Notional view of 2050 H₂ production and use: Gulf Coast vignette.

Large industrial facilities (2017)*

- Bulk Chemicals - petrochemicals
- Bulk Chemicals - Hydrogen
- Bulk Chemicals - Ammonia
- Bulk Chemicals - All other
- Cement and Lime
- Iron and Steel
- Petroleum Products Manufacturing [Refining]
- Food products/processing
- Paper and Allied Products
- Glass and Glass Products
- Fabricated Metals
- Machinery
- Computers and Electronics
- Transportation Equipment
- Electrical Equipment, Appliance and Components
- Wood Products
- Plastic and Rubber Products
- Balance of Manufacturing (NEMS IDM category end)
- Other Nonmetallic Mineral Product Manufacturing (except mineral wool)

* Source: Environmental Protection Agency, Facility Level Information on GreenHouse gases Tool (FLIGHT) database.
Notional 2050 H$_2$ production and use clusters: South/SE vignettes.

**2050 H$_2$ supply system (E+)**
- H$_2$ from biomass with CO$_2$ capture
- H$_2$ from natural gas with CO$_2$ capture
- H$_2$ trunk pipeline
- H$_2$ spur pipeline
- Large industrial facilities
- (2017)

---

**Texas/Louisiana Gulf Coast**

**South Carolina**
Notional 2050 H₂ production and use clusters: Midwest vignettes.

2050 H₂ supply system (E+)

- H₂ from biomass with CO₂ capture
- H₂ from natural gas with CO₂ capture
- H₂ trunk pipeline
- H₂ spur pipeline
- Large industrial facilities
- (2017)

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Notional 2050 H₂ production and use clusters: West Coast vignettes.

2050 H₂ supply system (E+)
- H₂ from biomass with CO₂ capture
- H₂ from natural gas with CO₂ capture
- H₂ trunk pipeline
- H₂ spur pipeline
- Large industrial facilities
- (2017)
Pillar 4: CO$_2$ capture, transport, and utilization or geologic storage

Summary of this section

- CO$_2$ capture is deployed at large scale in all NZA scenarios. Geological storage is deployed at large scale in all NZA scenarios, except E+RE+, where all captured CO$_2$ is utilized for synthetic fuels.
- CO$_2$ capture is deployed on cement production, gas- and biomass-fired power generation, natural gas reforming, biomass derived fuels production, and in some cases from direct atmospheric air capture.
- Geological sequestration rates range from almost 1 to 1.7 billion tonnes of CO$_2$ per annum by 2050, servicing more than a thousand capture facilities distributed across the nation.
- The majority of geologic sequestration takes place in the Texas gulf coast but other basins host sequestration of 10’s to more than 100 million tonnes of CO$_2$ per year.
- An investment of 13 B$ is estimated for stakeholder engagement plus characterization, appraisal and permitting across multiple storage basins and injection sites before 2035 to enable rapid expansion thereafter.
- The CO$_2$ capture utilization and storage (CCUS) industry is enabled by around 110,000 km of new CO$_2$ pipeline infrastructure with an estimated capital cost of $170 billion (for E+) to $230 billion (for E-B+).
- Estimated unit costs for CO$_2$ transport and storage average $17 to $23 per tonne stored depending on the ultimate scale of deployment.
- The scale of CO$_2$ transport and storage in these scenarios ranges from 1.3 to 2.4 times current US oil production on a volume equivalent basis.
- See Annex I for details around downscaling analysis of CO$_2$ transport and geologic storage.
CO₂ capture at multiple facility types and some CO₂ utilization in all pathways; significant CO₂ storage in all but one pathway

By 2050

• 0.7 to 1.8 Gt/y CO₂ captured.
• 0.9 to 1.7 Gt/y CO₂ sequestered.
• 0.1 to 0.7 Gt/y CO₂ converted to fuels.

CO₂ sources

Direct air capture
Natural gas hydrogen (autothermal reforming)
BECCS electricity (gasifier-Allam cycle)
Natural gas electricity (Allam cycle)
BECCS hydrogen (gasifier/water gas shift)
BECCS pyrolysis (hydrocatalytic)
Cement via 90% capture (post-combustion).

CO₂ uses

Synthetic liquids = synthesis of fuels from H₂ + CO₂.
Synthetic gas = methane synthesis from H₂ + CO₂.
Sequestration = geological storage
Some capture plants online by 2030, followed by rapid growth in 2030s and 2040s. E+ and E+RE- pathways are shown here.

<table>
<thead>
<tr>
<th>Year</th>
<th>E+</th>
<th>E+RE-</th>
<th>E+</th>
<th>E+RE-</th>
<th>E+</th>
<th>E+RE-</th>
<th>E+</th>
<th>E+RE-</th>
</tr>
</thead>
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<tr>
<td>2030</td>
<td>65</td>
<td>200</td>
<td>250</td>
<td>580</td>
<td>440</td>
<td>890</td>
<td>720</td>
<td>1,270</td>
</tr>
<tr>
<td>2035</td>
<td>200</td>
<td>250</td>
<td>580</td>
<td>890</td>
<td>720</td>
<td>1,270</td>
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<td></td>
</tr>
<tr>
<td>2040</td>
<td>440</td>
<td>1,060</td>
<td>720</td>
<td>1,270</td>
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<tr>
<td>2045</td>
<td>1,270</td>
<td></td>
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<td></td>
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<tr>
<td>2050</td>
<td></td>
<td>1,060</td>
<td></td>
<td></td>
<td>1,670</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Captured CO₂ (million tonnes/y)

- **ATR-CCS**
- **DAC**
- **BECCS-H₂**
- **BECCS-pyrolysis**
- **BECCS-electricity**
- **NGCC-CCS**
- **Cement and lime**

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CO₂ injection rates grow from small today to 27% of 2018 oil & gas extraction rates in 2050 (at notional in situ reservoir conditions)

Volumetric Production & Injection Rates*
(billion cubic meters / year)

* At notional in situ reservoir conditions (2,000 m depth)

CO₂ transport network design combines state-of-art understanding of storage basins and geospatial downscaling of CO₂ point sources.

1. The most prospective CO₂ storage basins were identified based on practicable storage capacity (accessible, sustainable annual injection rates) estimates of Teletzke et al. (2018).
2. Notional supply-cost curve for CO₂ transport and storage established using expert judgement and industry consultation (BP, ExxonMobil, Occidental), assuming shared transport infrastructure.
3. RIO chooses CO₂ capture and storage (CCS) to mitigate emissions from power sector, fuels production and industry sectors across 14 regions, where economically competitive for scenarios that allow CCS.
4. Downscaling defines locations for each capture facility at county level.
5. Notional CO₂ trunk line network drawn ‘by eye’ to pick up major clusters of point sources, with build program to deliver CO₂ transport infrastructure in advance of start of CO₂ capture activity.
6. Point source downscaling repeated to locate all point sources within 200 km of trunk lines.
7. Spur lines connect point sources to trunk lines using minimum distance and following existing ROWs.*
8. Trunk lines sized and costed using FE/NELT CO₂ Transport Cost Model, and build-out programmed to meet expansion of CO₂ point sources for all trunk line catchment areas. Spur lines costed using a simple \( \text{Cost} = f(\text{tpa}, \text{km}) \) equation derived from the FE/NELT CO₂ Transport Cost Model.
9. Levelized cost of CO₂ transport established based on capital cost estimates, build schedules, and CO₂ expansion using discounted cash flow model.
10. Cost-supply curves calculated for different potential capacity-charge arrangements.

See Annex I for additional details

* Existing ROWs include natural gas, NH₃ and CO₂ pipelines, railways, interstate highways, and > 220kV electricity transmission lines, as mapped in Edwards and Celia, “Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States,” PNAS, 115(38): E8815-E8824, 2018.
Notional CO₂ storage capacity appraised, permitted and developed in 2050 is up to 1.8 billion t/y, mostly in Gulf Coast.

Gulf Coast provides 75% of annual storage capacity.

Existing CO₂ pipelines shown.

CO₂ Storage Basins
(Selected for practicable storage capacities, based on Teletzke et al., 2018.)
13 B$ invested in stakeholder engagement and characterization, appraisal & permitting pre-2035 enables rapid expansion thereafter.

<table>
<thead>
<tr>
<th>Item</th>
<th>2021-25 Investment (Million $)</th>
<th>2026-30 Investment (Million $)</th>
<th>2031-35 Investment (Million $)</th>
<th>Notional Capacity Appraised (MMtpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Basin-wide Assessments</strong>*</td>
<td>1,500</td>
<td>1,500</td>
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<td></td>
</tr>
<tr>
<td><strong>CO₂ Site Appraisal and Permitting</strong> **</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area A1</td>
<td>0</td>
<td>700</td>
<td>400</td>
<td>110</td>
</tr>
<tr>
<td>Area A2</td>
<td>0</td>
<td>4,000</td>
<td>2,700</td>
<td>670</td>
</tr>
<tr>
<td>Area B</td>
<td>0</td>
<td>100</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>Area C</td>
<td>0</td>
<td>200</td>
<td>300</td>
<td>50</td>
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<td>Area D</td>
<td>0</td>
<td>200</td>
<td>200</td>
<td>40</td>
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<tr>
<td>Area E</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>30</td>
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<tr>
<td>Area F</td>
<td>0</td>
<td>300</td>
<td>500</td>
<td>80</td>
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<tr>
<td><strong>Totals</strong></td>
<td><strong>1,500</strong></td>
<td><strong>7,100</strong></td>
<td><strong>4,400</strong></td>
<td><strong>1,000</strong></td>
</tr>
</tbody>
</table>

* Estimated to be $500 million per basin (basins A – F identified in prior slide).
** See previous slide for basin labels.
Existing CO$_2$ pipeline network

- ~ 80 million tCO$_2$/yr transported
- ~ 8,500 km of pipelines
- Servicing enhanced oil recovery operations
- Majority in Permian Basin (West Texas and southeast New Mexico)
Trunk line construction begins before 2025 with connection between Permian Basin and Gulf Coast

E+ scenario
No CO₂ flow in this period
700 km new pipelines
Capital in-service: $70B

CO₂ point source type
- CO₂ point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO₂ captured (MMTPA)
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA)
- < 100
- 100 - 200
- > 200
Trunk line build out continues and initial CO$_2$ capture plants come online, with spur lines connecting to trunk network.

**E+ scenario**

- 65 million tCO$_2$/y
- 19,000 km pipelines
- Capital in-service: $70B

CO$_2$ point source type:
- CO$_2$ point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO$_2$ captured (MMTPA):
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA):
- < 100
- 100 - 200
- > 200

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Trunk network routes complete; some sections add parallel lines as more capture projects are built and connected

**E+ scenario**

- 246 million tCO$_2$/y
- 41,000 km pipelines
- Capital in service: $115B

**CO2 point source type**
- CO2 point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

**CO2 captured (MMTPA)**
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

**Trunk lines (capacity in MMTPA)**
- < 100
- 100 - 200
- > 200
More individual trunk line duplications as number of capture projects continues to grow

**E+ scenario**

435 million tCO$_2$/y
51,000 km pipelines
Capital in service: $125B

**CO2 point source type**
- CO2 point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

**CO2 captured (MMTPA)**
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

**Trunk lines (capacity in MMTPA)**
- < 100
- 100 - 200
- > 200

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CO₂ capture plants connected to trunk lines grow rapidly

E+ scenario
687 million tCO₂/y
70,000 km pipelines
Capital in service: $135B

CO₂ point source type
- CO₂ point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO₂ captured (MMTPA)
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA)
- < 100
- 100 - 200
- > 200
2050 totals: 21,000 km trunk lines + 85,000 km spur lines (equivalent to ~22% of US natural gas transmission pipeline total)

E+ scenario
929 million tCO$_2$/y
106,000 km pipelines
Capital in service: $170B

CO$_2$ point source type
- CO$_2$ point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

CO$_2$ captured (MMTPA)
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

Trunk lines (capacity in MMTPA)
- < 100
- 100 - 200
- > 200

Note: On a volume basis (at reservoir pressure), CO$_2$ flow in 2050 is 1.3x current U.S. oil production and ¼ of current oil + gas production.
E-B+ utilizes the same trunk network, but with some additional parallel pipes in some corridors

**E-B+ scenario**

1,361 million tCO\(_2\)/y  
111,000 km pipelines  
Capital in service: $220B

**CO2 point source type**
- CO2 point sources
- BECCS - power and fuels
- Cement w/ ccs
- Natural gas power ccs oxyfuel

**CO2 captured (MMTPA)**
- 0.0006449
- 7.9144
- 15.8282
- 23.7419

**Trunk lines (capacity in MMTPA)**
- < 100
- 100 - 200
- > 200

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Costs (2020$)*
<table>
<thead>
<tr>
<th></th>
<th>E+</th>
<th>E-B+</th>
</tr>
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<tbody>
<tr>
<td>Trunk lines</td>
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<td></td>
</tr>
<tr>
<td>Total length, km</td>
<td>21,100</td>
<td>25,400</td>
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<tr>
<td>Total installed capital cost, billion 2020$</td>
<td>101</td>
<td>135</td>
</tr>
<tr>
<td>National network-access charge, $/tCO₂ delivered</td>
<td>11.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Center-East network-access charge, $/tCO₂ delivered</td>
<td>11.3</td>
<td>7.4</td>
</tr>
<tr>
<td>West network-access charge, $/tCO₂ delivered</td>
<td>11.6</td>
<td>10.4</td>
</tr>
<tr>
<td>Spur lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total length, km</td>
<td>85,800</td>
<td>85,700</td>
</tr>
<tr>
<td>Total installed capital cost, billion 2020$</td>
<td>69</td>
<td>88</td>
</tr>
<tr>
<td>National network-access charge, $/tCO₂ delivered</td>
<td>4.6</td>
<td>3.0</td>
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<tr>
<td>Total trunk + spur lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>National network-access charge, $/tCO₂ delivered</td>
<td>15.9</td>
<td>10.6</td>
</tr>
</tbody>
</table>

* Costs, including pipelines and compressors, were estimated using the DOE/NETL CO₂ Transport Cost Model (version 2b).

Higher charge for West than for Center-East trunk network
Amortizing investments across all users avoids prohibitively high costs of small-capacity point sources financing their own spur lines.

Rapidly rising transport costs for smaller point sources with longer spur lines

**CO₂ transport costs (E+)**

**CO₂ transport costs (E- B+)**

- **Red** line: Trunk + spur line network-access charge. (All point sources charged equally, regardless of scale, location, or on-stream date.)
- **Blue** line: Trunk line network-access charge. (All point sources charged equally, regardless of scale, location, or on-stream date.)
- **Green** line: Cost-supply curve assuming trunk line network-access charge + spur line investment by individual point sources.
Storage adds $7/tCO₂ (DOE low-end estimate) and EOR provides credit of $19/tCO₂ (for $50/bbl oil*).

CO₂ transport and storage costs calculated from the downscaling analysis are somewhat lower than the costs assumed in the RIO modeling of E+ pathway.

* Rubin, et al. (2015) wrote that “conventional wisdom suggests that the price that EOR projects can afford to pay for CO₂ (in $/1000 standard ft³) is 2% of the oil price in $/bbl.”
Pillar 5: Reduced non-CO$_2$ emissions

Summary of this section

• In a net-zero future, non-CO$_2$ greenhouse gas emissions each year must be compensated by removal of an equivalent amount of CO$_2$ from the atmosphere. In the modeling here, negative emissions can be achieved by permanent storage underground (or in long-lived plastics or similar products) of CO$_2$ derived from biomass or directly captured from the air, or (as discussed below under Pillar 6) by uptake in soils and trees.

• Sources of methane and nitrous oxides – the majority of non-CO$_2$ emissions today – are widely dispersed, making mitigation more challenging, and non-CO$_2$ emissions are projected to grow in the future under business-as-usual.

• The Net-Zero America study team did not conduct original analysis assessing mitigation options, but assumed as an input to the modeling a level of mitigation from 2020 to 2050 consistent with recent analysis from the U.S. Environmental Protection Agency (EPA).

• We also note that EPA’s mitigation estimates assume future levels of oil and gas use that are closer to those of a “business-as-usual” future than a net-zero emissions future. In the latter, fossil fuel use is at least 70% to 80% lower than today by 2050. The EPA projections assume some mitigation of non-CO$_2$ emissions associated with producing and transporting fossil fuels. Under a net-zero scenario, these emissions would be significantly lower due to the reduced fossil fuel use.

• See Annex O for additional discussion of non-CO$_2$ emissions.
Non-CO$_2$ emissions today are 1.25 GtCO$_{2e}$/year

Source: EPA, 2020 GHG Inventory
Methane emissions follow energy and agricultural production patterns and population densities

Agricultural emissions are dominated by livestock and dairy production

Oil and gas upstream emissions align with production & processing; downstream with pop.

Waste emissions are aligned with population density

Coal upstream emissions are dominated by Appalachian subsurface mining.

2012 emissions (tCH$_4$/km$^2$)
(All emissions in the National GHG Inventory)

Source: EPA
N$_2$O emissions occur mostly outside of the energy sector and in states with significant agricultural production.

N$_2$O emissions from agriculture plus production of adipic and nitric acids (2018)

- Agricultural soil management: 338
- Manure management: 19
- Adipic & nitric acid production: 20
- Stationary & mobile combustion: 44
- Other: 15
- Total: 436

Note: 10.4 mmtc02e in Florida in 2018 (> 80% of Florida’s N$_2$O emissions) were attributed to one acid production facility.
Without mitigation efforts, non-CO$_2$ emissions grow gradually to 1.45 GtCO$_{2e}$ by 2050, with CH$_4$ and N$_2$O contributing most.

Historical and projected non-CO$_2$ emissions by gas type under business as usual (BAU)

Without mitigation, non-CO₂ emissions grow gradually to 1.45 GtCO₂e by 2050, with agriculture and energy remaining dominant.

Historical and projected non-CO₂ emissions by sector under business as usual (BAU)

Mitigation can reduce non-CO$_2$ emissions substantially by 2030

By 2030, EPA projects:

- Under EPA BAU (no mitigation), non-CO$_2$ emissions reach 1.35 GtCO$_{2e}$/y
- Under E+ BAU (energy mitigation but no non-CO$_2$ mitigation), non-CO$_2$ emissions fall to 1.28 GtCO$_{2e}$/y as nearly all coal production ceases and oil/gas output drops ~10%
- Very low-cost mitigation yields 1.18 GtCO$_{2e}$/y while measures costing <$100/tCO$_{2e}$ yield 0.97 GtCO$_{2e}$/y
- Further research needed to identify additional reductions

Mitigation can reduce emissions to ~1 Gt per year by 2050, but beyond that the path to deeper reductions remains uncharted.

By 2050, EPA projects:

- Under EPA BAU (no mitigation), non-CO₂ emissions reach 1.45 GtCO₂e/y
- Under E+ BAU (energy mitigation but no non-CO₂ mitigation), non-CO₂ emissions fall to 1.22 GtCO₂e/y as nearly all coal production ceases and oil/gas output drops ~75%
- Very low-cost mitigation yields 1.11 GtCO₂e/y while measures costing <$100/tCO₂e yield 0.90 GtCO₂e/y
- E+ scenario assumes non-CO₂ abatement efforts yield ~1 GtCO₂e/y by 2050

Non-\( \text{CO}_2 \) emissions are assumed to be reduced to 1 Gt\( \text{CO}_2 \text{e} \) by 2050, or ~20% below 2020 and ~30% below EPA’s BAU forecast for 2050.

Estimated abatement potential by 2050 @ \( \leq \$100/\text{tCO}_2\text{e} \) avoided

<table>
<thead>
<tr>
<th>Source</th>
<th>2050 Abatement (10^8 tCO_2e/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agriculture</strong></td>
<td></td>
</tr>
<tr>
<td>Croplands/Rice</td>
<td>11</td>
</tr>
<tr>
<td>Livestock</td>
<td>49</td>
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<tr>
<td><strong>Energy</strong></td>
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<tr>
<td>Coal</td>
<td>5</td>
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<tr>
<td>Oil and gas</td>
<td>48</td>
</tr>
<tr>
<td><strong>Industrial</strong></td>
<td></td>
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<tr>
<td>Nitric &amp; Adipic Acid Production (( \text{N}_2\text{O} ))</td>
<td>36</td>
</tr>
<tr>
<td>Refrigerants/AC (F-gases)</td>
<td>146</td>
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<tr>
<td>Other</td>
<td>9.0</td>
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<tr>
<td><strong>Waste</strong></td>
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<tr>
<td>Landfill</td>
<td>13</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>316</strong></td>
</tr>
</tbody>
</table>

**Non-\( \text{CO}_2 \) Abatement Potential:**

- Mitigation measures costing <$100/t\text{CO}_2\text{e}$ can drive non-\( \text{CO}_2 \) emissions from 1.45 to 0.90 Gt\( \text{CO}_2\text{e}/y \) by 2050
- F-gases account for nearly half of this mitigation potential

Source: EPA, *Global Non-\text{CO}_2 Greenhouse Gas Emission Projections & Mitigation*, Oct. 2019, but with coal and oil and gas adjustments to reflect E+ scenario: coal abatement is limited to mitigation of abandoned mines and oil/gas abatement is reduced by ~75% to account for lower oil production under E+. 
Pillar 6: Enhanced land sinks

Summary of this section

• Land carbon sinks, i.e., annual removal of carbon from the air and permanent storage in soil or trees, are critical for net-zero emission scenarios, because they offset positive greenhouse gas emissions from elsewhere in the economy.

• In the cost-minimized net-zero scenarios developed in this study, the last unit of CO$_2$ emission avoided from the energy/industrial system is the most expensive one to avoid. Thus, land sinks avoid using the most costly measures for CO$_2$ emissions reductions in the energy/industrial system.

• There is uncertainty about what the magnitude of the U.S. land sink is today, but 0.7 GtCO$_{eq}$/y is thought to be a reasonable estimate, and there is an expectation that the natural land sink will weaken in the future to as low as 0.3 Gt/y by 2050 due to maturing of forest regrowth in the U.S.

• Geographically-resolved analysis by Net-Zero America researchers estimates a technical potential for enhanced land sinks by 2050 of up to 0.2 GtCO$_{eq}$/y in agriculture (see Annex Q) and from 0.5 to 1.5 GtCO$_{eq}$/y in forestry (see Annex P).

• The net-zero modeling in this study assumes the land sink as a whole grows to 0.85 GtCO$_{eq}$/y by 2050, which implies a concerted effort to deploy agricultural and/or forestry land sink maintenance/enhancement measures from 2020 to 2050.
Extent of carbon uptake in soils and trees impacts the decarbonization challenge for the energy/industrial system

- The current natural land sink is uncertain, but estimates are in the range of 0.7 GtCO$_2$e/y.
- Without efforts to enhance the natural land sink, it is projected to decline to 0.3 GtCO$_2$e/y by 2050.
- Significant modification of agricultural and forestry practices, if widely adopted, can help maintain/enhance the land sink.

<table>
<thead>
<tr>
<th>2050</th>
<th>E+ (and other scenarios)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land sink, GtCO$_2$e/y (assumed)</td>
<td>- 0.85</td>
</tr>
<tr>
<td>Non-CO2 emissions, GtCO2e/y (assumed)</td>
<td>1.02</td>
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<tr>
<td>Energy/industry emissions, GtCO$_2$/y</td>
<td>- 0.17</td>
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</tbody>
</table>
To reach net-zero emissions economy wide in 2050, emissions “allowed” by the energy/industrial system in 2050 depend on the net emissions occurring outside of energy/industry, i.e., land sinks and non-CO₂ emissions. The degree of net land sinks + non-CO₂ emissions that will be achieved is uncertain. Compared with E+:

- If the net outside emissions are higher (E+ Land-), electricity generation is much higher by 2050, with most of the increase being solar and wind. Electrolytic H₂ production is also higher, deployment of direct air capture is significant, and about 60% more CO₂ sequestration is required. NPV of the total energy-supply system (2020 – 2050) increases by 3%.

- If the net outside emissions by 2050 are lower (E+ Land+), less total electricity is needed in 2050, and a greater fraction comes from NGCC without CC. There is also less H₂ demand because more petroleum-derived fuels can be used. NPV of the total energy-supply system (2020 – 2050) decreases by 2%.

See Annex B for additional details.

**Input assumptions that vary between cases**

<table>
<thead>
<tr>
<th>Billion metric tCO₂e in 2050</th>
<th>E+</th>
<th>E+ Land+</th>
<th>E+ Land-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land sink</td>
<td>- 0.85</td>
<td>- 1.30</td>
<td>- 0.30</td>
</tr>
<tr>
<td>Non-CO₂ emissions</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>Net emissions outside</td>
<td>0.17</td>
<td>- 0.27</td>
<td>0.73</td>
</tr>
<tr>
<td>of energy/industry system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allowed energy/industrial</td>
<td>- 0.17</td>
<td>0.27</td>
<td>- 0.73</td>
</tr>
<tr>
<td>CO₂ emissions in 2050</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

See Annex B for additional details.
Agricultural measures can yield > 200 million tCO$_2$e/year of additional carbon storage in soils by 2050*.

<table>
<thead>
<tr>
<th>With 100% adoption of conservation measures</th>
<th>E+</th>
<th>E- B+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10$^6$ ha</td>
<td>10$^6$ tCO$_2$e/y</td>
</tr>
<tr>
<td>Ethanol-corn land $\rightarrow$ perennial energy grasses</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>CRP area converted to perennial energy grasses</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Other croplands converted to</td>
<td></td>
<td></td>
</tr>
<tr>
<td>perennial energy grasses</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>woody energy crops</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>permanent herbaceous cover</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>Pasture converted to perennial energy crops</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other croplands remaining as cropland</td>
<td>136</td>
<td>204</td>
</tr>
<tr>
<td>Pasture remaining as pasture</td>
<td>155</td>
<td>no estimate</td>
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<tr>
<td>Totals</td>
<td>327</td>
<td>234</td>
</tr>
</tbody>
</table>

* See Swan, et al. (Annex Q).
Maximum annual carbon uptake potential on agricultural lands by county; Midwestern states account for >80% of the potential.

Carbon storage across all agricultural lands (160 million ha)

Carbon storage on ethanol-corn land converted to energy grasses (11 Mha)

Total U.S. potential: 230 million tCO$_{2e}$

Total U.S. potential: 23 million tCO$_{2e}$

See Swan, et al. (Annex Q).

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Top 20 states account for > 85% of the carbon storage potential on agricultural lands in 2050 (E+ scenario)

Most of the potential is in measures applied to cropland, with carbon storage per acre averaging 1.5 tCO$_2$/ha/yr; ethanol-corn land conversion to energy grasses is highest (2.1 tCO$_2$/ha/yr).

**Annual C Storage & GHG Emission Reductions**

**Land area impacted**

- Cropland Remaining Cropland
- Ethanol-Corn and Other Cropland Converted to Perennial Energy Grasses
- Cropland Converted to Herbaceous Cover

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Technical potential for carbon uptake by forest measures is estimated to be 0.5 to 1.5 GtCO$_2$e/y.*

<table>
<thead>
<tr>
<th>Activity</th>
<th>Low Estimate (GtCO$_2$e/y)</th>
<th>High Estimate (GtCO$_2$e/y)</th>
<th>Land area affected (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reforestation of agricultural lands (a)</td>
<td>0.141</td>
<td>0.506</td>
<td>9 – 34</td>
</tr>
<tr>
<td>Croplands</td>
<td>0.121</td>
<td>0.242</td>
<td>8 – 16</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.020</td>
<td>0.264</td>
<td>1.3 – 17.5</td>
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<tr>
<td><strong>Improved forest management</strong></td>
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<tr>
<td>Accelerate regeneration</td>
<td>0.025</td>
<td>0.049</td>
<td>4 – 8</td>
</tr>
<tr>
<td>Restore productivity of degraded forests</td>
<td>0.060</td>
<td>0.178</td>
<td>36 – 154</td>
</tr>
<tr>
<td>Extend rotation lengths</td>
<td>0.116</td>
<td>0.302</td>
<td>59 – 154</td>
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<tr>
<td>Improve productivity of plantations</td>
<td>0.029</td>
<td>0.057</td>
<td>11 – 21</td>
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<tr>
<td>Increase stocking of trees outside forests</td>
<td>0.021</td>
<td>0.060</td>
<td>3 – 6</td>
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<tr>
<td><strong>Increased C retention in harvested wood</strong></td>
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<tr>
<td>Reduced deforestation</td>
<td>0.100</td>
<td>0.300</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Total potential</strong></td>
<td>0.500</td>
<td>1.53</td>
<td>132 – 342</td>
</tr>
</tbody>
</table>

(a) Agricultural lands that are assumed to otherwise be enrolled as Conservation Reserve Program acreage.

* See Birdsey, 2020 (Annex P).
1 GtCO$_{2e}$/yr technical potential for enhanced carbon storage on forest lands (mid-range of estimates)

25 states shown in the bar graph have 80% of total US technical potential.

* > 130 Mha, or more than ½ of all forest area, are impacted.
Summary of goals for the six pillars
Rapid expansion is needed, 2020 – 2050, across all six pillars to achieve net-zero emissions. 2050 goals for each pillar include:

1. **Efficiency & Electrification**
   - Consumer energy investment and use behaviors change
     - Light-duty EVs: 210 million (E-) to 330 million (E+)
     - Residential heat pump heaters: 80 million (E-) to 120 million (E+)
   - Industrial efficiency gains
     - Energy intensity declines 1.9%/yr.
     - Steel making evolves to all EAF and direct (H₂) reduced iron

2. **Clean Electricity**
   - Wind and solar
     - 1.3 to 5.9 GW of solar and wind installed, up from 0.2 GW in 2020
     - 2x to 5x today’s transmission
   - Nuclear
     - In RE- scenario site up to 250 new 1-GW reactors (or 3,800 SMRs).
     - Spent fuel disposal.
   - NGCC-CCS
     - In RE-, 300+ plants (@750 MW)
   - Flexible resources
     - Combustion turbines w/high H₂
     - Large flexible loads: electrolysis, electric boilers, direct air capture
     - 50 - 180 GW of 6-hour batteries

3. **Zero-Carbon Fuels**
   - Major bioenergy industry
     - 100s of new conversion facilities
     - 620 million t/y biomass feedstock production (1.2 Bt/y in E- B+)
   - H₂ and synfuels industries
     - 8-19 EJ H₂ from biomass with CCS (BECCS), electrolysis, and/or methane reforming with CCS
     - Largest H₂ use is for fuels synthesis in most scenarios

4. **CO₂ capture & storage**
   - Geologic storage of 0.9 – 1.7 GtCO₂/y
     - Capture at ~1,000+ facilities
     - 21,000 to 25,000 km interstate CO₂ trunk pipeline network
     - 85,000 km of spur pipelines delivering CO₂ to trunk lines
     - Thousands of injection wells

5. **Non-CO₂ Emissions**
   - Methane, N₂O, Fluorocarbons
     - 20% below 2020 emissions (CO₂e) by 2050 (30% below 2050 REF).
   - Methane, N₂O, Fluorocarbons
     - 20% below 2020 emissions (CO₂e) by 2050 (30% below 2050 REF).

6. **Enhanced land sinks**
   - Forest management
     - Potential sink of 0.5 to 1 GtCO₂e/y, impacting ½ or more of all US forest area (≥ 130 Mha).
   - Agricultural practices
     - Potential sink ~0.20 GtCO₂e/y if conservation measures adopted across 1 – 2 million farms.

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Implications of net-zero transitions

Summary of this section

• Significant implications of transitions to net-zero emissions are illustrated quantitatively here for land use, capital mobilization, fossil fuel industries, employment, and air pollution-related health impacts.
Land use

Summary of this section

• Direct land use for wind turbine construction in net-zero scenarios is small, but the (visual) footprint of wind farms is significant. In 2050, total wind farm area visual footprint is smallest for E+RE- at ¼ million km², or the equivalent of the combined land areas of Illinois and Indiana. The footprint is largest for E+RE+ @ 1 million km², or the equivalent of land areas of Arkansas, Iowa, Kansas, Missouri, Nebraska, and Oklahoma combined.

  • Wind projects are concentrated in the Great Plains, Midwest, and Texas, primarily on crop, pasture, and forested lands.

• Land use for solar farms in 2050 is much smaller than the visual footprint of wind farms, ranging from an area equivalent to the area of Connecticut for E+RE- to that of West Virginia for E+RE+.

  • Solar deployment is greatest in the Northeast and Southeast, and forested lands make up the largest directly impacted land cover type.

• The only scenario for which there is significant land-use change associated with biomass use is in the E-B+ scenario, where land area equivalent to the combined areas of Alabama and Mississippi (> ¼ million km²) is converted from crop or pasture land to dedicated cultivation of perennial energy crops.

• With constrained site availability, only 6% of solar candidate project areas (CPA) in E+RE+ are selected, indicating potential to substantially reconfigure solar siting in any scenario to minimize conflicts. Wind projects use 45% of CPAs in E+ and 90% of CPAs in E+RE+, indicating greater potential for wind to be constrained by siting challenges.
Total land area/visual footprint in 2050 for solar, wind, and biomass across scenarios is 0.25 to 1.1 million km$^2$.

U.S. land use today, Lower-48
(7.7 Million km$^2$)

Notes: In these maps, the sum of land areas of colored states is roughly the same as the area nationally of the indicated uses.

Equivalent land area for Total land area/visual footprint in 2050 for solar, wind, and biomass across scenarios is 0.25 to 1.1 million km$^2$.

E+ RE+
[1.0]
[0.061]

E+ RE-
[0.038]
[0.014]

E+
[0.55]
[0.0038]

E-
[0.70]
[0.038]

E- B+
[0.47]
[0.031]

E- B-
[0.26]

Note: Directly impacted land area for wind farms (equipment footprint) is indicated by ■. For solar and biomass, directly impacted areas are 91% and 100% of shaded area shown.

* On lands converted from food production.
Land use summary for wind and solar capacity for downscaled net-zero pathways.

<table>
<thead>
<tr>
<th></th>
<th>E+</th>
<th>E+ RE-</th>
<th>E+ RE+</th>
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<tbody>
<tr>
<td></td>
<td>2020 2030 2040 2050</td>
<td>2020 2030 2040 2050</td>
<td>2020 2030 2040 2050</td>
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<tr>
<td><strong>Solar</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>63,093 319,791 849,698 1,494,953</td>
<td>75,786 265,380 457,047 638,177</td>
<td>65,638 401,952 1,232,705 2,750,263</td>
</tr>
<tr>
<td>Total solar farm area (km²)</td>
<td>1,078 7,752 21,530 38,307</td>
<td>1,387 5,788 10,100 14,241</td>
<td>1,122 8,671 26,937 61,212</td>
</tr>
<tr>
<td>Direct land use (km²)</td>
<td>981 7,055 19,592 34,859</td>
<td>1,262 5,267 9,191 12,959</td>
<td>1,021 7,891 24,512 55,703</td>
</tr>
<tr>
<td>Total land, % of Candidate Project Areas</td>
<td>0.0% 0.3% 0.7% 1.3%</td>
<td>0.0% 0.2% 0.3% 0.5%</td>
<td>0.0% 0.3% 0.9% 2.0%</td>
</tr>
<tr>
<td><strong>Base land availability assumptions</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>Land-based wind</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>147,364 414,298 948,379 1,479,035</td>
<td>142,976 267,651 450,686 650,670</td>
<td>146,120 461,584 1,322,129 2,699,955</td>
</tr>
<tr>
<td>Total wind farm extent (km²)</td>
<td>57,913 156,777 354,585 551,124</td>
<td>56,288 102,464 170,254 244,323</td>
<td>57,452 174,291 493,011 1,003,317</td>
</tr>
<tr>
<td>Direct land use (km²)*</td>
<td>579 1,568 3,546 5,511</td>
<td>563 1,025 1,703 2,443</td>
<td>575 1,743 4,930 10,033</td>
</tr>
<tr>
<td>Total land, % of Candidate Project Areas</td>
<td>1.3% 3.5% 7.9% 12%</td>
<td>1.3% 2.3% 3.8% 5.5%</td>
<td>1.3% 3.9% 11% 22%</td>
</tr>
<tr>
<td><strong>Offshore wind</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>70 5,289 45,030 202,562</td>
<td>70 10,827 22,125 31,933</td>
<td>70 5,323 109,121 385,665</td>
</tr>
<tr>
<td>Total wind farm area (km²)</td>
<td>14 1,044 7,708 33,077</td>
<td>14 2,151 4,117 5,691</td>
<td>14 1,051 19,665 64,670</td>
</tr>
<tr>
<td>Direct area used (km²)</td>
<td>0 10 77 331</td>
<td>0 22 41 57</td>
<td>0 11 197 647</td>
</tr>
<tr>
<td>Total area, % of Candidate Project Areas</td>
<td>0.0% 0.4% 3.2% 14%</td>
<td>0.0% 0.9% 1.7% 2.4%</td>
<td>0.0% 0.4% 8.1% 27%</td>
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<tr>
<td><strong>Constrained land availability assumptions</strong></td>
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<tr>
<td><strong>Solar</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>56,456 329,044 839,108 1,474,990</td>
<td>73,049 266,950 469,629 664,068</td>
<td>65,919 417,727 1,233,766 2,763,554</td>
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<tr>
<td>Total solar farm area (km²)</td>
<td>936 8,023 21,258 37,818</td>
<td>1,130 5,652 10,239 14,817</td>
<td>1,193 9,389 28,249 63,784</td>
</tr>
<tr>
<td>Direct land use (km²)*</td>
<td>852 7,301 19,369 34,414</td>
<td>1,192 5,143 9,317 13,484</td>
<td>1,036 8,544 25,707 58,044</td>
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<tr>
<td>Total land, % of Candidate Project Areas</td>
<td>0.1% 0.8% 2.0% 3.6%</td>
<td>0.1% 0.5% 1.0% 1.4%</td>
<td>0.1% 0.9% 2.7% 6.0%</td>
</tr>
<tr>
<td><strong>Land-based wind</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed capacity (MW)</td>
<td>147,786 427,662 978,766 1,363,177</td>
<td>143,104 271,649 466,163 682,229</td>
<td>146,416 479,664 1,313,032 2,872,596</td>
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<tr>
<td>Total wind farm extent (km²)</td>
<td>54,735 158,377 362,489 504,864</td>
<td>56,335 103,944 175,986 256,011</td>
<td>57,562 180,987 489,642 1,015,149</td>
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<tr>
<td>Direct land use (km²)*</td>
<td>547 1,584 3,625 5,049</td>
<td>563 1,039 1,760 2,560</td>
<td>576 1,810 4,896 10,151</td>
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<tr>
<td>Total land, % of Candidate Project Areas</td>
<td>4.9% 14% 32% 45%</td>
<td>5.0% 9.3% 16% 23%</td>
<td>5.1% 16% 44% 90%</td>
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<tr>
<td><strong>Offshore wind</strong></td>
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<tr>
<td>Installed capacity (MW)</td>
<td>70 5,289 45,030 202,562</td>
<td>73 10,334 21,811 31,666</td>
<td>73 4,981 80,277 366,878</td>
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<tr>
<td>Total wind farm area (km²)</td>
<td>14 1,044 7,708 33,077</td>
<td>15 2,058 4,353 6,261</td>
<td>15 987 16,044 64,372</td>
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<tr>
<td>Direct area used (km²)</td>
<td>0 10 77 331</td>
<td>0 21 44 63</td>
<td>0 10 160 644</td>
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<tr>
<td>Total area, % of Candidate Project Areas</td>
<td>0.1% 4.1% 30% 129%</td>
<td>0.1% 8.0% 17% 24%</td>
<td>0.1% 3.9% 63% 252%</td>
</tr>
</tbody>
</table>

* Direct use of land or ocean area in this table refers to land on which equipment, roads, and other infrastructure are physically placed.
Total wind and solar farm area by 2050 is small in most states, with the exception of the Midwest, Great Plains, and Texas.

**Total area impacted by solar and wind development (1,000 km²)**

The impacted area by 2050 ranges from ~10 km² in Delaware to ~68,000 km² in Texas.

**Percent of state land area**

The share of land area impacted by mid-century ranges from <1% in Kentucky to ~37% in Iowa.

From downscaling assuming base site availability.
Direct land impacts by 2050 are greatest in states with high amounts of solar deployed, including in the Northeast and Southeast.

### Land area directly impacted by solar and wind development (1,000 km$^2$)

The impacted area by 2050 ranges from ~4 km$^2$ in Kentucky to ~4,400 km$^2$ in Texas.

### Percent of state land area

The share of land area impacted by mid-century ranges from <<1% in Kentucky to ~3% in Florida.

<table>
<thead>
<tr>
<th>State</th>
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<tr>
<td>FL</td>
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</tr>
</tbody>
</table>

Land Cover Type
- Crop, Pasture, Herbaceous
- Forest
- Other
- Scrub
- Wetland

From downscaling assuming base site availability.
States and land types impacted by wind and solar farms in E+RE+ by 2050 are similar to E+, but with much larger areas affected.

**Total area impacted by solar and wind development (1,000 km²)**

The impacted area by 2050 ranges from very little in several states up to 140,000 km² in Texas.

**Percent of state land area**

The share of land area impacted by 2050 ranges from very small in several states to over 50% in Iowa.

From downscaling assuming base site availability.
Direct land impacts by 2050 in E+RE+ are greatest in states with highest solar deployed, including in the Northeast and Southeast.

Land area directly impacted by solar and wind development (1,000 km²)
The impacted area by 2050 ranges from very small in some states to ~8,000 km² in Texas.

Percent of state land area
The share of land area impacted by 2050 ranges from very small in some states to nearly 5% in Florida.

Land Cover Type
- Crop, Pasture, Herbaceous
- Forest
- Other
- Scrub
- Wetland

From downscaling assuming base site availability.
More western states and fewer eastern states are impacted in E+RE- by 2050 than in E+ or E+RE+.

**Total area impacted by solar and wind development (1,000 km²)**

The impacted area by 2050 ranges from hardly any in several states to over 30,000 km² in Texas.

**Percent of state land area**

The share of land area impacted by 2050 ranges from very small in some states to 15% in Illinois and Missouri.
Direct land impacts by 2050 in E+RE- as percent of states’ areas are largest for states in the Northeast and Southeast.

### Land area directly impacted by solar and wind development (1,000 km²)

The impacted area by 2050 ranges from negligible in some states to ~2,000 km² in Texas and California.

- **Percent of state land area**

  The share of land area impacted by 2050 is about 1% or less in all states.

- **Direct land impacts by 2050 in E+RE- as percent of states’ areas**

  The impacted area by 2050 ranges from negligible in some states to ~2,000 km² in Texas and California.

- **Land Cover Type**

  - Crop, Pasture, Herbaceous
  - Forest
  - Other
  - Scrub
  - Wetland

  From downscaling assuming base site availability.
Summary of this section

- Modeled net-zero scenarios are 2 to 4 times more capital intensive than the REF scenario. E+ requires > 2.6 T$ of energy supply-side risk-capital before 2030 and >10 T$ trillion by 2050 (in addition to demand-side capital investments such as vehicles).
- Net-zero scenarios depend critically on timely mobilization of large sums of capital. Capital investments are long-lived, so timing of investments and divestments are critical. The macro-energy systems optimization model used in this study assumes rational and efficient markets that see investors respond instantly to incentives to mobilize capital. In reality, capital is mobilized through a sequence of decisions and activities which require considerable lead times and resources.
- E+ requires on the order of 190 B$ of investment before financial investment decisions (FID) are made on energy-supply projects through 2030 and 600 B$ by 2050. Pre-FID investment typically occurs 2-10 years in advance of when projects come online. Pre-FID costs are fully at-risk, since as there is no guarantee that a given project will proceed past FID to generate value.
- Risk capital includes pre-FID capital, as well as all additional capital committed prior to the Commercial Operation Date (COD) of a project. Pre-COD capital is exposed to various development, market, construction and technology performance risks which can impact project cashflows and hence project valuation. These risks can limit the availability, and increase the cost, of investment capital.
- Net-zero scenarios are characterized by a high degree of foresight and seamless integration between sectors; but investors face deep uncertainty around future technology costs and performance, policy priorities of future governments, investment preferences among peers, customers and competitors, and public acceptance of certain technologies.
- Gaps between optimization modeling and the real investment decision making obscure a number of potential challenges to mobilizing risk-capital for project development and construction that must be mitigated through policy mechanisms to meet the 2050 net-zero target.
- Such mechanisms include investment during the 2020’s to create real options for technologies needed post 2030, including multiple full-scale ‘first-N-of-a-kind’ projects to de-risk and reduce the cost of less-mature technologies and investment in critical enabling infrastructure (e.g. electricity transmission and CO$_2$ pipelines) to serve various future supply-side investments.
- See Annex M for details of capital mobilization analysis.
To avoid lock-in and reduce cost of transition, net-zero pathways capitalize on timing of stock turnover for long-lived assets

**Typical asset replacement times for various durable assets**

- Bulbs
- Other appliances
- Air conditioners & Heaters
- Vehicles
- Industrial boilers
- Conventional power plants
- Pipelines

Image credit: Ryan Jones, Evolved Energy Research
Capital dominates energy system costs in net-zero pathways: Supply-side capital in service by 2050 is 2 to 4 times REF.

- Capital-investment decision processes typically involve greater pre-investment capital-at-risk and corporate scrutiny than operating-cost decisions.
- The sheer number of capital decisions implied in these pathways represents a challenge for the transition schedule.
- Policy environment will be a key determinant of pace/scale of capital investment.

* Estimatef capital cost of energy supply assets including power generation, transmission and distribution, fuels conversion assets and CO$_2$ transport infrastructure. Excludes liquid and gaseous fuel distribution infrastructure for which very significant investments will be needed across all net-zero pathways. Also excludes pre-investment studies, permitting and finance costs.
RIO assumes that energy supply assets come online ‘overnight’ as needed to meet demands; but investment lead times are significant.

Stylized decision-gated sequence, where stages feature increasing investment to reduce risk and uncertainty, implies that substantial sums of risk capital will need to be mobilized:

- **FID** (Final Investment Decision)
- **COD** (Commercial Operation Date)

**Decision Gate**

---

Stage-gate decisions are informed by activities, the scopes of which include, but aren’t limited to:

- Engineering, logistics and cost estimating;
- Resource characterization;
- Site evaluation and selection;
- Environmental and social impact assessments;
- Stakeholder engagement;
- Land access agreements
- Market analysis and offtake agreements;
- Technology license agreement;
- EPC contract negotiations;
- Permitting & licensing.

Pre-FID activities are generally equity funded and entirely ‘at-risk’; not all proposed projects will achieve FID, so estimation of study costs must allow for a percentage of ‘failure cases’.

Post-FID, the majority of projects will be project financed using a mix of debt and equity; debt finance will be subject to finance fees that must be paid before first drawdown (i.e., at FID).

Historical experience is that depending on the risk profile, debt funds and some classes of equity investment funds may be attracted to invest only after the date commercial operations have commenced (COD).

Pre-FID investment costs, lead-times and success rates (in moving from FID to COD), along with construction times for each technology were estimated on the basis of the NZA team’s industrial experience, and in consultation with expert practitioners.
All net-zero scenarios are capital intensive. Mobilizing risk capital for development and construction will be a significant challenge.

Almost $10 trillion cumulative capital investment in supply-side plant & infrastructure (incl. pre-FID and FOAK demonstration costs)

$600 billion at-risk Pre-FID development costs to support >$9 trillion in capital investment decisions

Note: Excludes investments in demand-side transport, buildings and industry; fuels transport & distribution systems; biomass crop establishment; and land sink enhancements.
Average project development times and pre-FID costs used to estimate E+ capital mobilization requirements in the power sector.

<table>
<thead>
<tr>
<th>Generation Assets</th>
<th>Pre-FID Study Time (years)</th>
<th>Pre-FID Cost (% of TIC)</th>
<th>Financing Cost (% of TIC)</th>
<th>Total Pre-FID Cost (% of TIC)</th>
<th>Financial Close (years)</th>
<th>Construction Time (years) FID to COD</th>
<th>Overall Dev Time (years) Concept to COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass w cc</td>
<td>2.5</td>
<td>9.0%</td>
<td>1.5%</td>
<td>10.5%</td>
<td>0.5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>CCGT</td>
<td>1</td>
<td>4.5%</td>
<td>1.0%</td>
<td>5.5%</td>
<td>0.5</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>CCGT w CC</td>
<td>2.5</td>
<td>9.0%</td>
<td>1.5%</td>
<td>10.5%</td>
<td>0.5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>CT</td>
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<td>4.5%</td>
<td>1.0%</td>
<td>5.5%</td>
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<td>geothermal</td>
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<td>10.0%</td>
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<td>2</td>
<td>4.5</td>
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<td>nuclear</td>
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<td>27.1%</td>
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<td>5</td>
<td>11</td>
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<td>offshore wind</td>
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<td>10.0%</td>
<td>1.5%</td>
<td>11.5%</td>
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<td>3</td>
<td>6</td>
</tr>
<tr>
<td>onshore wind</td>
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<td>5.5%</td>
<td>1.0%</td>
<td>6.5%</td>
<td>0.5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>solar pv</td>
<td>1</td>
<td>5.5%</td>
<td>1.0%</td>
<td>6.5%</td>
<td>0.5</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>storage li-ion</td>
<td>1</td>
<td>4.5%</td>
<td>1.0%</td>
<td>5.5%</td>
<td>0.5</td>
<td>1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

| Transmission and Distribution Assets | | | | | | | |
|--------------------------------------|---|---|---|---|---|---|
| Transmission (average)               | 2.5 | 5.7% | 1.0% | 6.7% | 0.5 | 4 |
| Distribution networks                | 1 | 2.5% | 0.5% | 3.0% | 0.5 | 1 | 2.5 |
## Average project development times and Pre-FID costs used for fuel conversion, CO$_2$, and industry sectors

<table>
<thead>
<tr>
<th>FUEL CONVERSION</th>
<th>Pre-FID Time (years)</th>
<th>Pre-FID Cost (% of TIC)</th>
<th>Financing Cost (% of TIC)</th>
<th>Total Pre-FID Cost (% of TIC)</th>
<th>Financial Close (y) FID to COD</th>
<th>Construction Time (y) FID to COD</th>
<th>Overall Dev Time (y) Concept to COD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR Hydrogen</td>
<td>2</td>
<td>4.5%</td>
<td>1.0%</td>
<td>5.5%</td>
<td>1</td>
<td>2</td>
<td>5</td>
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<tr>
<td>ATR Hydrogen with CCU</td>
<td>2</td>
<td>9.0%</td>
<td>1.5%</td>
<td>10.5%</td>
<td>2</td>
<td>3</td>
<td>7</td>
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<tr>
<td>BECCS Hydrogen</td>
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<td>9.0%</td>
<td>1.0%</td>
<td>10.0%</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<tr>
<td>Biomass to SynGas</td>
<td>2</td>
<td>9.0%</td>
<td>1.5%</td>
<td>10.5%</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Biomass to SynGas with CCU</td>
<td>2</td>
<td>9.0%</td>
<td>1.0%</td>
<td>10.0%</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<tr>
<td>Biomass FT to Diesel</td>
<td>2</td>
<td>9.0%</td>
<td>1.0%</td>
<td>10.0%</td>
<td>2</td>
<td>3</td>
<td>7</td>
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<tr>
<td>Biomass FT to Diesel with CCU</td>
<td>2</td>
<td>9.0%</td>
<td>3.0%</td>
<td>12.0%</td>
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<td>4</td>
<td>8</td>
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<tr>
<td>Biomass Pyrolysis</td>
<td>2</td>
<td>4.5%</td>
<td>1.5%</td>
<td>6.0%</td>
<td>2</td>
<td>3</td>
<td>7</td>
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<tr>
<td>Biomass Pyrolysis with CCU</td>
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<td>9.0%</td>
<td>1.0%</td>
<td>10.0%</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<tr>
<td>Electrolysis</td>
<td>2</td>
<td>4.5%</td>
<td>1.0%</td>
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<td>1</td>
<td>2</td>
<td>5</td>
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<td>DAC for Synfuels</td>
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<td>1.0%</td>
<td>10.0%</td>
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<tr>
<td>Electric Boiler</td>
<td>2</td>
<td>9.0%</td>
<td>1.0%</td>
<td>10.0%</td>
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<tr>
<td>Hydrogen Blend</td>
<td>1</td>
<td>4.5%</td>
<td>1.0%</td>
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<td>1</td>
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<tr>
<td>Industrial Hydrogen Boiler</td>
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<td>4.5%</td>
<td>1.0%</td>
<td>5.5%</td>
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<td>2</td>
<td>5</td>
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<tr>
<td>Industrial Pipeline Gas Boiler</td>
<td>2</td>
<td>4.5%</td>
<td>1.0%</td>
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<tr>
<td>Power to Liquids</td>
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<td>9.0%</td>
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<td>6.5</td>
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<tr>
<td>Power to Gas</td>
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<td>10.0%</td>
<td>1.5</td>
<td>3</td>
<td>6.5</td>
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## CO$_2$ TRANSPORT & STORAGE

<table>
<thead>
<tr>
<th>CO$_2$ TRANSPORT &amp; STORAGE</th>
<th>Pre-FID Time (years)</th>
<th>Pre-FID Cost (% of TIC)</th>
<th>Financing Cost (% of TIC)</th>
<th>Total Pre-FID Cost (% of TIC)</th>
<th>Financial Close (y) FID to COD</th>
<th>Construction Time (y) FID to COD</th>
<th>Overall Dev Time (y) Concept to COD</th>
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<td>Inter-Regional Trunk Lines</td>
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<td>14.5%</td>
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<tr>
<td>Spur Lines</td>
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<td>1.0%</td>
<td>5.2%</td>
<td>0.5</td>
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<td>6</td>
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<tr>
<td>E&amp;A, Wells &amp; Facilities</td>
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<td>5.0%</td>
<td>0.0%</td>
<td>5.0%</td>
<td>0</td>
<td>1</td>
<td>2</td>
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</table>

## INDUSTRY

<table>
<thead>
<tr>
<th>INDUSTRY</th>
<th>Pre-FID Time (years)</th>
<th>Pre-FID Cost (% of TIC)</th>
<th>Financing Cost (% of TIC)</th>
<th>Total Pre-FID Cost (% of TIC)</th>
<th>Financial Close (y) FID to COD</th>
<th>Construction Time (y) FID to COD</th>
<th>Overall Dev Time (y) Concept to COD</th>
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</thead>
<tbody>
<tr>
<td>Cement</td>
<td>2.5</td>
<td>4.2%</td>
<td>1.0%</td>
<td>5.2%</td>
<td>0.5</td>
<td>4</td>
<td>7</td>
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<tr>
<td>Steel</td>
<td>2.5</td>
<td>4.2%</td>
<td>1.0%</td>
<td>5.2%</td>
<td>0.5</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

RETURN TO TABLE OF CONTENTS
The 2020s is the decade to invest in maturing and improving a range of technologies that improve options for the longer term.

- Several technologies will require multiple full-scale ‘first-N-of-a-kind’ (FOAK) projects to reduce costs and technology risks in order to make them ‘commercial ready’ for deployment at scale.
- Assumed investment premium is estimated at 150% over and above reference costs across pre-FID, design, construction and commissioning.

<table>
<thead>
<tr>
<th>FOAK Project Unit</th>
<th>No. of Projects</th>
<th>Mature cost* (used in RIO model)</th>
<th>FOAK cost multiplier on mature cost**</th>
<th>Total FOAK Investment (B$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Nuclear</td>
<td>300 MW</td>
<td>6,465 $/kW</td>
<td>2.5</td>
<td>19.4</td>
</tr>
<tr>
<td>CCGT with CC</td>
<td>300 MW</td>
<td>2,176 $/kW</td>
<td>2.5</td>
<td>8.2</td>
</tr>
<tr>
<td>CCGT with CC (Oxy)</td>
<td>300 MW</td>
<td>1,924 $/kW</td>
<td>2.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Bio-gasifier GT with CC</td>
<td>300 MW</td>
<td>6,338 $/kW</td>
<td>2.5</td>
<td>23.8</td>
</tr>
<tr>
<td>High-H₂ GT</td>
<td>100 MW</td>
<td>520 $/kW</td>
<td>2.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Advanced Geothermal</td>
<td>100 MW</td>
<td>5,472 $/kW</td>
<td>2.5</td>
<td>4.1</td>
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<td><strong>Fuels</strong></td>
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</tr>
<tr>
<td>ATR Hydrogen with CC</td>
<td>300 MW</td>
<td>782 $/kW</td>
<td>2.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Bio-gasifier H₂ with CC</td>
<td>300 MW</td>
<td>2,599 $/kW</td>
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<td>9.7</td>
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<td>100 MW</td>
<td>3,991 $/kW</td>
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<td>5.0</td>
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<td>Electrolysis</td>
<td>100 MW</td>
<td>1,790 $/kW</td>
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<td>4.5</td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>100 ktpa</td>
<td>18,954 $/ktpa CO₂</td>
<td>2.5</td>
<td>2.7</td>
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<tr>
<td><strong>Industry</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cement with CC</td>
<td>2.8 Mtpa</td>
<td>3.5 B$/plant</td>
<td>2.5</td>
<td>43.8</td>
</tr>
<tr>
<td>H₂-Direct Reduced Iron</td>
<td>2.25 Mtpa</td>
<td>400 M$/plant</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>67</td>
<td>136.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Overnight installed capital cost per unit output. For fuels, output is expressed on a higher heating value basis.

** Including pre-FID, based on Guidelines for First-of-a-kind Cost estimation [1.5 applies to FOAK plants already committed in 2020’s]
Fossil fuel industries

Summary of this section

All fossil fuel industries see rapidly declining consumption and production throughout the transition. Thermal coal consumption and production ceases by 2030.

- Over 700 coal mines close and some 500 coal-fired power plants are retired.
- The majority of coal plants retire at >30 years age, with just 8% retiring at <20 years and 50% retiring at >50 years.

Oil production declines 25% to 85% across the suite of NZA scenarios, relative to the REF scenario

- Consumption declines 60% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Oil production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on recent growth rates indicating the need to slow pace of exploration and development over time to avoid stranded assets.

Natural gas production declines between 20% and 90% across the suite of NZA scenarios, relative to the REF scenario

- Consumption declines 50% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Revenues decline significantly for producers, and remediation costs of some $25 billion are brought forward.
- Gas production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on historical growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.
- Significant stranded asset risks for gas transmission and distribution networks. A declining customer base over time will challenge cost recovery and raise equity concerns, especially in high electrification scenarios.

See Annex N for details.
Coal

Summary of this section

Thermal coal consumption and production ceases by 2030.

- Over 700 coal mines close and some 500 coal-fired power plants are retired.
- The majority of coal plants retire at >30 years age, with just 8% retiring at <20 years and 50% retiring at >50 years.
- By assumption, the US continues to produce coal post-2030 to meet domestic non-power demands as well as projected exports consistent with the EIA projections to 2050.
In all net-zero pathways most of the nearly 700 mines close by 2030, impacting all coal-producing regions.

Note: We assume that the US continues to produce coal post-2030 to meet domestic industrial and coking demand as well as projected exports consistent with the EIA 2020 AEO Reference case projections. We assume that coal imports are trivial. In 2030 for the E+ scenario, we assume that continued coal production to meet export demand occurs in states that have historically produced coal for export; we use the 2019 historical state origin of exports to spatially allocate future production.
All coal power plants (500+) close by 2030.

Retirement period of coal generators in E+ scenario

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Capacity retired from 2020 to 2050 (GW)
Average annual coal retirements in all net-zero scenarios is close to the historical peak rate observed in 2015.
The U.S. coal fleet is old. Half of plants retire 50+ years old in the 2020’s. Less than 8% (23 GW) retire before reaching 20 years.

Average age of coal plants today is 45 years.

Retirement of coal generators for E+ scenario
Generators indicated in red retire prior to the typical 50-year lifespan of coal generators, consistent with Grubert (2020).
Oil

Summary of this section

• Oil production declines 25% to 85% across the suite of NZA scenarios, relative to the reference scenario.
• Consumption declines 55% to 100% by 2050 in net-zero scenarios.
• By assumptions, exports remain in line with AEO projections to 2050.
• Oil production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on recent growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.
Oil consumption declines 55% to 100% by 2050 for net-zero scenarios relative to REF; production declines 25% to 85%.

Note: Production projections assume US produces at a rate consistent with or lower than the 2019 EIA AEO Reference case and continues to export oil at rate consistent with the AEO projection. As domestic consumption declines, an increasing share of demand is met through domestic production and a decreasing share of oil is imported. Starting around 2035, domestic demand has fallen to the point that oil imports are no longer needed, and with further demand declines thereafter, US production also declines.
Cumulative oil production through 2030 exceeds current proved reserves, but continued additions could risk stranding assets.

- Cumulative oil production to 2050 in REF and net-zero scenarios exceeds current proven reserves, indicating that all current reserves can be produced in these scenarios.

- If recent annual rates of reserve addition persist, however, proved reserves could surpass projected cumulative oil production and result in some stranded assets.
Natural Gas

Summary of this section

- Natural gas production declines between 25% and 85% across the suite of NZA scenarios, relative to the reference scenario.
- Consumption declines 50% to 100% by 2050 in net-zero scenarios.
- By assumption, exports remain in line with AEO projections to 2050.
- Significant declines in revenues for producers and bringing forward some $25 billion in remediation costs.
- Gas production to 2050 in net-zero scenarios exceeds current proven reserves, but is less than projected reserves based on historical growth rates, indicating the need to slow pace of exploration and development over time to avoid stranded assets.
- Significant stranded asset and write-down risks for transmission and distribution networks. A declining customer base over time will challenge cost recovery and raise equity concerns, especially in high electrification scenarios.
Natural gas consumption declines 50% to 100% by 2050 in net-zero scenarios relative to REF.

- Over ½ million gas wells close in 2020’s; plug and abandonment costs are estimated to be ~$25 billion.
Natural gas production through 2030 is less than current proved reserves, but continued reserve additions could risk stranding assets.

2020-2030 Near-term production and reserves
Cumulative gas production to 2030 in E+ is less than today’s proved reserves, even without reserve additions at short-term historical growth rates (8%/year).

2020-2050 Long-term production and reserves
Cumulative gas production to 2050 in E+ exceeds today’s reserves, but is less than reserves if reserves grow at long-term historical rate (4%/year).

EIA reserves estimates.
Declines in natural gas consumption will impact gas transmission and distribution infrastructure.

The existing gas pipeline network is vast:
- 20,000 miles of gathering lines (50% > 30 years old)
- 300,000 miles of transmission lines (70% > 30 years old)
- 1,300,000 miles of distribution mains (50% > 30 years old)
- 70,000,000 service lines

The transmission network is aging, but some distribution system replacements have accompanied the shale gas boom:
As gas use falls, volumetric revenues will decline, prompting need to review rate design and network asset valuations.

Decline in natural gas market revenue (E+ vs. REF) assuming volumetric rates.

Reduced spending, assuming gas prices constant across scenarios.

Revenue includes pass-through commodity cost.

*Revenue includes pass-through commodity cost.
Declining customer base over time will challenge cost recovery and raise equity concerns.

Percent reduction in number of gas-fired residential heaters from 2020

Map showing the percent reduction in number of gas-fired residential heaters from 2020 to 2030, 2040, and 2050.
Summary of this section

- A model was built to assess energy supply-related employment, wages, and workforce development requirements in energy-system transitions. (Energy efficiency, vehicle and appliance related employment is not modeled in this study.)
- To support modeled net-zero transitions, the supply-side energy workforce expands 12-24% in the 2020s across different net-zero scenarios and by 24-152% by 2050. Today ~1.5% of the labor force is directly employed in energy supply-related jobs. By 2050, this grows to 2-4% across different net-zero scenarios.
- Net-zero pathways support ~3 million energy supply-related jobs by 2030, a net increase of 0.3-0.6 million jobs relative to the REF scenario.
- Net job losses in fossil fuel sectors across the transition are more than offset (in aggregate) by increases in low-carbon sectors, especially solar, wind, and electric-grid sectors. Construction comprises an increasing proportion of jobs over time, and mining (i.e., oil, gas, coal upstream activities) comprises a declining portion.
- All employment modeling assumes current domestic content shares persist for major manufactured components.
- This modeling explicitly considers impacts of labor productivity changes on future employment. Changes in productivity have a large influence on modeled employment outcomes and more broadly on the energy transition as whole.
- An annual average of ~$170-180 billion in wages are generated in the 2020s, a net increase of $20-30 billion over the REF scenario. Supply-side energy sector employment generates ~2% of total U.S. wages, rising to as much as 4.5% by mid-century.
- A number of modifiable sociotechnical factors influence the spatial distribution of labor. With assumptions used here, all states see energy-related employment grow as a share of the total state labor force except for a few with very high shares of the current labor force employed in upstream fossil fuel industries (e.g., WY). In some states with high renewable resource quality (e.g., NE, MT, IA), energy industries grow to become dominant employers.
- There will be an increasing demand for workers with a diversity of education, experience, and training backgrounds.
Decarbonization Employment & Energy Systems model (DEERS)

Labor model assesses supply-side employment, wages, and workforce development requirements associated with energy-system transitions.

- Pairs with output of economy-wide or spatially downscaled macro-energy system modeling.
- Architecture largely derived based on current data of economic accounts and energy activity.
- Models the distribution of labor impacts across 50 states, 9 economic sectors, 9 resource supply chains, 50 industries, and 1000+ occupations.
- Includes time-variant factors, such as labor productivity and wage inflation, relevant for long-term planning.
- Can be used to evaluate policy and planning decisions, such as just-transition funds, workforce development needs, domestic manufacturing, oil/gas exports, and facility siting.

See Annex R for DEERS model details.

Note: In this analysis, we focus on energy supply-related resource supply chains (i.e., biomass, CO₂, coal, electric power grid, natural gas, nuclear, oil, solar, wind). We do not model employment related to energy efficiency, electric vehicles, or consumer electronics/appliances.
Employment simulated using DEERS (based on actual 2018 activity data) compares well with actual 2018 employment.

Model calibration results
~3 million direct energy supply-related jobs annually in the 2020s in net-zero scenarios, or ~0.5 million more than REF scenario.

Employment pathways are influenced by:
- Technology selection
- Rate of electrification
- Extent of renewables deployment
- Changes in labor productivity
1.5% of the U.S. labor force is directly employed in energy-supply today, increasing to 2-4% by 2050 in net-zero scenarios.
Net job losses in fossil fuel sectors in near- and long-term are more than offset (in aggregate) by increases in low carbon sectors.
Solar, wind, and grid dominate energy-sector jobs. Construction share increases over time, while mining (upstream fossil) declines.
Changes in labor productivity have a large influence on employment outcomes and more broadly the energy transition as whole.

Historical changes in labor productivity

**Short-term**

<table>
<thead>
<tr>
<th>Industry</th>
<th>10-y Average annual change in productivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture, Forestry, Fishery</td>
<td>1.8%</td>
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<tr>
<td>Construction</td>
<td>2.5%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>1.5%</td>
</tr>
<tr>
<td>Other Services</td>
<td>1.1%</td>
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<tr>
<td>Wholesale Trade</td>
<td>2.3%</td>
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</table>

**Long-term**

<table>
<thead>
<tr>
<th>Industry</th>
<th>30-y Average annual change in productivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture, Forestry, Fishery</td>
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</tr>
<tr>
<td>Construction</td>
<td>2.8%</td>
</tr>
<tr>
<td>Mining</td>
<td>2.3%</td>
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<tr>
<td>Other Services</td>
<td>1.1%</td>
</tr>
<tr>
<td>Wholesale Trade</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Note: Other employment modeling results shown in this report correspond to the results with increasing labor productivity shown on this slide.
Modifiable socio-technical factors influence spatial distribution of employment. Below is one instantiation of the future (out of many).

Modifiable sociotechnical factors that influence the spatial distribution of employment:

- Resource quality and availability
- Rate of electrification
- Technology selection
- Domestic manufacturing
- Siting constraints
- Oil and gas exports
- Political and policy processes and constraints

There are several degrees of freedom that can reduce transition risks and be leveraged for political bargaining.
Transitioning to a net-zero energy system has the potential to transform state and local economies. 

Annual employment, E+ scenario (thousand jobs)

Color indicates change in average decadal employment:

- > 15% above 2021
- within ±15% of 2021
- > 15% below 2021

Note: Spatial redistribution of solar and wind manufacturing facilities and increasing the domestic manufacturing share offer opportunities to ameliorate losses in fossil fuel extraction states. For assumptions used here in siting solar and wind manufacturing jobs, see this slide.
State-level distributions of employment by resource sector change dramatically over the transition.

Employment by resource sector (%)

E+ scenario
Solar, wind, and grid jobs are increasingly dominant in many states, but regional heterogeneity could be a risk to a just transition.
In most states, energy-related employment grows as a share of total employment through the transition to 2050.

- In a few states with a very high share of the current labor force employed in upstream fossil fuel industries (e.g., WY), energy-related employment decreases as a share of the total employment through the transition.
- In states with high renewable resource quality (e.g., NE, MT, and IA), energy industries grow to become major employers.
Oil is the largest resource sector today, with \( \frac{1}{3} \) of supply-side energy jobs: \(~800,000\) oil-sector jobs today (model estimate).

Oil employment declines in both REF and net-zero scenarios, influenced by the rate of electrification, extent of renewables deployment, and oil imports and exports. By 2050, employment in the REF scenario is approaching half that today, and in the net-zero scenarios it declines by 60-95%.

Note: all fossil energy sectors are assumed to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.
The natural gas sector is the 2\textsuperscript{nd} largest energy-employer, but upstream jobs have been rapidly declining for several years.

Natural gas sector supports 600,000 jobs associated with production (60%), transmission & distribution (30%), and power generation (10%) in model year 2021.

Employment in oil & gas extraction industry has been rapidly declining for years, and has accelerated during the COVID-19 pandemic.

Natural gas extraction industry currently is a major employer in several counties, although part of the workforce is transient. During the peak of the shale gas boom, the natural gas industry comprised upwards of 60% of combined direct, indirect, and induced employment in one West Virginia county.
Jobs in natural gas value chain decline to 2050, except for gas power generation. The Appalachian and Permian basins are most affected.

Natural gas employment decline is influenced by the rate of electrification, extent of renewables deployment, and natural gas exports.

Spatial distribution of supply chain employment for E+ scenario

Note: all fossil energy sectors are assumed to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.
Coal mining jobs have been declining for 3 decades. Phasing out coal has greatest impact on resource-dependent rural labor markets.

At the national-scale, the coal sector is relatively small, representing 5% of the energy workforce in 2021. For model year 2021, there are 150,000 jobs associated with production (40%), transport (20%), and power generation (40%).

Over past three decades, employment in coal mining industry has declined dramatically (62%). Average decline rate of 3%/yr (3,000 jobs/yr) and peak decline rate in 2016 of 21%/yr (13,000 jobs/yr).

Coal mining industry currently is a major employer in several counties. The coal sector represents 5% or greater of labor force in 35 counties. This includes only jobs within the mining industry, not indirect and induced employment.
Coal jobs continue to decline at recent historical rate. Impacts are concentrated in the Appalachian & Powder River River basins.

Eliminating coal for power by 2030 implies an annual decline rate of 14,000 jobs/yr, compared to a decline rate of 8,000 jobs/yr in the reference scenario over the first decade (6,000 jobs/yr mining/upstream, 2,000 jobs/yr transportation, 7,000 jobs/yr power generation)

Job losses concentrated in mining regions.

Note: all fossil energy sectors are assume to continue domestic extraction to supply projected exports consistent with the EIA AEO 2020 Reference case.
By 2050, employment in solar comprises a quarter of energy-related jobs in net-zero scenarios. Even in the reference scenario, solar emerges to be equivalent in size to the oil sector.

Spatial distribution of employment is influenced by resource quality, siting constraints and decisions, and extent and location of domestic manufacturing.

Note: solar and wind related manufacturing employment estimates assume continuation of current domestic content shares.
By 2050, employment in the wind sector comprises 10 to 25% of energy-related jobs in the net-zero scenarios, surpassing the size of the current natural gas sector.

Spatial distribution of employment is influenced by resource quality, siting constraints and decisions, and extent and location of domestic manufacturing.

Note: solar and wind related manufacturing employment estimates assume continuation of current domestic content shares.
Solar and wind manufacturing offer opportunities to distribute employment benefits across multiple states

There are degrees of freedom in siting solar and wind manufacturing facilities and the amount of manufacturing done domestically. This flexibility can be leveraged to offset job losses in communities, build coalitions, and facilitate legislative bargaining.

• To maintain current domestic shares of manufacturing (79% wind, 15% solar), manufacturing capacity must increase in most scenarios:
  • by 2030: 3-7X for wind, 1-4X for solar
  • by 2050: 2-20X wind, 1-8X solar

• Increasing domestic content share has minimal impact on technology costs, while supporting additional domestic jobs.

Note: Spatial redistribution of solar and wind manufacturing facilities and increasing the domestic manufacturing share offer opportunities to ameliorate losses in fossil fuel extraction states. The estimates here assume 1) manufacturing is sited within the logistic region (see next slide) where solar and wind generation are sited to account for transport between manufacturing and generation, 2) the distribution of manufacturing by state within a logistic region is consistent with the distribution of 2018 energy-related jobs (next slide), and 3) the domestic share of manufacturing is consistent with the historical domestic share (i.e., 79% wind, 15% solar).
Assumptions for modeling the state-wise distribution of solar and wind manufacturing jobs

The state-wise distribution of solar and wind manufacturing jobs assumes 1) manufacturing is sited within the logistic region where solar and wind generation are sited, 2) the distribution of manufacturing by state within a logistic region is consistent with the distribution of 2018 energy-related jobs, and 3) the domestic share of manufacturing is consistent with the historical domestic share (i.e., 79% wind, 15% solar).
~450k grid-related jobs today represent ~20% of energy supply-related workforce. By 2050, these grow to 35-45%.

Growing employment is largely associated with the 2-4x expansion of the grid and ongoing O&M of existing and expanding grid infrastructure. Employment growth is generally correlated with renewables deployment.

Spatial distribution generally correlates with existing grid infrastructure and new renewables.

Employment (jobs)
- 0K
- 100K
- 200K
- 300K
- 400K

Transmission & distribution
Wages for energy-supply related employment increase through net-zero transitions.

Annual wage income is 170 to 180 B$ in net-zero scenarios in the 2020s, an increase of 20-30 B$ over REF

Energy-related wages represent ~2% of total wages today and 2-4.5% by mid-century in net-zero scenarios.
Modifiable socio-technical factors influence spatial distribution of wages. Below is one instantiation of the future.

Annual wages based on downscaled E+ scenario
(billion 2019$)

There are several degrees of freedom that can reduce transition risks and be leveraged for political bargaining.

- Resource quality and availability
- Rate of electrification
- Technology selection
- Domestic manufacturing
- Siting constraints
- Oil and gas exports
- Political and policy processes and constraints

Note: Green, yellow, and red coloring indicate whether average annual wages within a decade is more than 15% higher, within 15%, or more than 15% lower than 2021 wages, respectively.