting convention for indicating ‘positive’ and ‘negative’ CO_2 emissions. We harmonized the CO_2 emissions values to align with the reporting conventions in the LCRI and OEO studies. The table here provides an example of this adjustment, showing the original and harmonized CO_2 emissions results for the High Hydrogen Scenario from the EER study. The adjustments to this data entail three assumptions. First, the industrial process emissions are assumed to be associated with fossil fuel sources in all scenarios. Second, any CO_2 utilization first uses CO_2 captured from biogenic sources, then from direct air capture, and then from fossil fuel sources; the remaining captured CO_2 is geologically sequestered. Third, the bunkered emissions are deducted from the positive CO_2 emissions for the scenarios with fossil fuels but are assumed to represent biogenic sequestration in durable goods and counted as BECCS for the scenarios that restrict fossil fuels (EER’s 100% Renewables, Princeton’s E+RE+ and DA’s No Fossil).

Example CO_2 Emissions Conversion – EER High Hydrogen Scenario

Original CO_2 Emissions Data

Category	$GtCO_2$	Data Source
CO_2 - Oil	0.651	Fig. 42 from EER study
CO_2 - Coal	0.009	Fig. 42 from EER study
CO_2 - Natural Gas	0.348	Fig. 42 from EER study
CO_2 - Industrial Process	0.125	Fig. 42 from EER study
CO_2 - Product and Bunker	-0.376	Fig. 42 from EER study
CO_2 - Geologic Sequestration	-0.559	Fig. 42 from EER study
CC - Direct Air Capture	0.000	Fig. 13 from EER study
CC - Biofuels Production	0.501	Fig. 13 from EER study
CC - Blue Hydrogen	0.110	Fig. 13 from EER study
CC - Power Generation: Bio	0.000	Fig. 13 from EER study
CC - Power Generation: Gas	0.000	Fig. 13 from EER study
CC - Industrial Process	0.098	Fig. 13 from EER study
CCU - gas	0.000	Fig. 12 from EER study
CCU - liquids	0.145	Fig. 12 from EER study
CCS	0.559	Fig. 12 from EER study

Harmonized CO_2 Emissions as Reported in this Meta-Analysis

Category	$GtCO_2$
Abated CO_2 via CCS	0.209
CO_2 Emissions	0.548
DACCS	0.000
BECCS	-0.356

Steam Data

The EER, Princeton, and DA studies—all used the EnergyPATHWAYS model—included steam as a separate category in final energy and the end uses. The LCRI and OEO studies did not include steam as a separate category. Hence, steam was decomposed into the input energies used to produce the steam. Boiler efficiencies in EnergyPATHWAYS were 99% for electric boilers and 80% for non-electric (fuels-based) boilers. An example of the input energy calculation: if 4 EJ of steam is produced from a pipeline gas boiler, and the efficiency of this gas boiler is 80%, then 5 EJ of pipeline gas was consumed to make this steam. We assumed that the proportion of each steam source is the same for each end use where steam is used (Buildings and Industry).

Cost Data

Studies differed in how they calculated and reported the costs of scenarios. These methods and results are summarized in this section.

Low Carbon Resources Initiative

LCRI calculated annual economy-wide expenditures on delivered energy in Figure 19 of their report. The following text is copied from page 37 of their report. "For the Reference scenario, there is a roughly 30% decline in real economy-wide energy costs in 2050 relative to today, which with assumed growth in population and GDP implies a 45% reduction in total energy costs per capita and a 60% reduction in total energy costs as a share of GDP. In the net zero scenarios, total energy costs increase significantly, ranging from a roughly 33% increase relative to the Reference case in the Net-Zero All Options scenario to more than double the Reference case level in the Net-Zero Limited Options. As a share of projected GDP in 2050, these increases translate to 0.7% and 3.3%, respectively."

			2050 Net-Zero Scenarios		
Figure 19 of LCRI Report	**2020**	**2050 Reference**	**All Options**	**Higher Fuel Cost**	**Limited Options**
Expenditures (trillion $2015)	1.2	0.8	1.1	1.4	2.1
GDP (trillion $2015)	20.1	37.0	37.0	37.0	37.0
Share of GDP	5.9%	2.3%	3.0%	3.8%	5.6%

Open Energy Outlook

OEO calculated discounted and undiscounted investment costs for all scenarios in Figure 11 of their report. They also reported the (cumulative) discounted present value of system costs in Figure 10 of their report, summarized below. The following text is copied from page 13 of their report. "The investment costs in Figure 10 include the costs to replace existing energy assets as they reach their end of life and the costs of new assets needed to meet the growing demand for services and energy carriers."

Figure 10 of OEO Report	No Policy	State Action	COP26	Net Zero
Investment	16.5	17.6	17.4	18.9
Fixed O&M	1.9	1.9	2.3	2.3
Variable O&M	23.0	24.2	24.0	25.8
Fuel	12.6	10.6	10.7	10.6
Total (trillion $)	54.1	54.2	54.5	57.5

Evolved Energy Research

EER computed gross and net annual costs for all scenarios in Table 3 of their ADP 2022 report. EER defined gross costs as "the annualized cost capital and operating cost for both energy supply (electricity and fuels) and energy end-use technologies (in vehicles, buildings, factories, etc.)" on page 45 of their report. Net costs for net-zero scenarios reflect the avoided costs of avoiding expenditures on fuels.

Table 3 of EER Report	Baseline	Central	Drop-In	High Hydrogen	Low Demand	Low Land	Slow Demand	100% Renewables
Gross Cost (trillion $)	1.3	1.5	1.8	1.6	1.2	1.6	1.6	1.7
Net Cost (trillion $)	N/A	0.2	0.5	0.3	N/A	0.3	0.3	0.4
GDP (trillion $)	40.1	40.1	40.1	40.1	40.1	40.1	40.1	40.1
Gross Cost - Share of GDP	3.2%	3.8%	4.5%	4.0%	3.0%	3.9%	4.0%	4.2%
Net Cost - Share of GDP	N/A	0.6%	1.2%	0.8%	N/A	0.7%	0.8%	1.0%

Princeton

Princeton reported more detailed financial calculations in their Annex A.1 and in their data published online, stating capital and fixed O&M costs for each type of energy infrastructure, along with cumulative capital expenditures for both demand-side and supply-side investments. For simplicity, we have summarized the total annualized costs only below.

Data from NZA website & Annex 1	REF	E+	E-	E-B+	E+RE-	E+RE+
Total – Annualized (trillion $2018)	1.2	1.7	2.1	1.8	1.7	2.2
GDP (trillion $2018)	38.4	38.4	38.4	38.4	38.4	38.4
Share of GDP	3.2%	4.5%	5.5%	4.6%	4.3%	5.7%

Decarb America

DA did not report costs.

Scenario Definitions

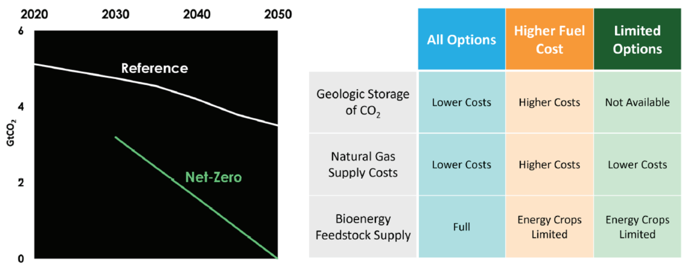
The five selected studies consist of 31 different scenarios. Scenarios differed by assumptions about supply, costs, and service demand. Each study had one business-as-usual (BAU) or reference scenario that modeled 2050 energy values assuming no new major policies were implemented. There were 23 variations of net-zero scenarios across the five studies. OEO and DA had two and one 'Other' scenarios respectively that modeled the effects of policies with less ambitious decarbonization targets.

The text and graphics in this section were copied from the study reports.

Low Carbon Resources Initiative

The following text and image were copied from pages 15 to 18 of the LCRI report.

Scenario Definition



	All Options	Higher Fuel Cost	Limited Options
Geologic Storage of CO_2	Lower Costs	Higher Costs	Not Available
Natural Gas Supply Costs	Lower Costs	Higher Costs	Lower Costs
Bioenergy Feedstock Supply	Full	Energy Crops Limited	Energy Crops Limited

"This study considers several scenarios for alternative assumptions about key input parameters. In each scenario, the model is used to solve for a least-cost allocation of resources and technologies to meet projected energy service demands while achieving a specified policy target for emissions. In the Reference scenario, only existing state-level policy targets are included, with no new state or federal policies or incentives. This analysis does not include the specific incentives in the recently enacted Inflation Reduction Act. Each of the other scenarios in this analysis assumes a target of economy-wide net-zero energy-related CO_2 emissions by 2050, which aligns with the stated goals of the Biden administration and several other public and private entities."

"The scenarios described in this analysis were chosen to show a range of different pathways for low-carbon technologies and to highlight key strategic trade-offs that arise in the context of an economy-wide net-zero framing. These scenarios should not be interpreted as likely or expected futures but rather as illustrative examples of how optimized model results depend on the range of input assumptions. Further LCRI research will build on this analysis to explore a broader range of scenarios around uncertainty in future technology development and other drivers.

NET-ZERO ALL OPTIONS SCENARIO

The All Options scenario assumes that the full portfolio of clean energy technologies is available, including renewables (solar, wind, and hydropower), nuclear, fossil and bioenergy with carbon capture and storage (CCS), electricity storage (e.g. battery storage and pumped hydro), hydrogen and hydrogen-derived fuels (e.g., synthetic jet fuel and synthetic natural gas), and biofuels (e.g., renewable natural gas and renewable diesel). Direct air capture technologies and opportunities for natural climate solutions are also available in this scenario. Future cost and performance improvements over time are assumed for most technologies, at varying rates (see us-regen-docs.epri.com for details). This scenario also assumes sustained low prices for the domestic production of natural gas, similar to recent projections (e.g., the Annual Energy Outlook 2022 Reference case).

NET-ZERO HIGHER FUEL COST SCENARIO

In the All Options scenario, natural gas, advanced cellulosic biofuels, and CCS, among other low-carbon technologies, each play a prominent role in the modeled least-cost net-zero energy system…These results are conditional on several key uncertainties: parts of these technology pathways are not yet proven at scale; cellulosic biomass feedstock supply costs and available quantities are uncertain and subject to land use and other constraints; and recent geopolitical events have raised the possibility of long-term disruptions in global fuel markets. In the Higher Fuel Cost scenario, all technologies are available, but with higher costs for the transport and geologic storage of captured carbon, tighter supply assumptions for bioenergy feedstocks, particularly energy crops and logs, and higher supply costs for natural gas and petroleum, to explore the sensitivity of trade-offs with other low-carbon pathways to these uncertain parameters."

"NET-ZERO LIMITED OPTIONS SCENARIO

The Limited Options scenario assumes that geologic storage of CO_2 is not available, whether for technical, regulatory, or other reasons. This limitation leads to a very different strategy for achieving net-zero emissions, as it significantly restricts the potential scale of negative emissions. Additionally, this scenario assumes that bioenergy supply is limited, as in the Higher Fuel Cost case. This scenario assumes reference natural gas and petroleum prices, although the emissions target in this scenario results in much smaller market size for fossil fuels given the limited potential for negative emissions. All other technologies are available in this scenario."

Open Energy Outlook

The following text was copied from pages 4 and 5 of the OEO report.

“This report focuses on a series of policy scenarios highlighting the interplay between policy and technology to achieve deep reductions in CO_2 emissions by 2050. The scenarios described below are meant to cover a wide range of plausible outcomes that lead to varying degrees of emissions reduction.

No new policy beyond 2021 (‘No Policy’)

This scenario assumes that all existing policies as of the end of 2021 remain in their current form, and no new federal or state policies are implemented. The results indicate how projected fuel prices and technology costs will shape the energy system in the absence of climate policies. A no-policy baseline provides a valuable point of comparison to the policy scenarios. The policies included in this scenario represent the policies in place by the end of 2021: state-level Renewable Portfolio Standards (RPS), the Cross-State Air Pollution Rule (CSAPR), the California cap and trade program, and the federal Investment Tax Credit (ITC). Note that these existing policies are also included in the other scenarios described below. In this No Policy scenario, exogenous fuel prices are set based on the EIA Annual Energy Outlook (AEO) 2022 Reference case.

It is worth noting that in August of 2022, the U.S. Congress passed the Inflation Reduction Act (IRA), which allocated ~ $385 billion in funding for climate mitigation activities between 2022 and 2031. This report does not include an explicit analysis of the IRA provisions. We do, however, explore how the provisions in the IRA align with the results of the scenarios included in our modeling efforts and their associated results.

State-level action in the absence of federal policy (‘State Action’)

This scenario considers the possibility of ambitious state-level action to reduce CO_2 emissions without any new federal policy beyond what was available by the end of 2021. The scenario assumes that a collection of U.S. states will implement legislation to achieve net-zero CO_2 emissions from electricity by 2050. To select the states that would most likely pursue such a policy, we include those states with a renewable or clean energy policy and that have demonstrated a potential willingness to pursue more ambitious actions (e.g., voting history). Figure 1 shows the states with net-zero targets for power generation in this State Action scenario. This scenario is not meant to serve as a policy forecast but rather an ambitious yet plausible scenario where a subset of state governments take action to reduce emissions. The results inform the degree to which bottom-up, state-level action can reduce emissions compared to the scenarios involving federal action. In this scenario, exogenous fuel prices are set based on the EIA AEO 2022 Low Oil Price case, consistent with price impacts from reductions in petroleum demand.

UNFCCC COP26 commitments (‘COP26’)

This scenario includes the policy commitments in the U.S. Nationally Determined Contribution (NDC), submitted to the UNFCCC as part of the COP26 negotiations. Compared to the No Policy scenario, the results from this scenario indicate how international commitments to climate mitigation can drive reductions in greenhouse gas emissions. Compared with the Net Zero scenario, this COP26 scenario shows the ambition gap between existing international commitments and achieving net-zero emissions. In this scenario, exogenous fuel prices are set based on the EIA AEO 2022 Low Oil Price case.

Policy neutral net-zero (‘Net Zero’)

This scenario assumes that the United States will reach net-zero CO_2 emissions by 2050. A constraint caps CO_2 emissions across the energy system to achieve this objective, with linear declines beginning in the 2025 model period and reaching net-zero by 2050. The ‘net’ term indicates that the model can balance any residual CO_2 emissions with carbon dioxide removal (CDR) technologies that draw CO_2 directly out of the atmosphere, including biomass integrated gasification combined cycle with carbon capture and sequestration (BECCS) and direct air capture (DAC). The results from this scenario provide a prescriptive look at the energy system transformation to net-zero without regard to the specific policy mechanisms required to achieve it. In this scenario, exogenous fuel prices are set based on the EIA AEO 2022 Low Oil Price case.

The scenarios in the report collectively represent a full range of emissions pathways. The No Policy and Net Zero scenarios form upper and lower bounds on the emissions trajectories. The remaining scenarios - State Action and COP26 - represent varying levels of policy ambition that will produce emissions trajectories within the prescribed range.

A note on fuel prices

Fuel prices are an exogenous input to the current version of Temoa used for this analysis. Specifically, this analysis relies on fuel prices reported in the Annual Energy Outlook 2022 published by the Energy Information Administration (EIA) (EIA, 2022b). Figure 2 shows the price ranges of natural gas for power generation, gasoline, diesel, and coal used in this analysis. The No Policy scenario relies on the prices in EIA’s reference case, while the State Action, COP26, and Net Zero scenarios rely on the prices in EIA’s low oil case. These differences in the prices among the scenarios aim to capture the price elasticity of supply: as demand for fuels decreases in the State Action, COP26, and Net Zero scenarios, the price also drops. The range presented for each case represents the distribution of regional fuel prices across the U.S."

Evolved Energy Research

The following text and table were copied from pages 7 and 8 of the EER ADP 2022 report.

"Scenarios represent different avenues to decarbonization based on societal preferences or policy restrictions regarding what technologies and resources may or may not be used, for example nuclear power or biomass, though they share many commonalities. For each scenario, the pathway to net-zero greenhouse gas emissions in 2050 is modeled in every year starting from the present, for all the infrastructure stocks and activities within all major economic sectors and subsectors, with a temporal granularity of every hour of the year for electricity, and a geographic granularity of 27 separate regions into which the U.S. is divided.

There are eight distinct scenarios, which are briefly described in Table 1 below. Six of these are very similar to those in our previous analysis (Link). This is partly for comparison purposes, but primarily because we think these still represent the most salient forks in the road for decarbonization in the U.S. Two new scenarios, "Drop-In" and "High Hydrogen," have also been added."

Scenario	Description
Baseline	This is a business-as-usual scenario based on the DOE's Annual Energy Outlook 2022. It has the same demand for energy services as the net-zero cases but does not achieve deep decarbonization. It is used as a basis of comparison for the cost, emissions, infrastructure, land use and other attributes of the net-zero cases.
Central	This is the least-cost pathway for achieving net-zero greenhouse gas emissions by 2050 in the U.S. It is economy-wide and includes energy and industrial CO_2, non-CO_2 GHGs, and the land CO_2 sink. It is built using a high electrification demand-side case, and on the supply-side has the fewest constraints on technologies and resources available for decarbonization.
Drop-In	This net-zero scenario prioritizes maintaining the use of existing infrastructure to the greatest extent possible consistent with carbon neutrality, implemented by placing cost penalties on new infrastructure build, delaying the uptake of electrification technologies by twenty years, and avoiding the uptake of other zero-carbon fuel-using technologies (hydrogen and ammonia). It is designed to explore the effects of trying to minimize dislocation on the existing energy industry in the U.S.
High Hydrogen	This net-zero scenario emphasizes the direct use of hydrogen in some applications in which the potential for electrification is uncertain, specifically in industry and heavier vehicles. It is designed to explore the effects of a hydrogen economy that extends all the way to energy end-users.
Low Demand	This net-zero scenario reduces the demand for energy services from that used in the other net-zero scenarios. It is designed to explore how high levels of conservation and energy efficiency, achieved through behavior, planning, policy, and other means, could reduce requirements for low-carbon infrastructure and land.
Low Land	This net-zero scenario limits the use of land-intensive mitigation solutions, including bioenergy crops, wind and solar power generating plants, and transmission lines. It is designed to explore the effect of societal barriers to the siting of low-carbon energy infrastructure for environmental and other reasons.
Slow Consumer Uptake	This net-zero scenario delays by twenty years the uptake of fuel-switching technologies including electric vehicles, heat pumps, fuel-cell vehicles, etc. It is designed to explore the effects of slow consumer adoption on energy system decarbonization, including the impacts on electricity and alternative fuel demand.
100% Renewables	This net-zero scenario allows only wind, solar, biomass, and other forms of renewable energy by 2050. It is designed to explore the effects of eliminating fossil fuels and nuclear power altogether on energy infrastructure, electric power, and the production of alternative fuels and feedstocks.

Princeton

The following text and image were copied from pages 23 and 24 of [the Princeton report](#).

"We define and model five different net-zero energy-system scenarios (or pathways), each with different assumptions about energy-demand and energy-supply technology options available in the future. The pathways help highlight the role of three key elements in energy system transitions: 1) extent of end-use electrification in transport & buildings, 2) extent of solar & wind electricity generation, and 3) extent of biomass utilization for energy. Each of the 5 scenarios has its own short-hand label used in presenting results:

E+ Assumes aggressive end-use electrification, but energy-supply options are relatively unconstrained for minimizing total energy-system cost to meet the goal of net-zero emissions in 2050

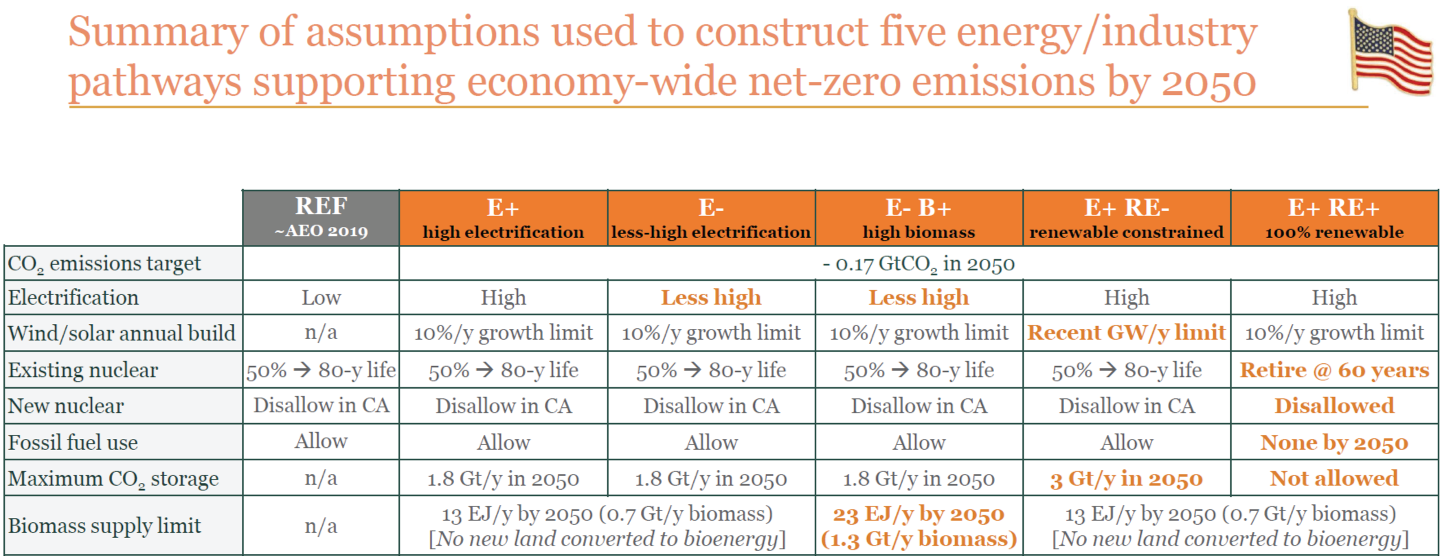
E- Less aggressive end-use electrification, but same supply-side options as E+

E-B+ Electrification level of E-; Higher biomass supply allowed to enable possible greater biomass-based liquid fuels production to help meet liquid fuel demands of non-electrified transport

E+ RE- Electrification level of E+; On supply-side, RE (wind and solar) rate of increase constrained to 35 GW/y (~30% greater than historical maximum single-year total). Higher CO_2 storage allowed to enable the option of more fossil fuel use than in E+

E+ RE+ Electrification level of E+; Supply-side constrained to be 100% renewable by 2050, with no new nuclear plants or underground carbon storage allowed, and fossil fuel use eliminated by 2050.

A large number of sensitivity cases were run to test the impact of changing input parameter values."



Summary of assumptions used to construct five energy/industry pathways supporting economy-wide net-zero emissions by 2050

	REF **~AEO 2019**	**E+** **high electrification**	**E-** **less-high electrification**	**E- B+** **high biomass**	**E+ RE-** **renewable constrained**	**E+ RE+** **100% renewable**
CO_2 emissions target		- 0.17 $GtCO_2$ in 2050				
Electrification	Low	High	**Less high**	**Less high**	High	High
Wind/solar annual build	n/a	10%/y growth limit	10%/y growth limit	10%/y growth limit	**Recent GW/y limit**	10%/y growth limit
Existing nuclear	50% → 80-y life	50% → 80-y life	50% → 80-y life	50% → 80-y life	50% → 80-y life	**Retire @ 60 years**
New nuclear	Disallow in CA	Disallow in CA	Disallow in CA	Disallow in CA	Disallow in CA	**Disallowed**
Fossil fuel use	Allow	Allow	Allow	Allow	Allow	**None by 2050**
Maximum CO_2 storage	n/a	1.8 Gt/y in 2050	1.8 Gt/y in 2050	1.8 Gt/y in 2050	**3 Gt/y in 2050**	**Not allowed**
Biomass supply limit	n/a	13 EJ/y by 2050 (0.7 Gt/y biomass) [*No new land converted to bioenergy*]		**23 EJ/y by 2050** **(1.3 Gt/y biomass)**	13 EJ/y by 2050 (0.7 Gt/y biomass) [*No new land converted to bioenergy*]	

Decarb America

The following text and table were copied from pages 3 and 4 of the Decarb America report.

"Evolved Energy Research modeled nine scenarios that make different assumptions about the policy and technology landscape for achieving net-zero U.S. greenhouse gas emissions over the next three decades."

Scenario	Description
Reference	Baseline scenario that assumes no additional policy changes. Uses the Energy Information Administration's Annual Energy Outlook (AEO) 2019 with updated fuel prices and clean energy policies from AEO 2020.
Sectoral Policies	Analyzes a package of frequently discussed low-carbon or clean energy policies in the transportation, electricity, buildings, and other sectors. Together, these policies are estimated to cut emissions by approximately 70% below current levels—a substantial reduction, but not enough to fully decarbonize the U.S. economy. This scenario combines a zero-emission vehicle standard, zero-carbon fuel standard (for diesel, gasoline, jet fuel, and hydrogen), electrification and efficiency standards for buildings, clean energy standard for the power sector (100% clean electricity by 2050), and policies to reduce emissions of methane and ozone-depleting substances.
High Renewables / High Electrification	Achieves net-zero greenhouse gas emissions across the U.S. economy by 2050. This scenario applies the sectoral policies analyzed above and then layers on additional actions to achieve net-zero. This scenario represents the most unconstrained economic, or cost-optimal deployment, of technologies and includes assumptions common to other net-zero analyses for achieving high levels of electrification and renewable energy deployment.
Constrained Renewables	Achieves net-zero emissions by 2050 with constraints on deployment of renewable electricity technologies to reflect siting challenges. Reduces available renewable energy to just 5% of the National Renewable Energy Laboratory's estimate of the technical potential for onshore wind, compared to 25% in the "Net-Zero by 2050" scenario. Solar deployment is limited by availability of land, with no more than 0.5% of available land area in any region allowed to be used for utility scale solar. Constrains offshore wind deployment to 25% of technical potential to reflect potential hurdles in siting supporting transmission infrastructure and avoiding encroachment on existing ocean uses.
Slow Consumer Adoption	Assumes that fuel-switching in the transportation, industrial, and buildings sectors is delayed by 20 years, reflecting slower consumer adoption of efficiency equipment, hydrogen end-use technologies, and electrification technologies. Zero-carbon fuels replace electricity and direct use of hydrogen to meet a large share of energy demands and still achieve net-zero.
Constrained Renewables & Slow Consumer Adoption	Pairs the demand-side assumptions from the "Slow Consumer Adoption" scenario with the renewable constraints used in the "Constrained Renewables" scenario. Given these constraints, this scenario relies heavily on zero-carbon fuels, electricity generation from non-renewables (e.g. nuclear), and carbon capture technologies to meet energy demands and still achieve net-zero.
High Conservation	Achieves net-zero emissions by 2050 with constraints on the overall footprint of the energy system. Assumes reduced energy demands in buildings, transportation, and industry. To reflect potential hurdles in siting utility-scale energy and transmission infrastructure, this scenario deploys distributed solar and energy storage technologies at 75% of technical potential to meet a significant share of electricity demand.
Low Biomass	Achieves net-zero emissions by 2050 with reduced availability of biomass feedstocks to produce hydrogen, other synthetic gases, liquid biofuels, and on-site heat and electricity. Assumes a maximum available feedstock supply of 460 million metric tons (MMT), compared to 710 MMT in the High Renewables/High Electrification scenario. Assumes that land currently used for corn ethanol will not be converted into land supplying other herbaceous energy crops, reducing available biomass supply by 34%.
No Fossil	Achieves net-zero emissions by 2050 by requiring the complete phase-out of fossil-derived energy by 2050. This is achieved by the use of a zero carbon fuel standard and the elimination of all fossil fuel combustion, resulting in a substantial increase in the use of hydrogen, synthetic hydrocarbons, and biofuels.

"What do pathways to net-zero look like under various technology and deployment constraints?

The intent of developing multiple decarbonization pathways was to make a robust case for the achievability of the net-zero-by-2050 goal despite the breadth and magnitude of the economic, socioeconomic, political, and technical challenges that lie ahead. Our modeling shows that net-zero can be achieved through a coherent set of technology choices and policies without necessitating a one size fits all approach. Different scenarios and assumptions produce substantially different outcomes based on regional resource endowments and the differing needs of the energy system. We designed our scenarios to explore a wide range of pathways while also bounding potential outcomes to reflect a variety of constraints that could materially affect the scale and mix of technologies used to produce, convert, deliver, and consume energy in a net-zero economy."

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About GTI Energy

GTI Energy is a leading technology development organization. Our trusted team works to scale impactful solutions that shape energy transitions by leveraging gases, liquids, infrastructure, and efficiency. We embrace systems thinking, innovation, and collaboration to develop, scale, and deploy the technologies needed for low-carbon, low-cost energy systems.

About Low-Carbon Resources Initiative (LCRI)

GTI Energy and EPRI are together addressing the need to accelerate development and demonstration of low- and zero-carbon energy technologies.

The Low-Carbon Resources Initiative (LCRI) will focus on large-scale deployment to 2030 and beyond. Fundamental advances in a variety of low-carbon electric generation technologies and low-carbon chemical energy carriers—such as clean hydrogen, bioenergy, and renewable natural gas—are needed to enable affordable pathways to economy-wide decarbonization.

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