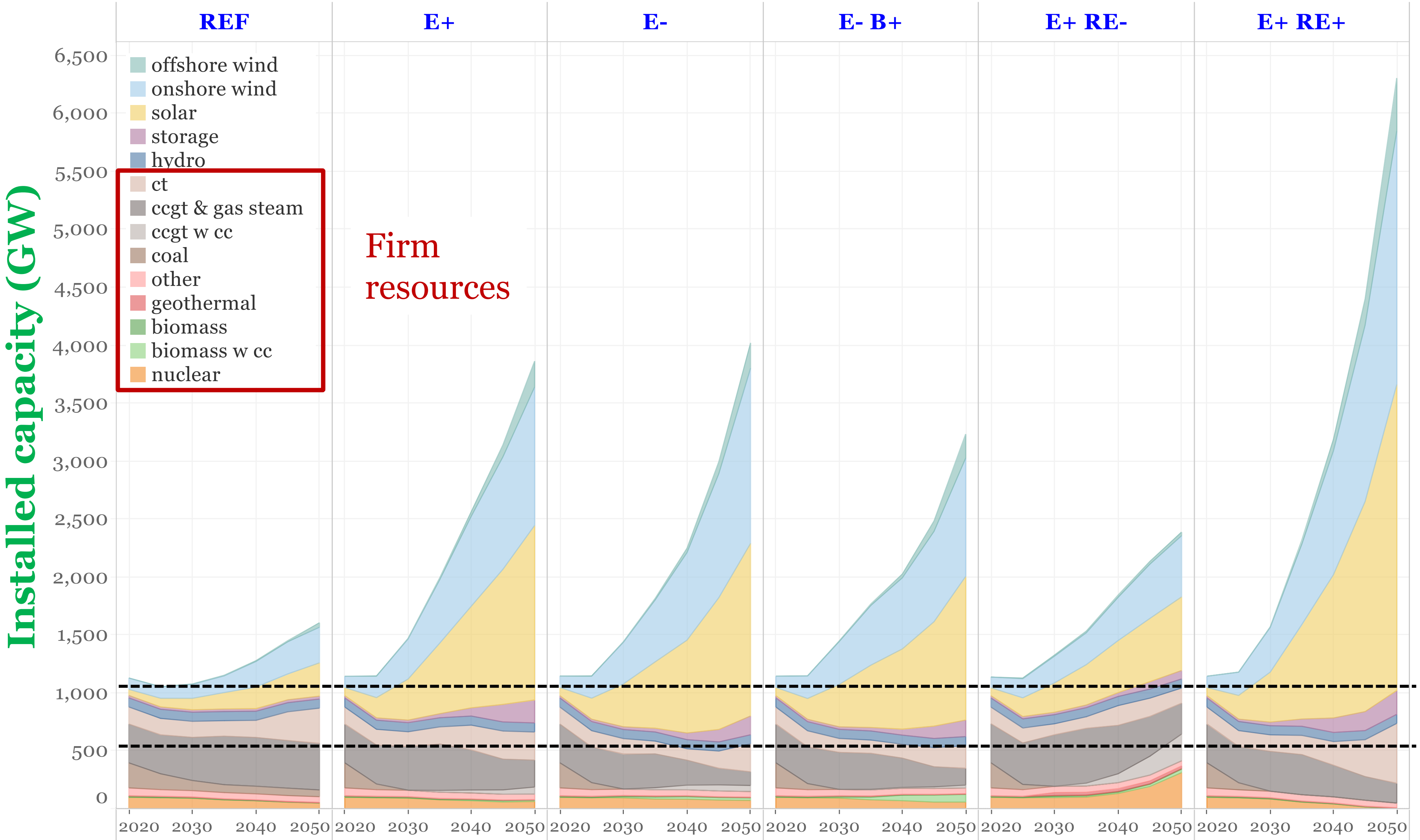
Firm capacity stays comparable to today; high H_2 fuel blends for gas turbines have important role; nuclear & gas w/CCS key in RE-



Note:

To reduce the carbon intensity of CCGT and CT generation, H_2 is blended as an increasing fraction of fuel to these units, up to an exogenously specified cap of 60% (HHV basis).

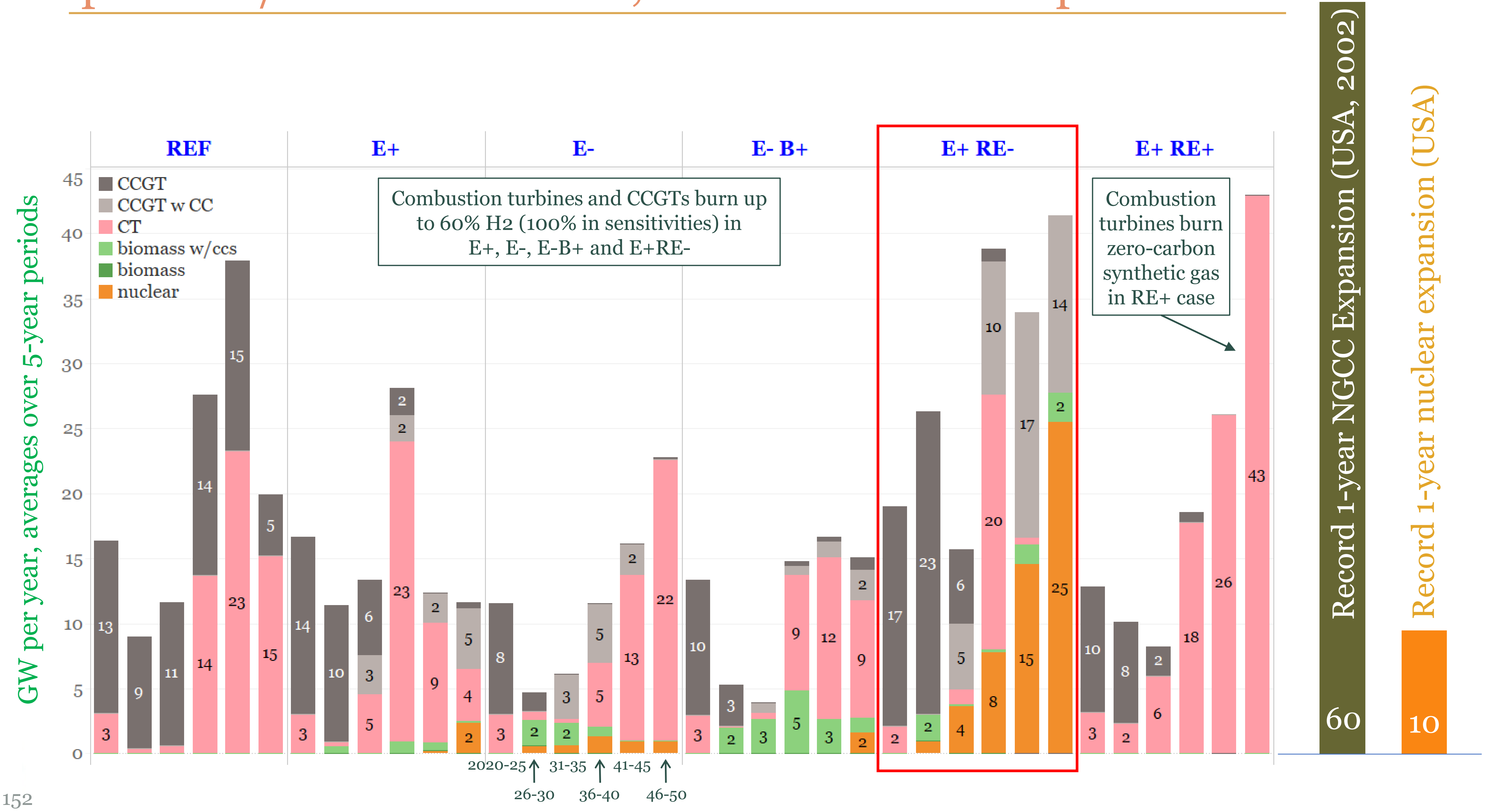
In sensitivities with 100% H_2 firing allowed, the model prefers 100% blend which modestly reduces total energy system costs. (See Annex B for additional details.)

Firm capacity (across all years)

~500-1000 GW

RETURN TO TABLE OF CONTENTS

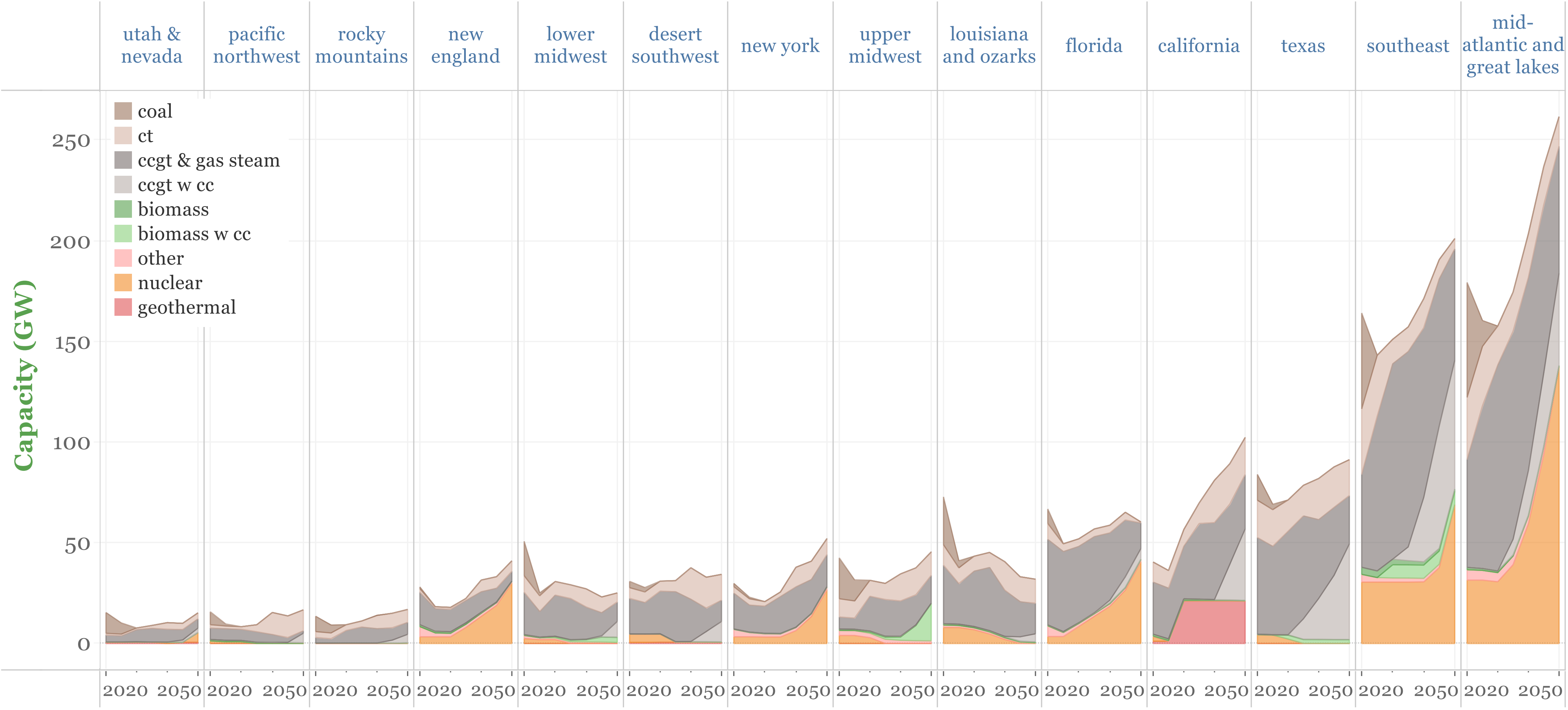
E+ RE- requires historically-unprecedented growth rates for gas plants w/CCS and nuclear, sustained for multiple decades



RETURN TO TABLE OF CONTENTS

New England, New York, California, Florida, Southeast and Mid-Atlantic/ Great Lakes regions see largest nuclear growth in RE-

E+ RE-



PRINCETON UNIVERSITY

andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Modeling conversion and retirement of coal, gas, and nuclear plants and sites considers operating costs and site suitability criteria.

Site suitability assessment

Evaluate potential sites based on suitability and exclusion criteria

- Safety
- Environmental / cultural
- Water intake
- Site size
- CO_2 infrastructure
- Environmental justice

Retirement simulation

Timing and location by plant type

- Regional & temporal retired capacity constraints
- Prioritize based on operating costs

Site conversion simulation

Conversion of existing thermal sites to new natural gas or nuclear sites

- Site conversions prioritized by extent of siting constraints for each technology
- Retirement of existing plants
- Regional & temporal incremental capacity constraints
- Site suitability constraints
- Re-development temporal lag constraints

See Annex E for additional discussion of thermal plant siting analysis.

PRINCETON UNIVERSITY

andlinger center for energy+the environment

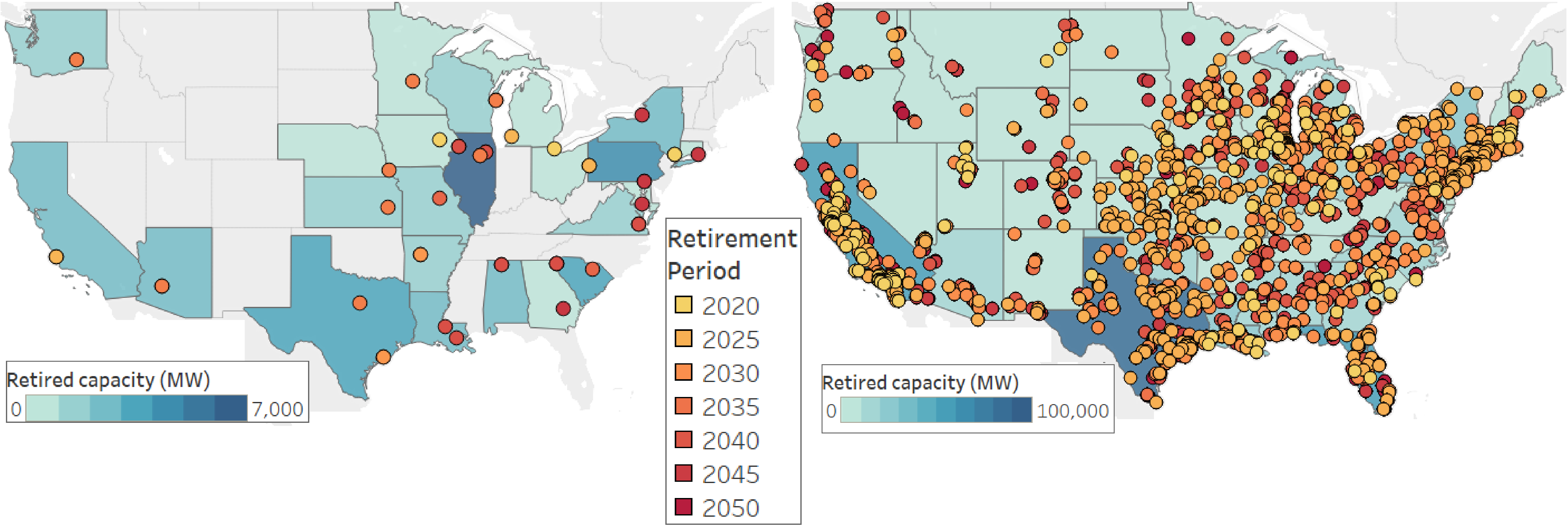
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

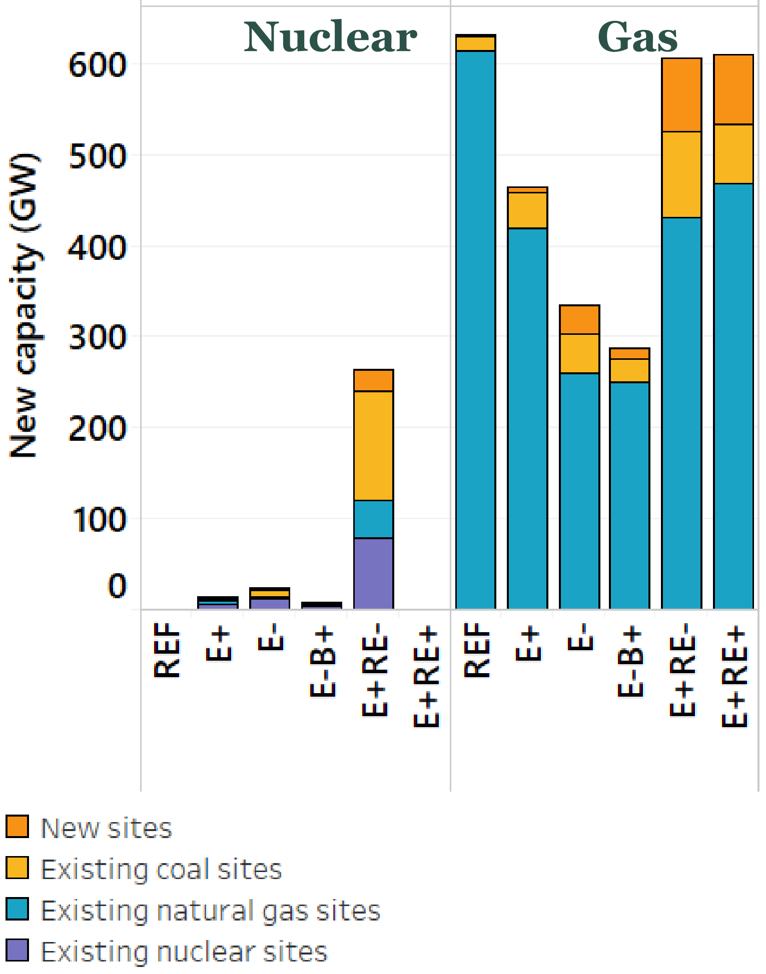
Due to age, 45% of nuclear and 80% of gas capacity retire by 2050; site repowering or conversion to low-carbon generators is possible.

Nuclear | Natural gas

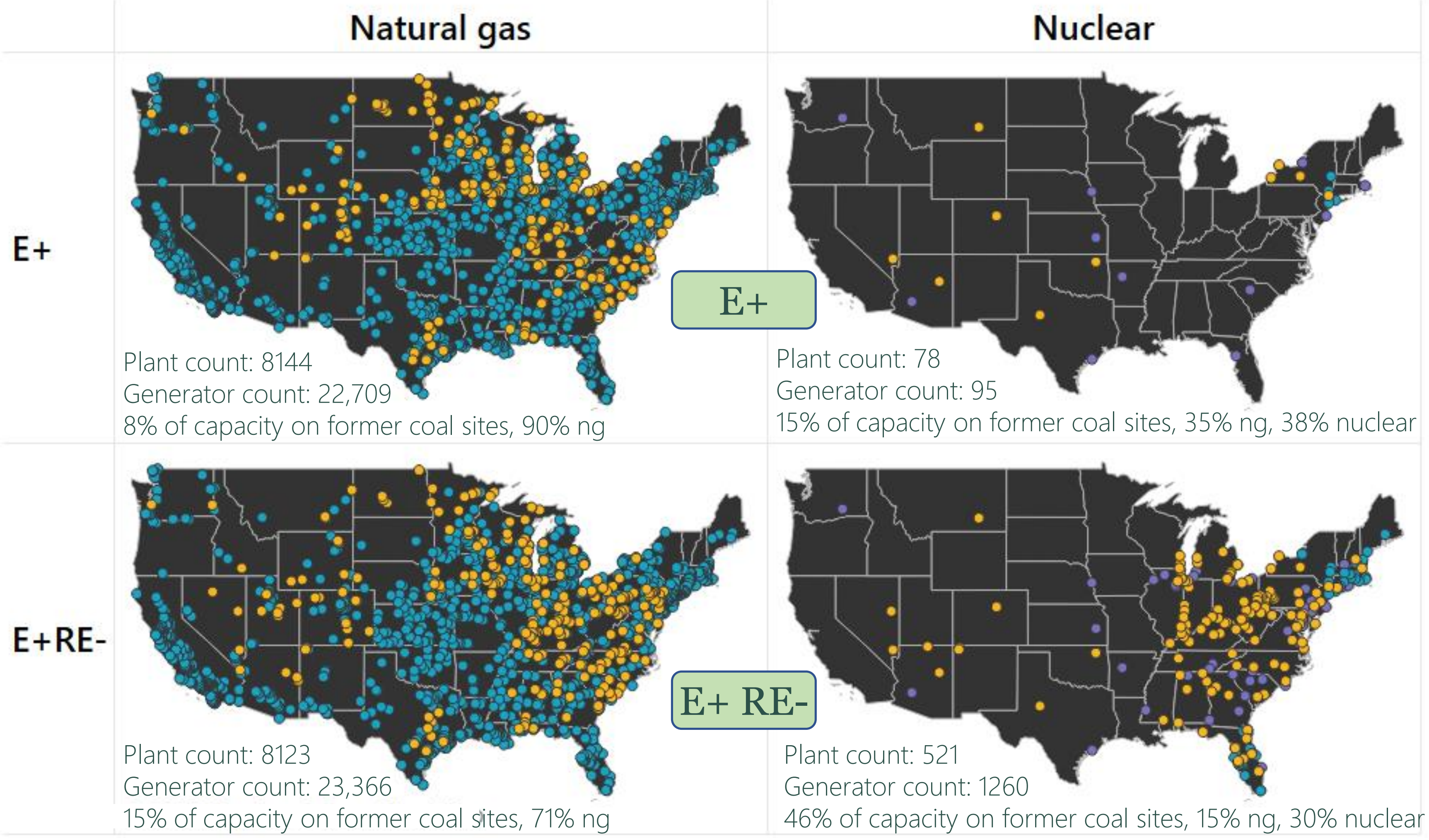


Most new gas and nuclear capacity can be accommodated at existing thermal plant sites, if no new siting restrictions are applied.

New capacity by site type cumulative 2020 - 2050



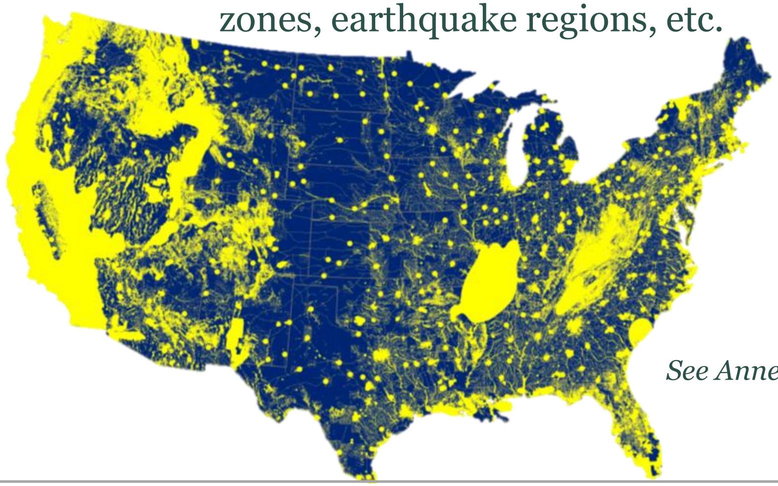
Site conversions by site type by 2050



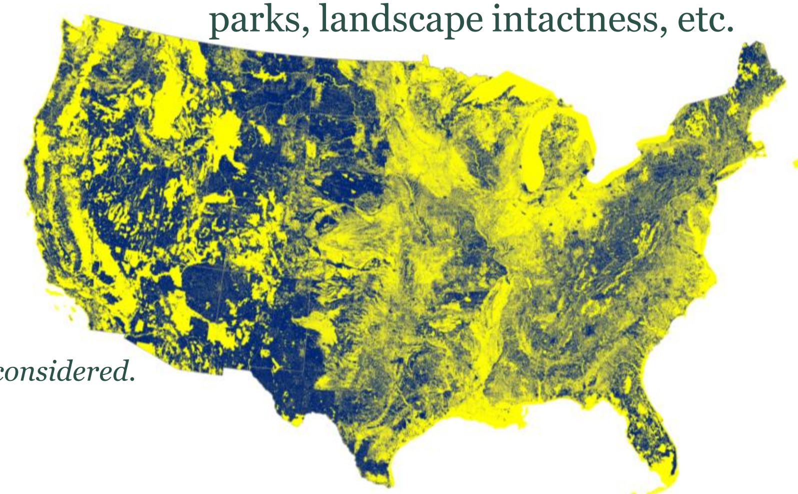
Siting constraints vary by region and are uncertain for emerging technologies (e.g., advanced nuclear).

Many brownfield sites may not meet all environmental and safety-related land-use criteria in a restrictive land use planning regime.

Safety exclusions *(12)*: urban areas, flood zones, earthquake regions, etc.



Environmental exclusions *(35)*: wetlands, national parks, landscape intactness, etc.

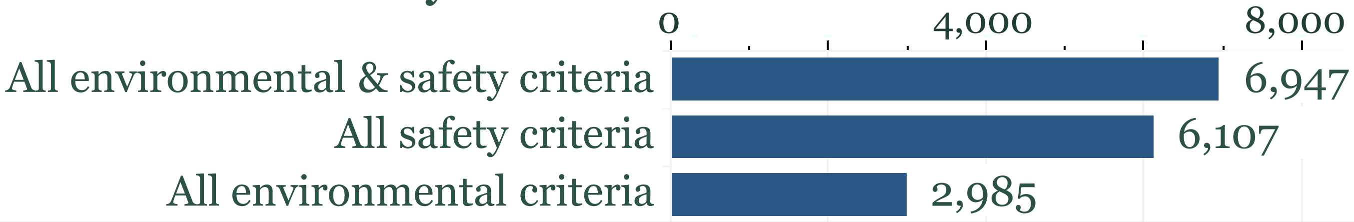


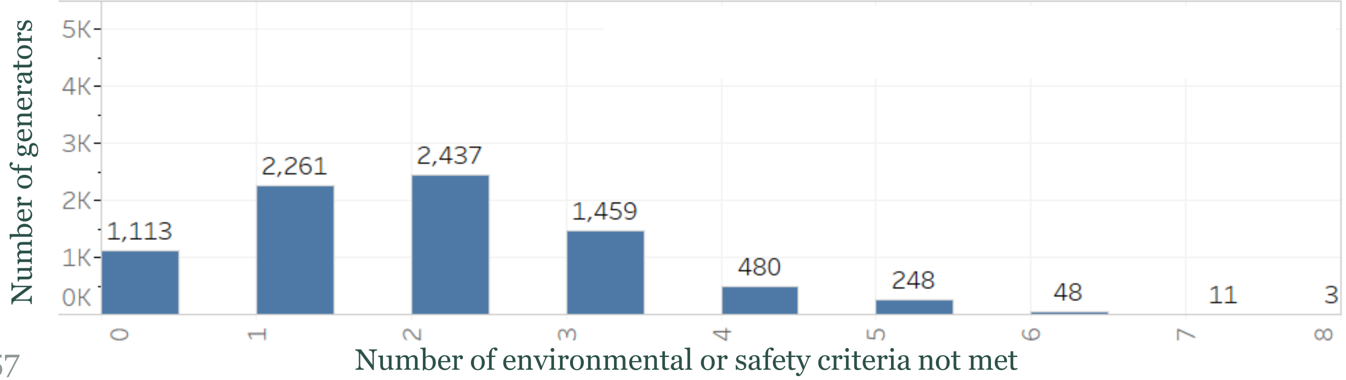
Unsuitable area

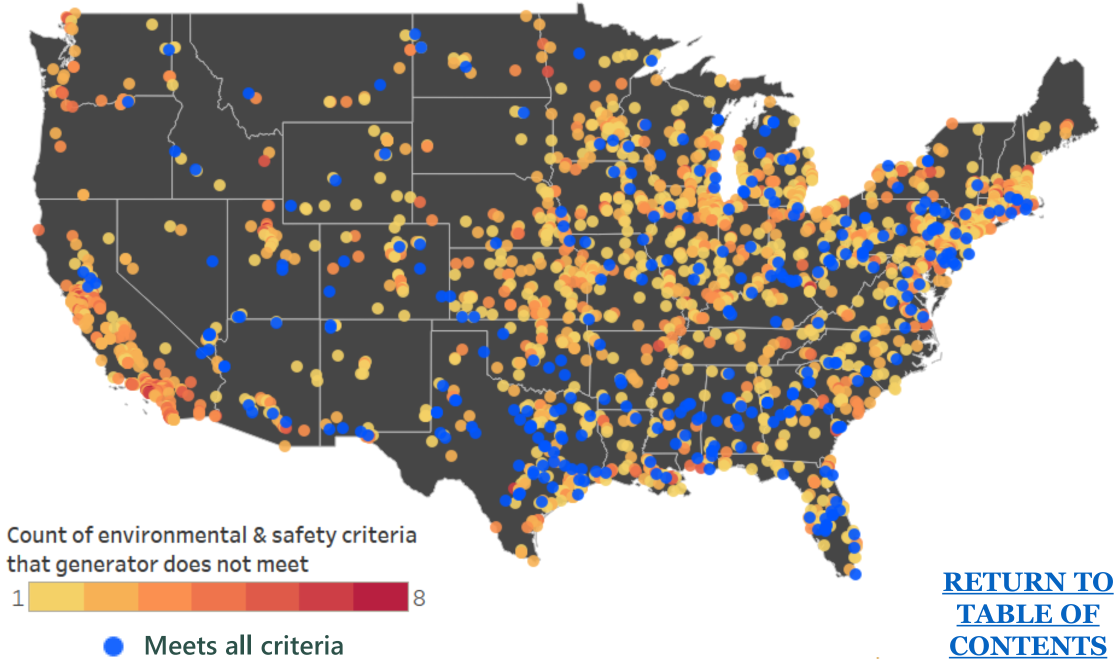
Suitable area

See Annex E for full list of exclusions considered.

Number of current generator locations that would fail to meet site suitability criteria

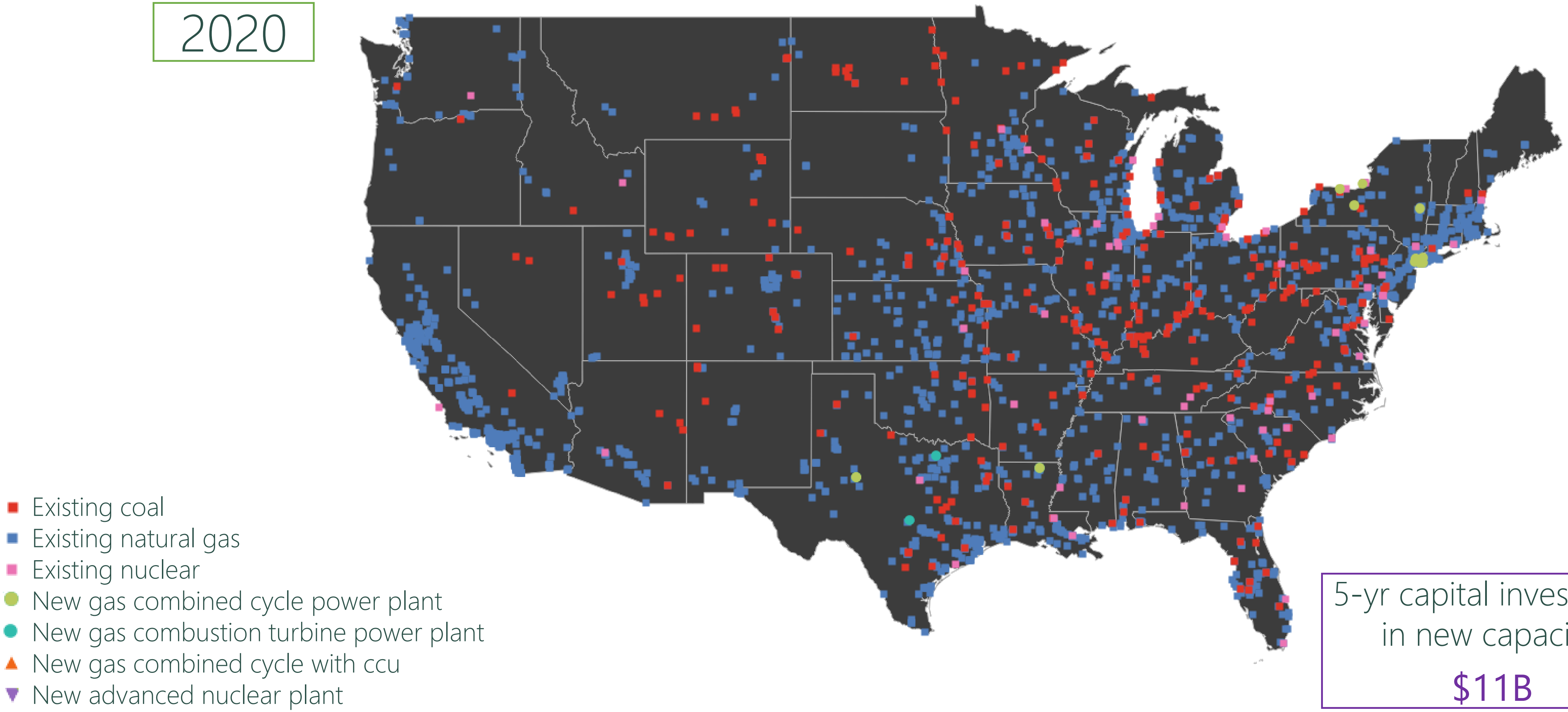






RETURN TO TABLE OF CONTENTS

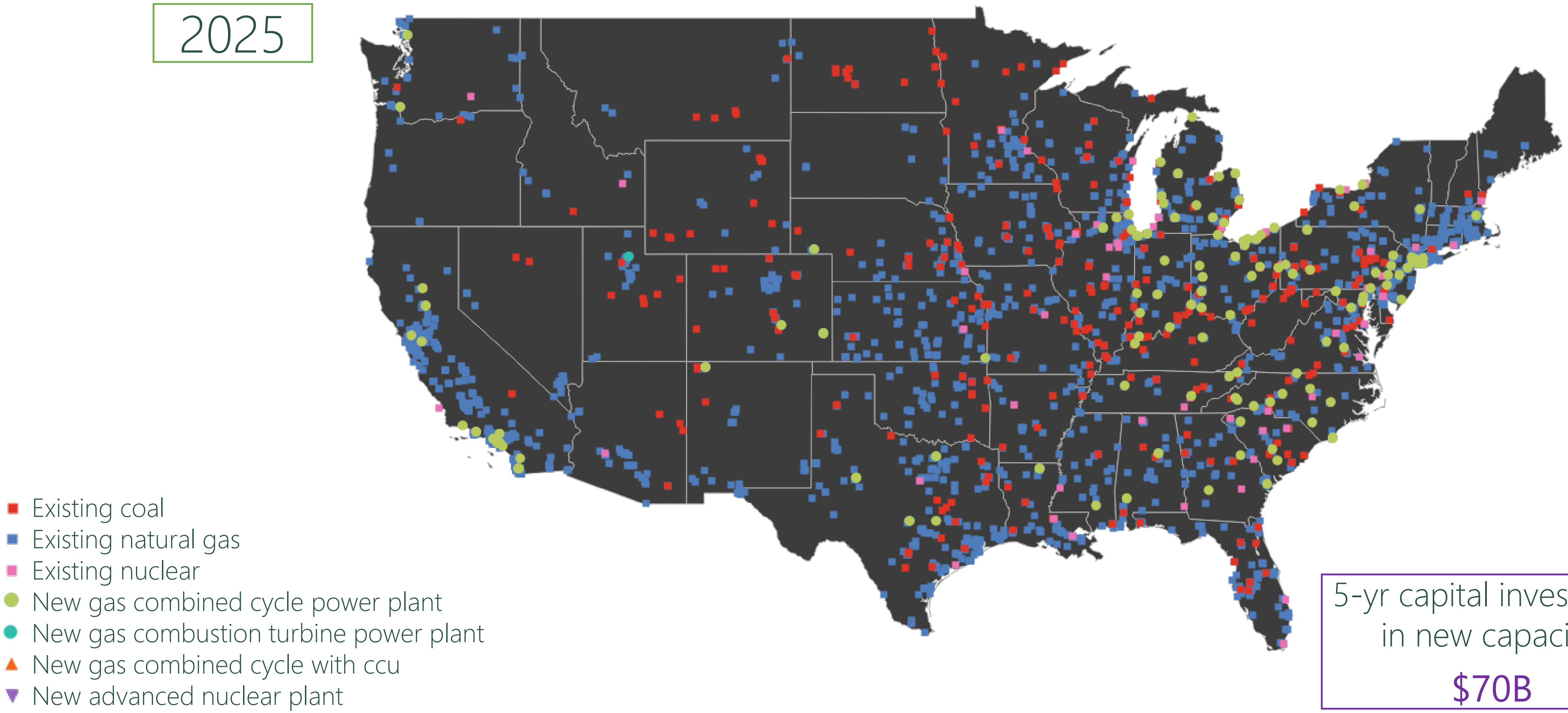
Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2020



5-yr capital investment in new capacity:

$11B

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2025



5-yr capital investment in new capacity:

$70B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

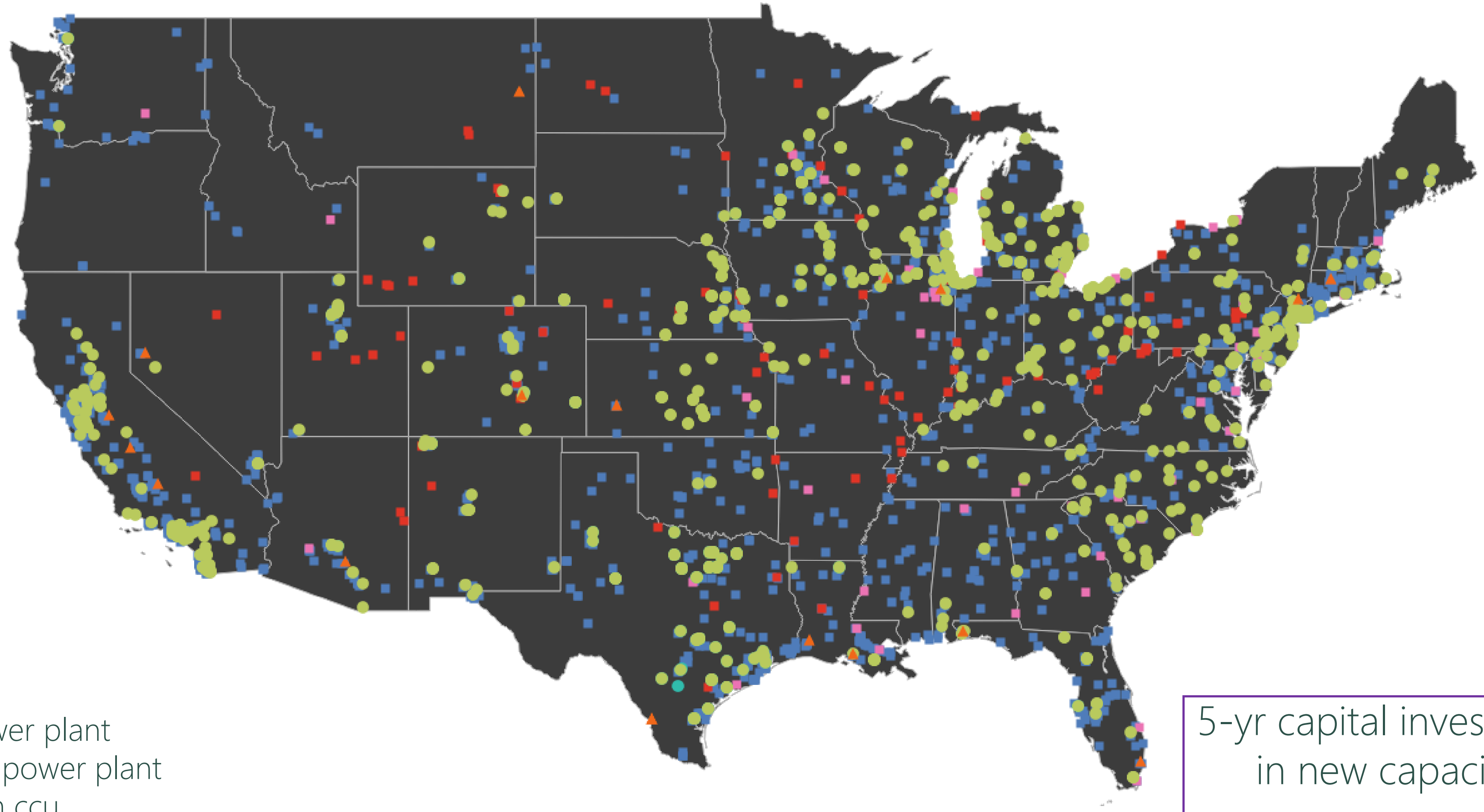
High Meadows Environmental Institute

Carbon Mitigation Initiative

RETURN TO TABLE OF CONTENTS

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2030

2030



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$46B

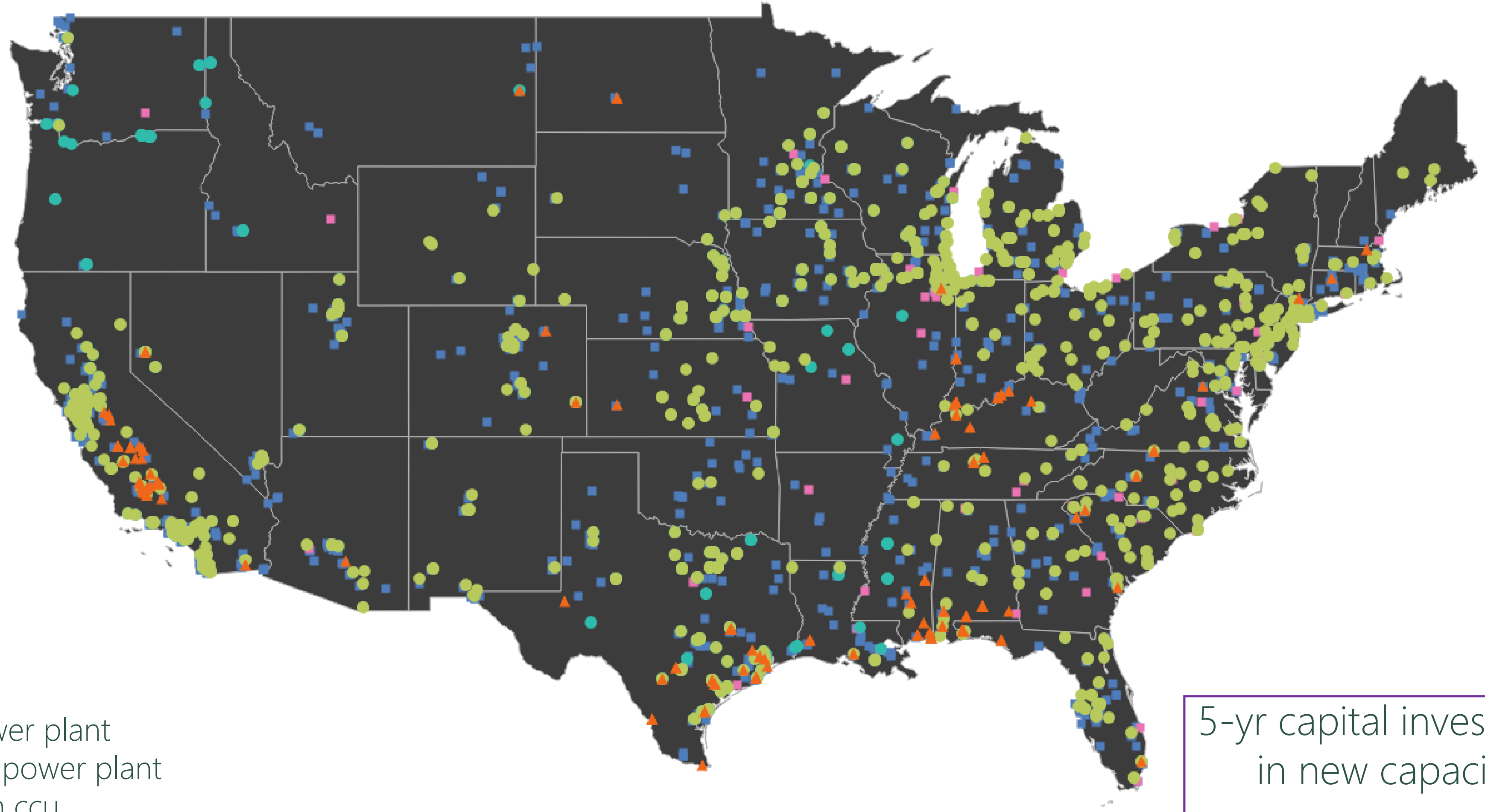
PRINCETON UNIVERSITY
andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute
Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2035

2035



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$66B

PRINCETON UNIVERSITY

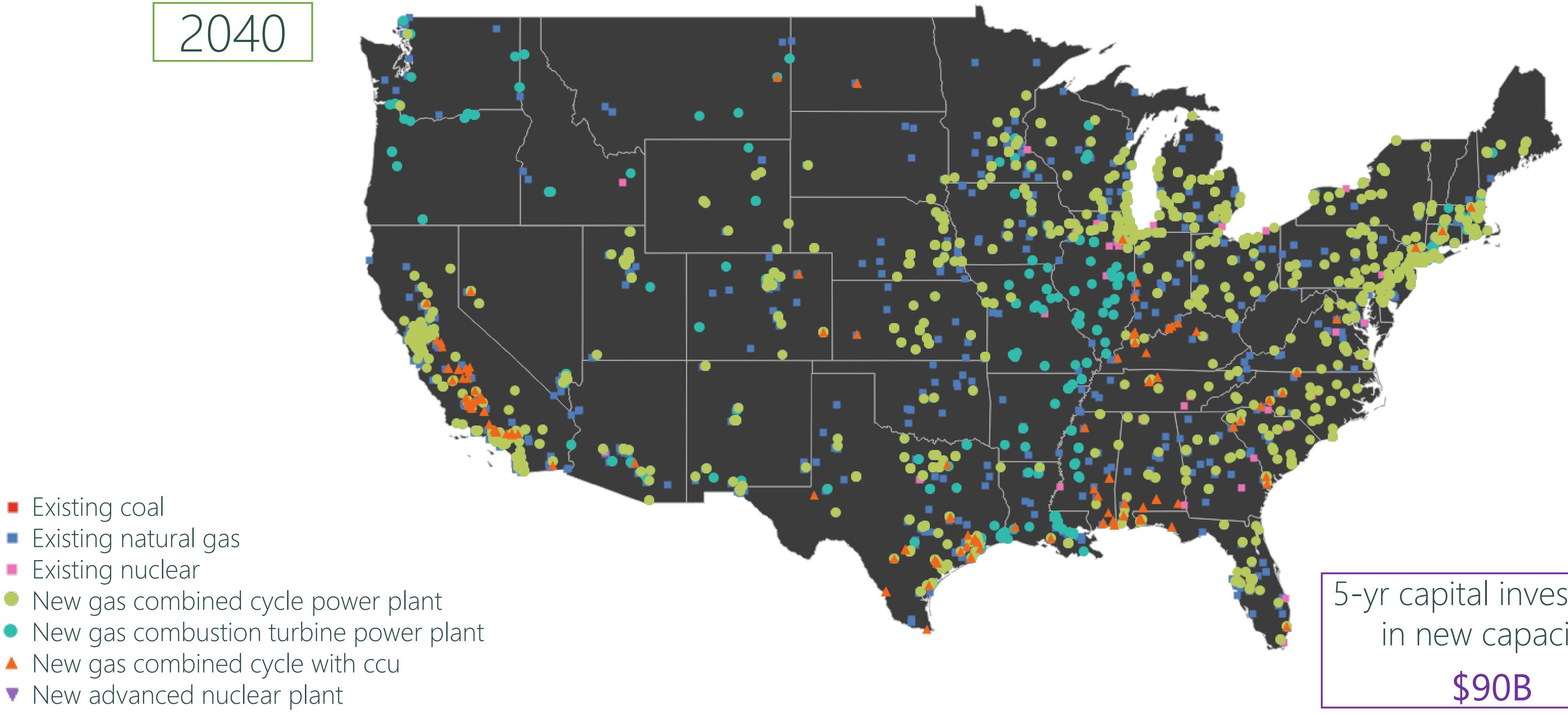
andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2040



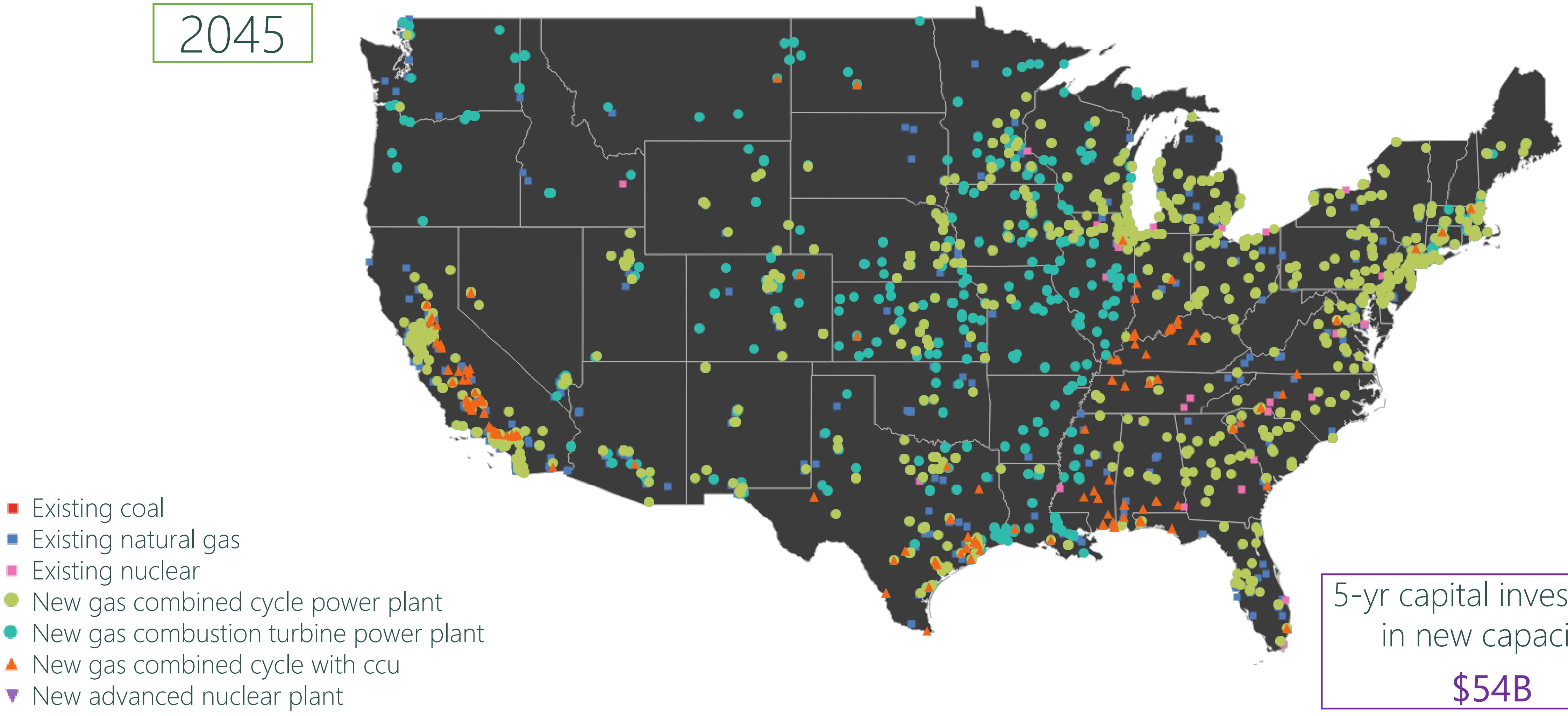
5-yr capital investment in new capacity:

$90B

PRINCETON UNIVERSITY | andlinger center for energy+the environment | High Meadows Environmental Institute | Carbon Mitigation Initiative

RETURN TO TABLE OF CONTENTS

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2045



5-yr capital investment in new capacity:

$54B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

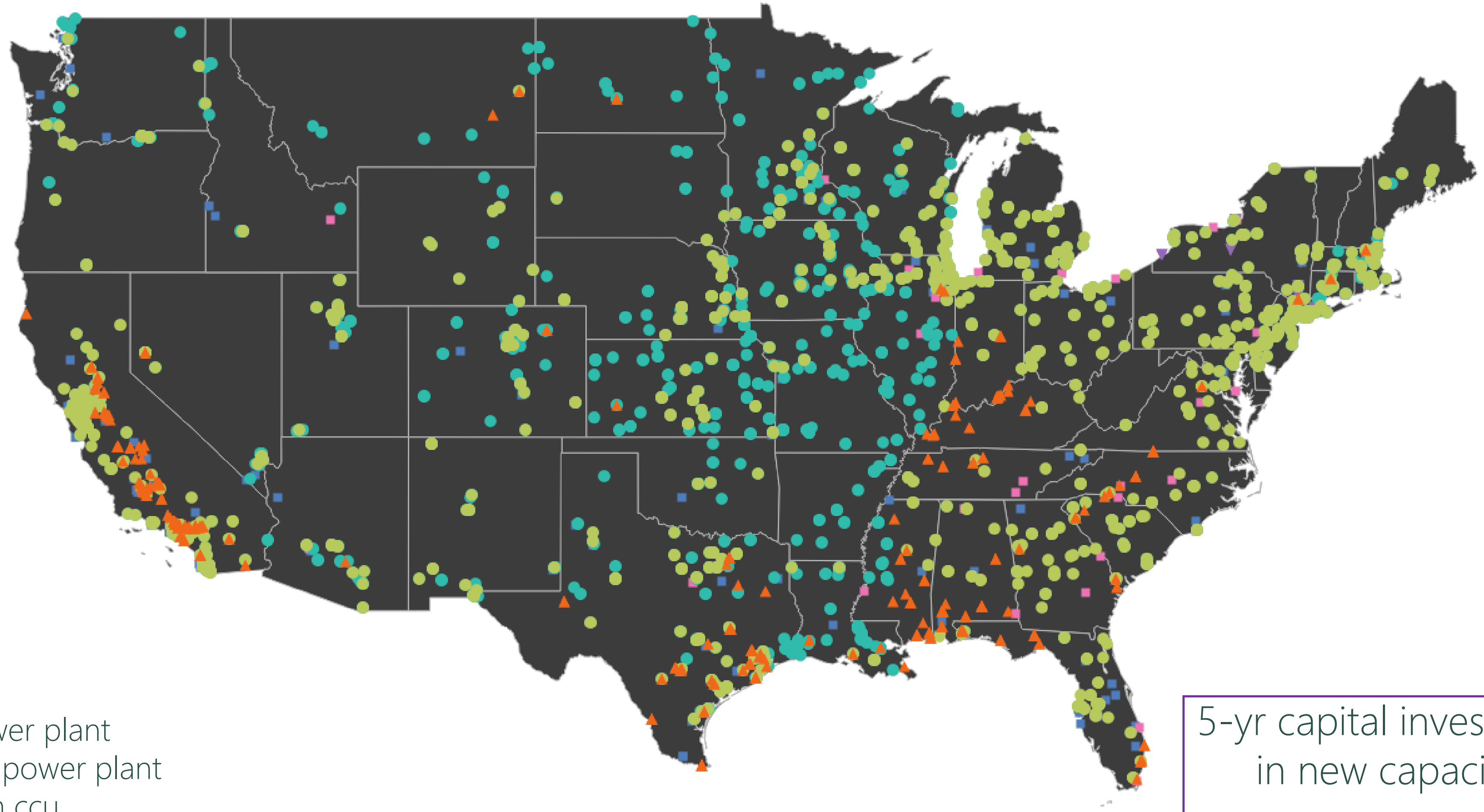
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+ if no new siting-criteria filters applied, 2050

2050



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

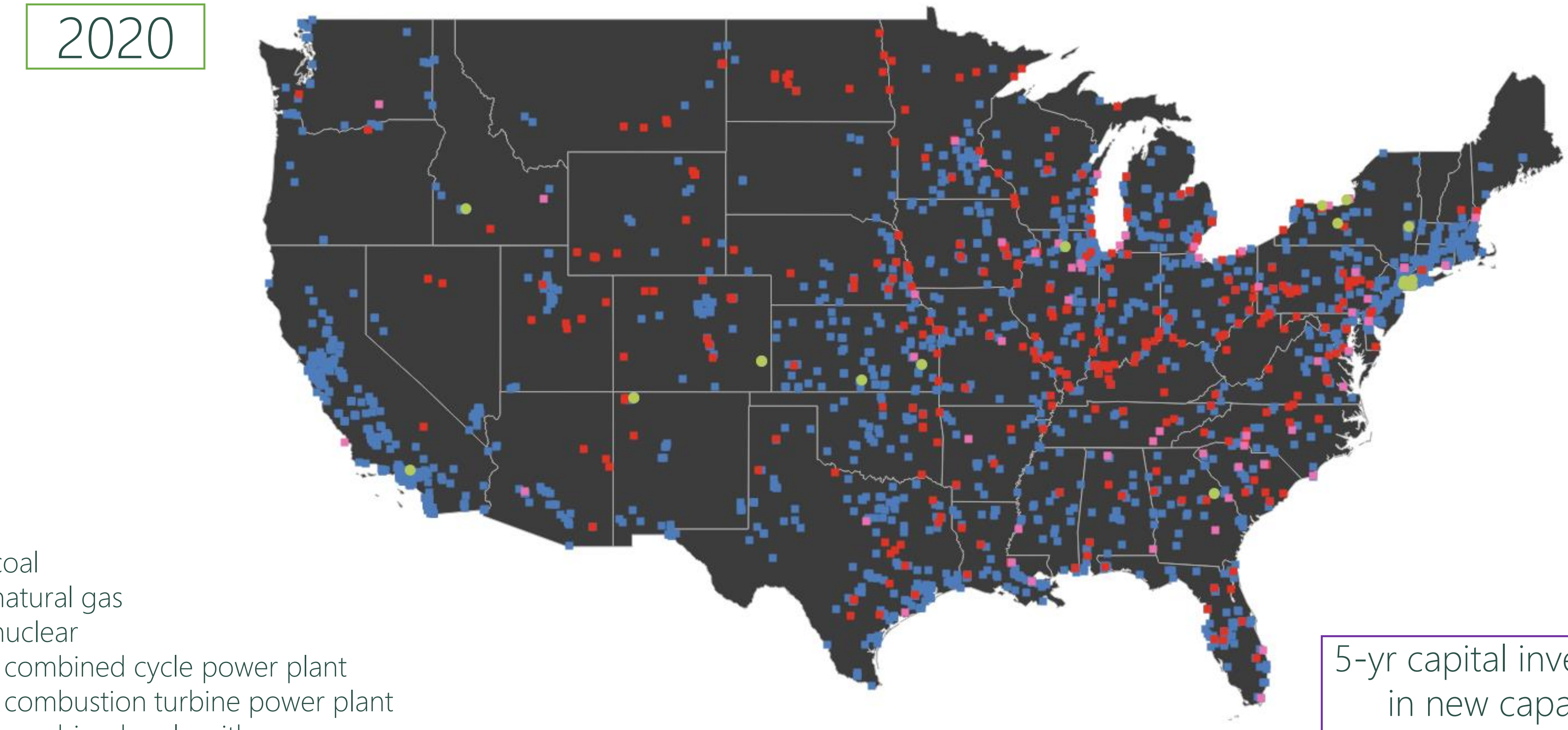
$123B

PRINCETON UNIVERSITY andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute | Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2020



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$12B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

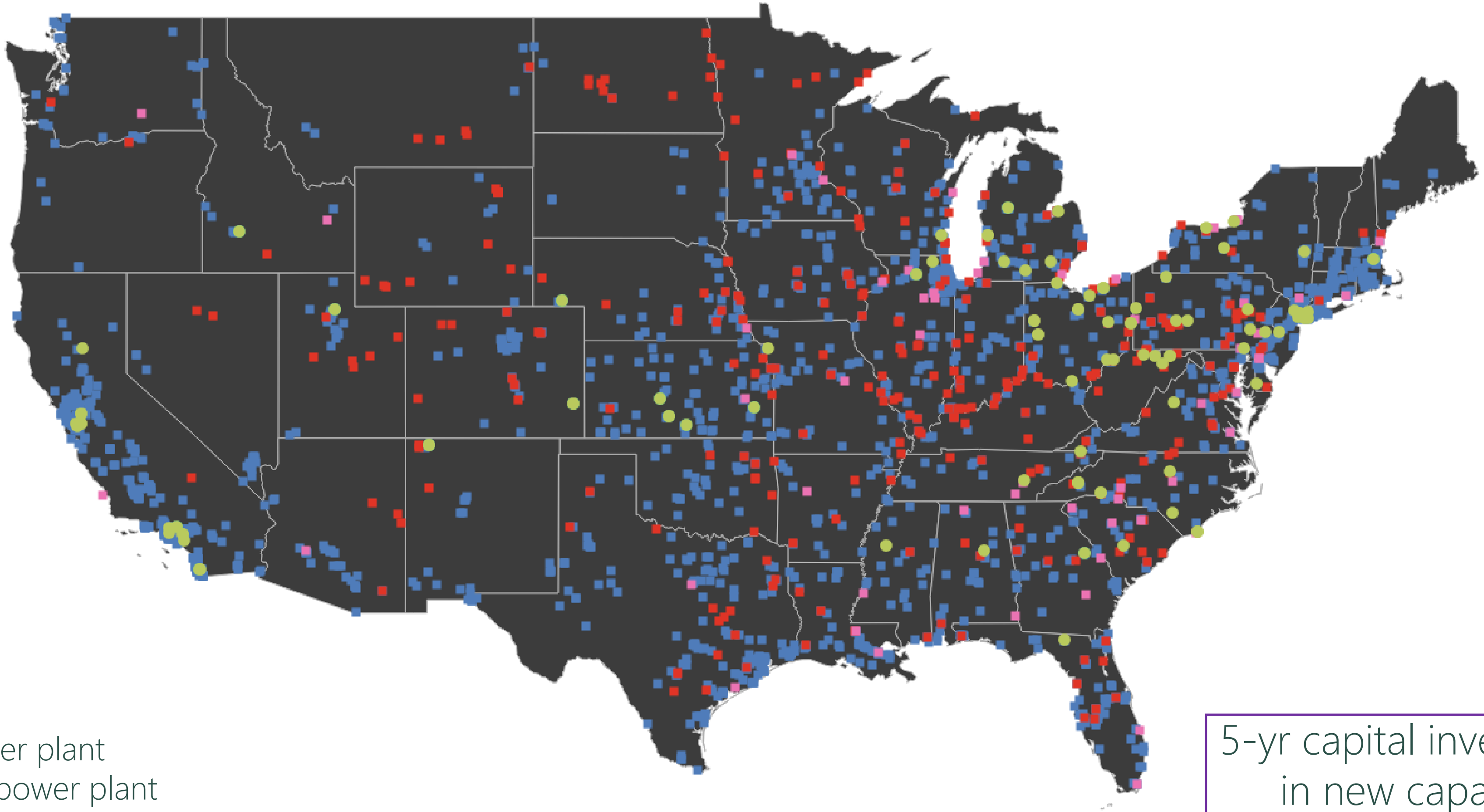
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2025

2025



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$83B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

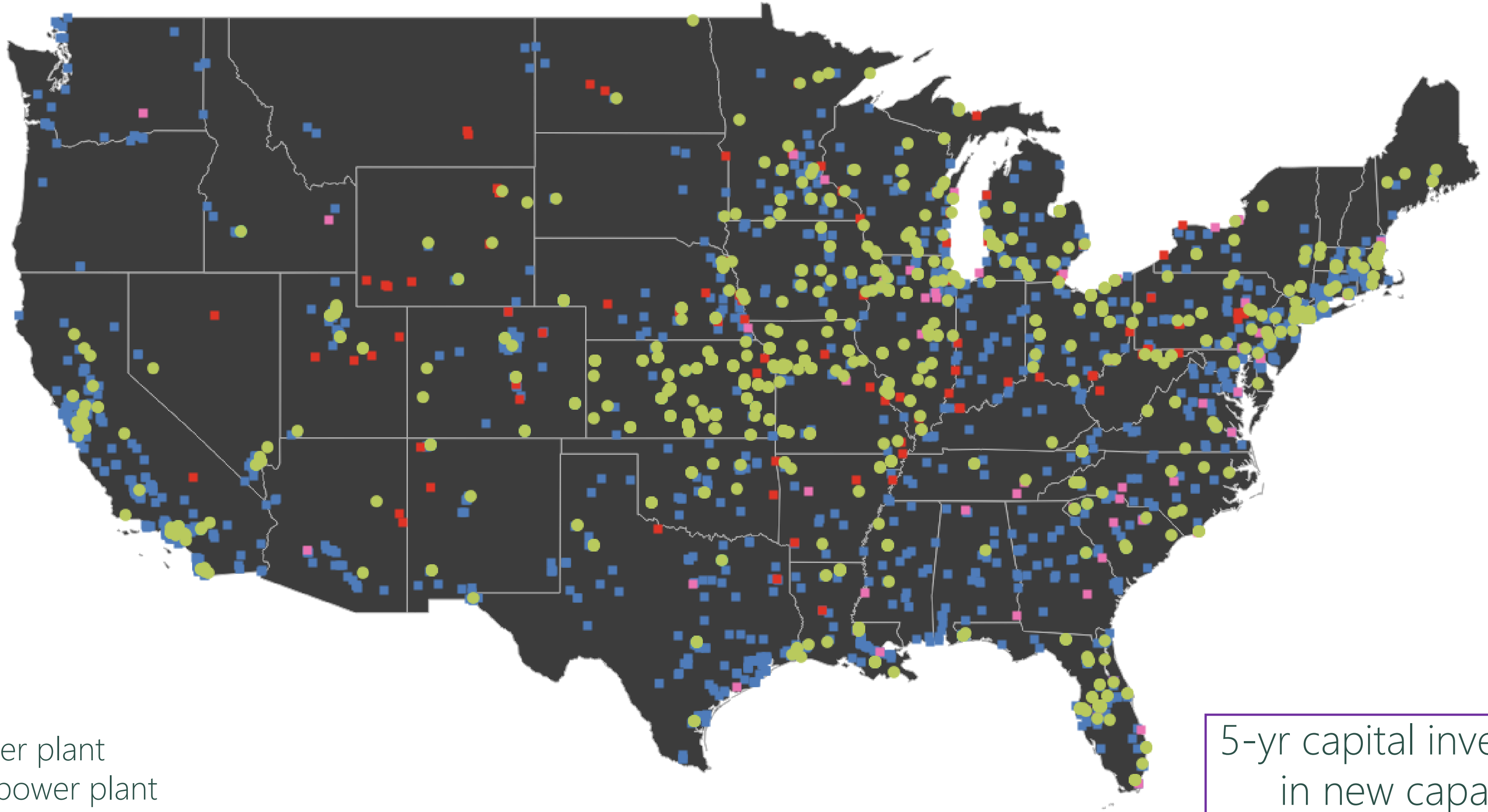
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2030

2030



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:
$129B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

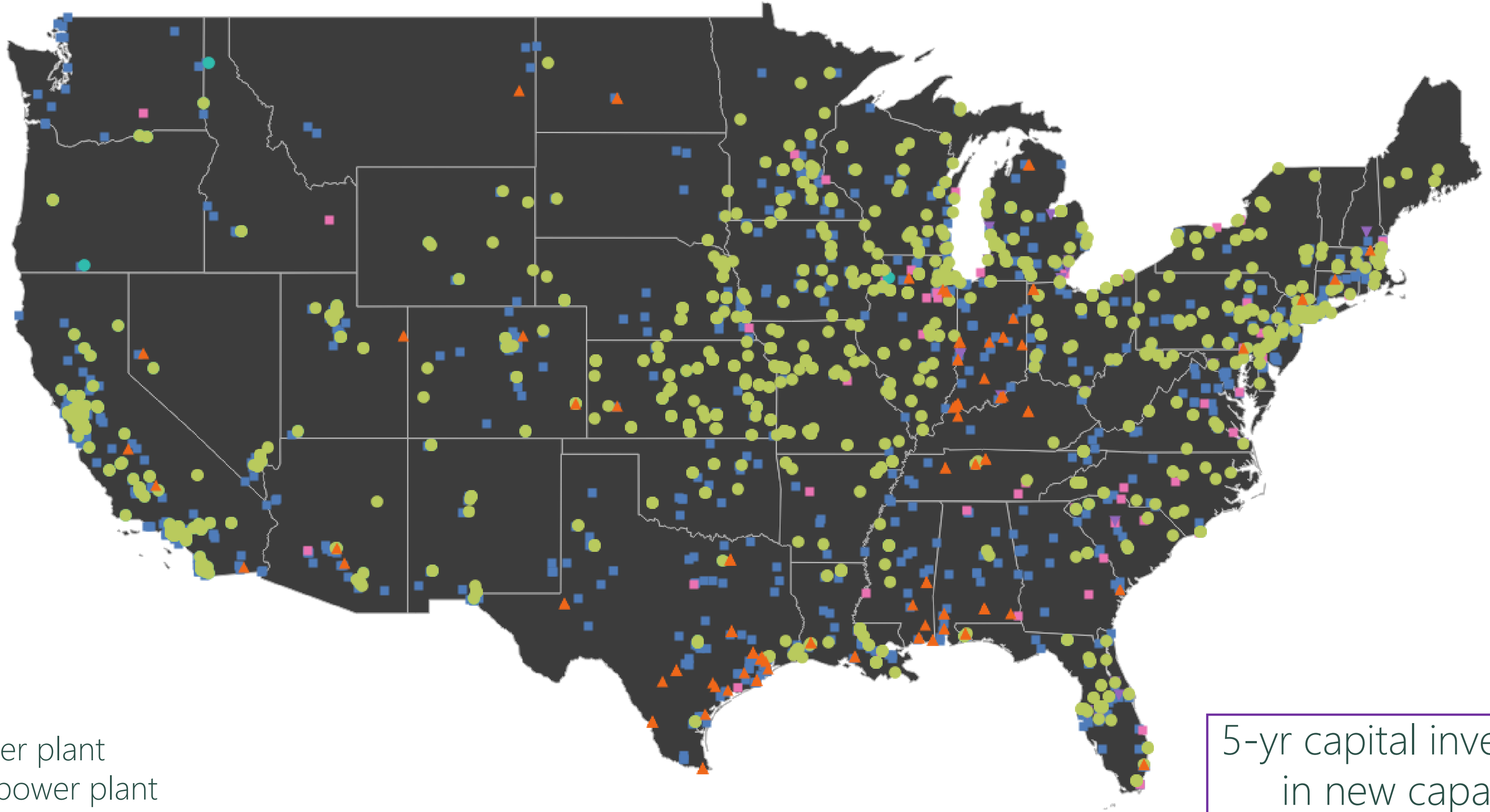
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2035

2035



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity: $184B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

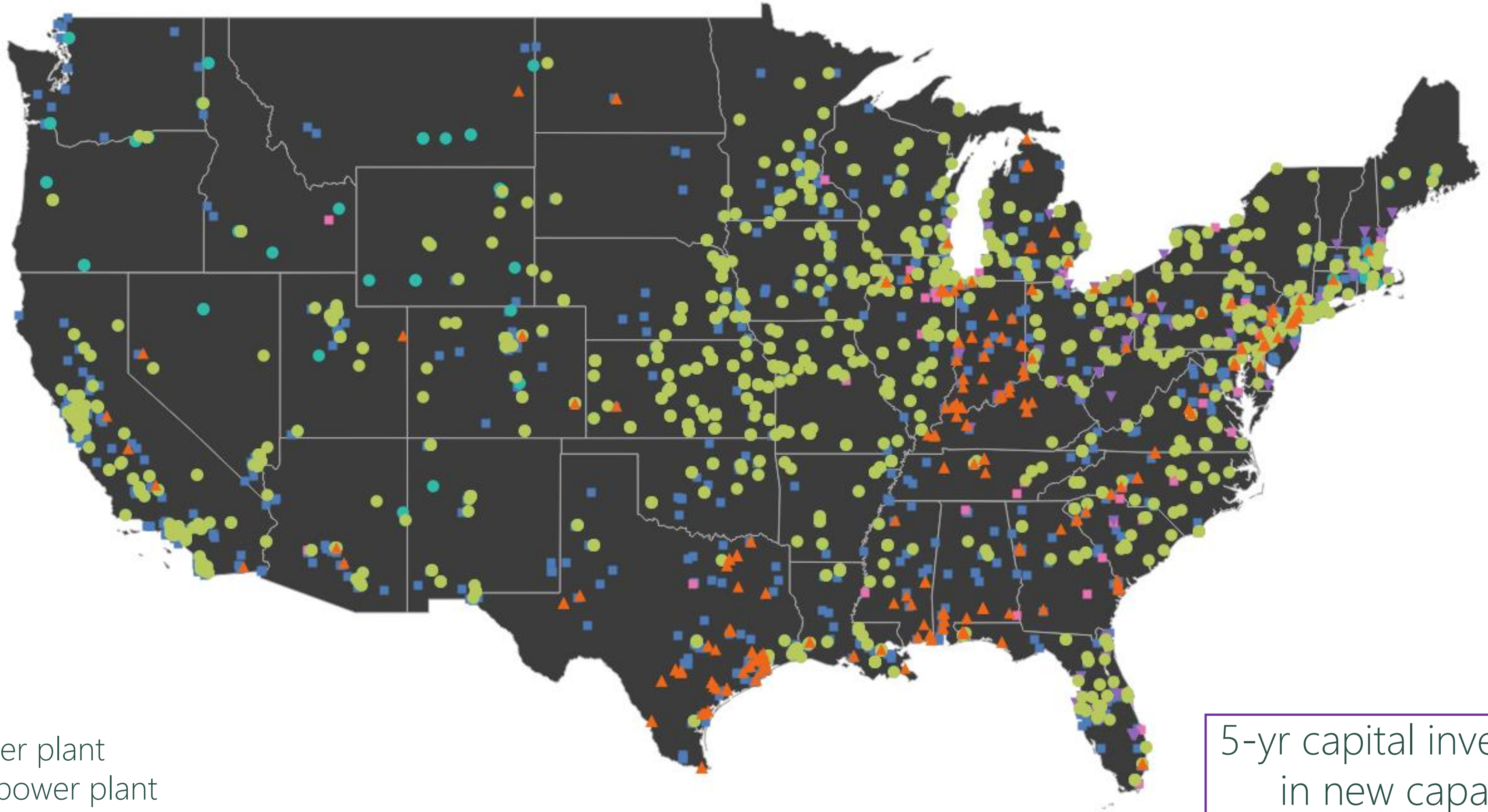
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2040

2040



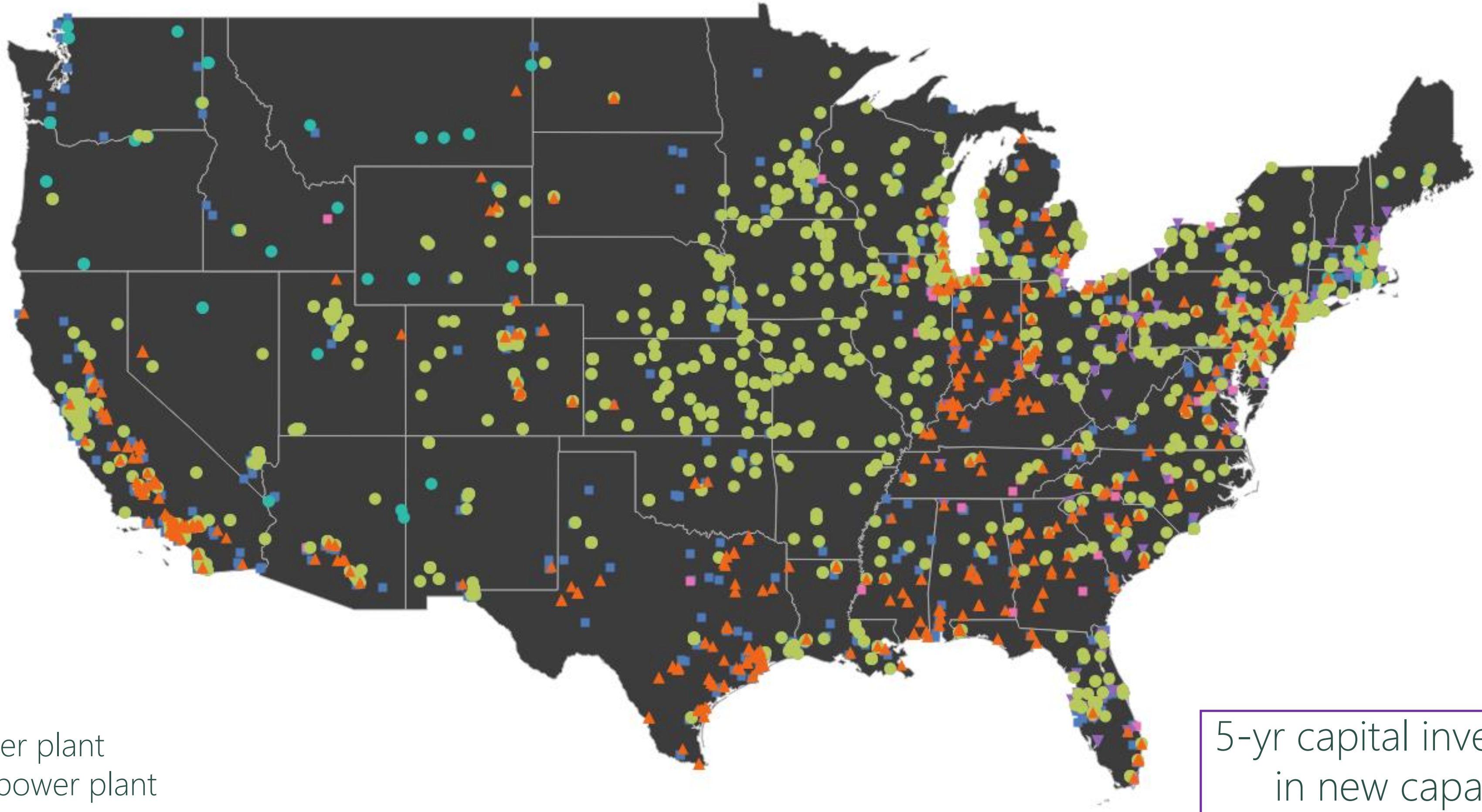
- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$382B

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2045

2045



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combined cycle power plant
- New gas combustion turbine power plant
- New gas combined cycle with ccu
- New advanced nuclear plant

5-yr capital investment in new capacity:

$583B

PRINCETON UNIVERSITY

andlinger center for energy+the environment

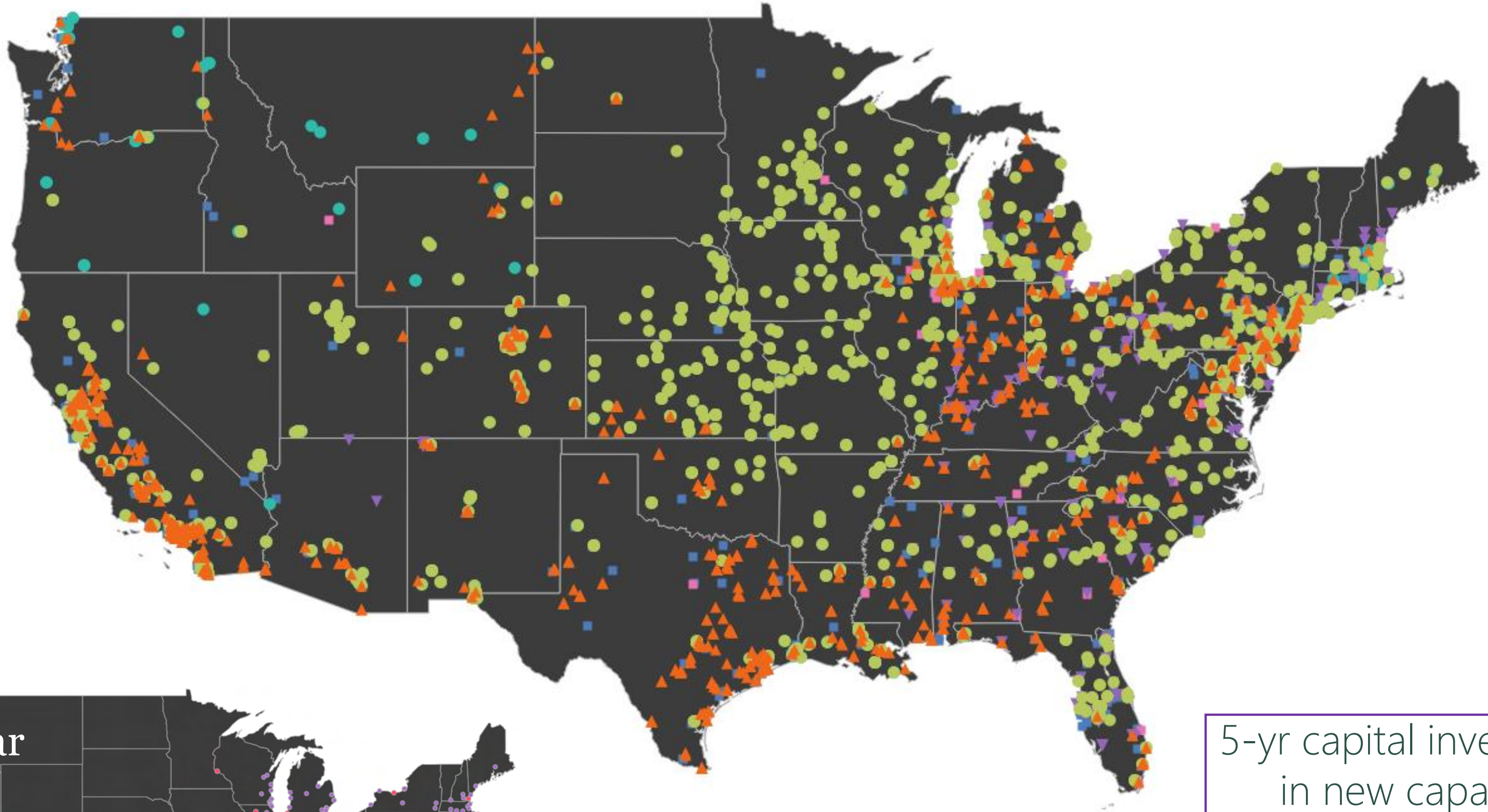
RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

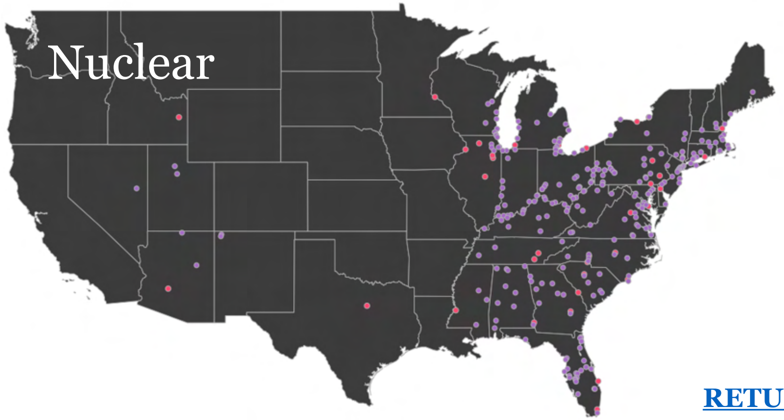
Carbon Mitigation Initiative

Evolution of coal, natural gas, and nuclear generators in E+RE- if no new siting-criteria filters applied, 2050

2050



- Existing coal
- Existing natural gas
- Existing nuclear
- New gas combine
- New gas combust
- New gas combine
- New advanced nu



5-yr capital investment in new capacity:

$833B

Pillar 3: Clean fuels: Bioenergy, hydrogen, and synthesized fuels

Summary of this section

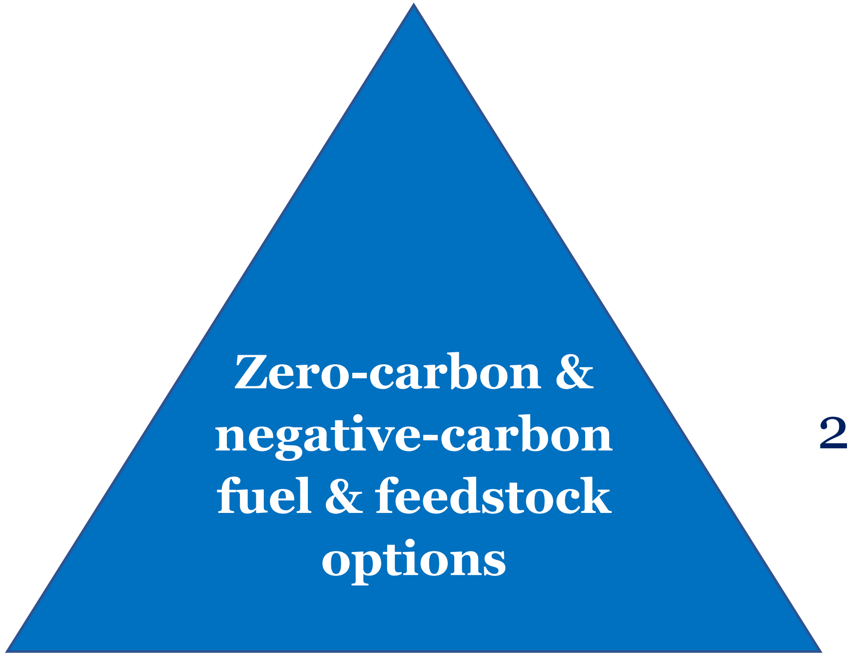
- The net-zero scenario modeling includes ways to realize carbon-neutral or carbon-negative fuels derived from fossil fuels, from biomass, and/or from clean electricity. Hydrogen is a key carbon-free intermediate or final fuel.
- Biomass plays an especially important role because *i*) it removes CO_2 from the atmosphere as it grows and so combustion of hydrocarbon fuels made with biomass carbon results in no net CO_2 emissions to the atmosphere, *ii*) it can be converted into H_2 while capturing and permanently sequestering its carbon, resulting in a net negative-emissions fuel, and *iii*) it can similarly be used to make negative-emissions electricity and replacements for petrochemical feedstocks (via pyrolysis).
- The biomass supply in 4 of the 5 net-zero scenarios consists of agricultural and forest residues, plus transitioning land area growing corn for ethanol to growing perennial grasses or equivalent for energy.* This supply scenario thus includes no conversion of land currently used for food or feed production.
- The high biomass supply case (E-B+ scenario) assumes all biomass identified in the US Department of Energy's "Billion Ton Study" is available for energy; this involves some cropland and pasture being converted to energy crops.
- Starting in the 2030s, H_2 from biomass with capture of CO_2 that is permanently sequestered is a highly cost-competitive technology option because of the high value of the associated negative emissions; negative-emissions bio-electricity is less valued because of abundant low-cost solar and wind electricity.

* The average rain-fed harvestable yield (t/ha/y, dry basis) of perennial energy grasses on former corn-growing land assumed in the modeling here is about ¾ of today's U.S. average whole-plant yield for corn. Conceptually, therefore, the biomass assumed to be supplied from converted corn-growing lands could equivalently be whole-corn-plant biomass with ¼ of the material left on the field for soil maintenance purposes.

RETURN TO TABLE OF CONTENTS

Key zero-carbon fuels and feedstocks

1. Fossil-derived fuels with negative emissions offsets



3. Drop-in liquid & gaseous fuels made from biomass or synthesized from H_2 + captured CO_2

2. Hydrogen made from biomass, NG w/CCS, or electrolysis and used directly or as hythane (blend of H_2 + CH_4)

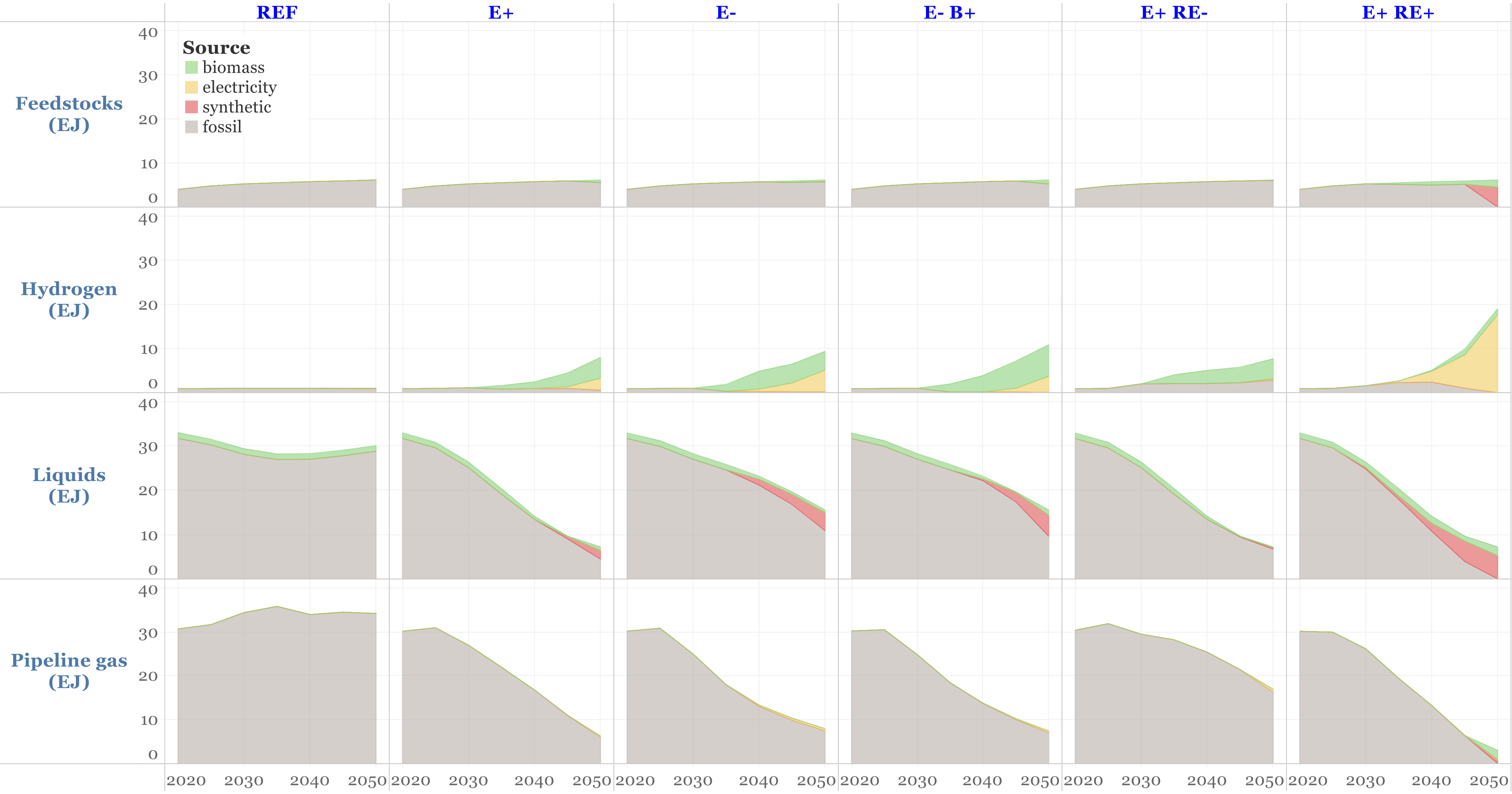
Use of fuels decreases substantially in all scenarios, and by 2050 zero-carbon fuels and feedstocks come from a diversity of sources

Zero-carbon fuel options include

1. Fossil fuels plus negative emission offsets
2. Hydrogen made from biomass, NG w/CCS, or electrolysis
3. Synthesized fuels (from biomass or H_2 + captured CO_2)

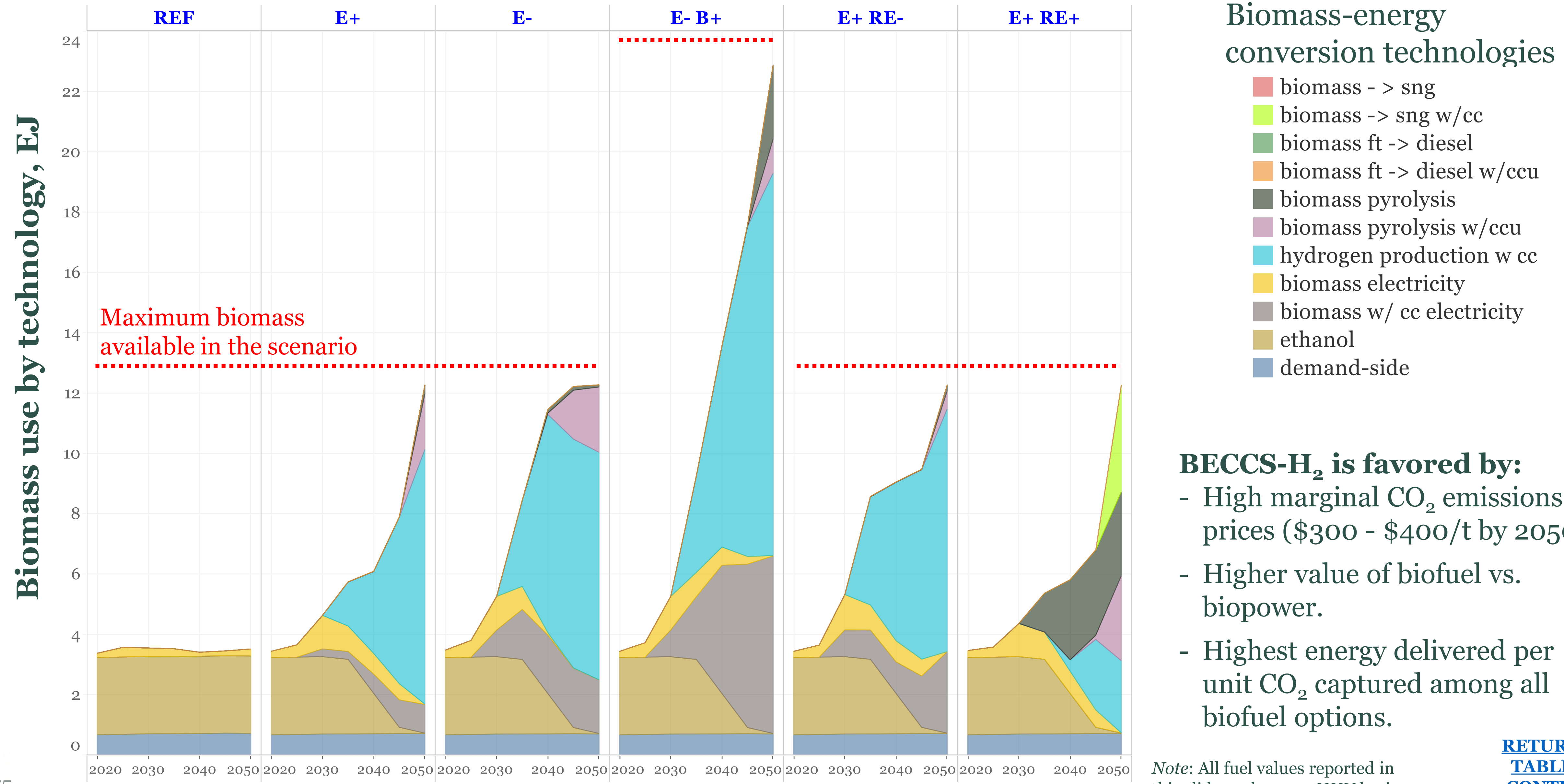
Note: All fuel values reported in this slide pack are on HHV basis.

Mix of fuels and feedstocks by source



PRINCETON UNIVERSITY

Essentially all available biomass is used in 2050. Rapid growth after 2030. H_2 from biomass with CO_2 capture is a key technology.



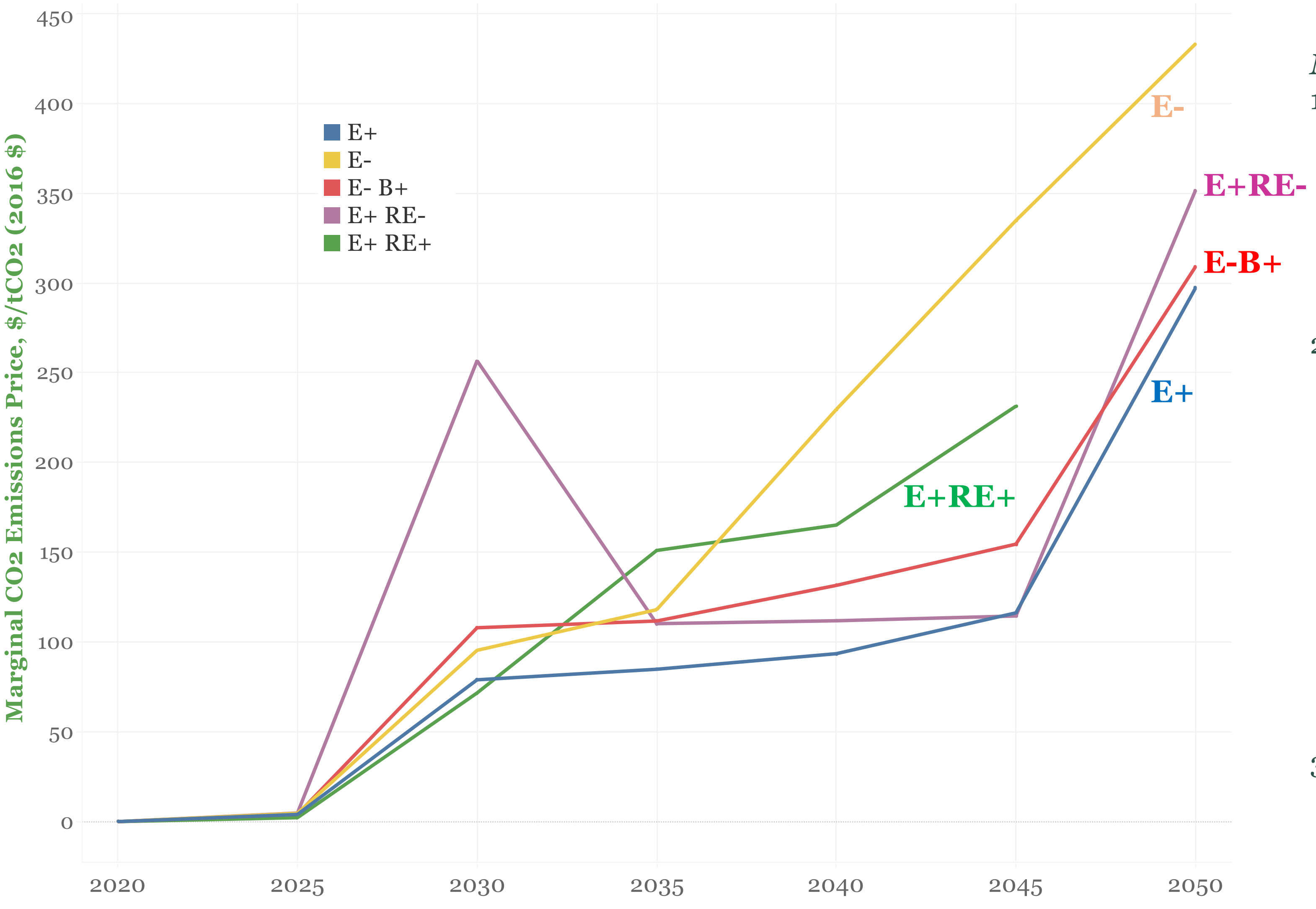
BECCS-H_2 is favored by:

- High marginal CO_2 emissions prices ($300 - $400/t by 2050).
- Higher value of biofuel vs. biopower.
- Highest energy delivered per unit CO_2 captured among all biofuel options.

Note: All fuel values reported in this slide pack are on HHV basis.

RETURN TO TABLE OF CONTENTS

High marginal CO_2 emission prices benefit negative emissions technologies & explain preference for biomass use in BECCS-H_2



Notes:

1) These prices represent overall supply-side system costs for reducing CO_2 emissions by one additional tonne. They do not take into consideration demand-side costs such as added costs for transport electrification in E+ compared with E-. As such, these prices should be interpreted as lower bound estimates of economy-wide carbon emission prices.
2) For E+RE-, the main factors contributing to the non-monotonic behavior from 2025-2035 are: (i) the exogenously imposed linear net-emissions reduction trajectory requires significant reductions by 2030, (ii) the limit on solar and wind power generation build rates means more nuclear and NG-CCS need to be installed; and what can be built of these by 2030 is costly, (iii) post-2030, things get easier because more nuclear and CCS can be built at lower cost, and the electrification of vehicles and buildings that started slowly in the 2020s (limited by stock turnover rates) begins to more significantly reduce fuel demands.
3) For E+RE+, no value is shown for 2050, because the constraint prohibiting fossil fuel use in 2050 is more binding than the annual emissions constraint, implying that the carbon price would (unrealistically) be zero in 2050.

PRINCETON UNIVERSITY

andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

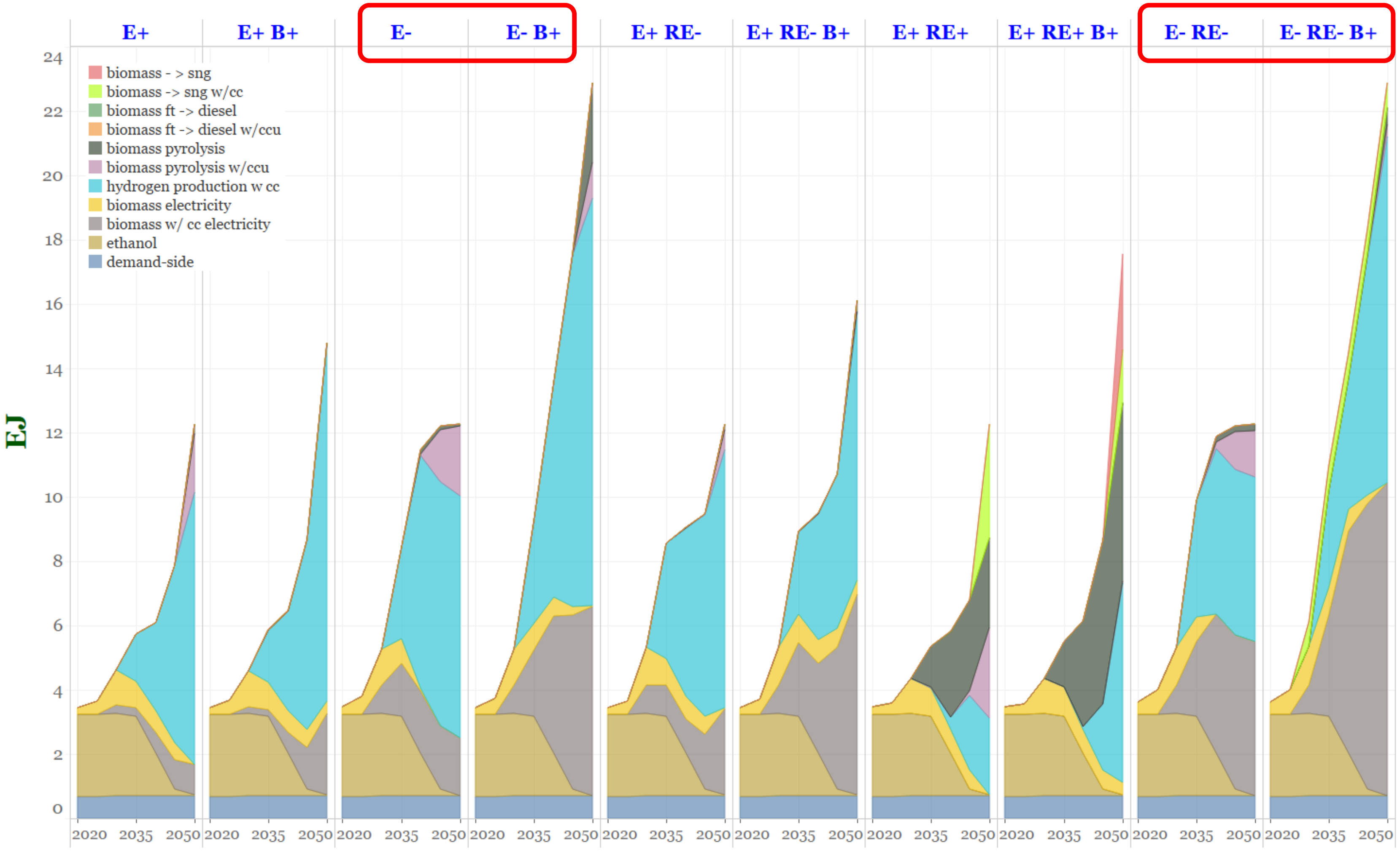
High Meadows Environmental Institute

Carbon Mitigation Initiative

Sensitivity modeling runs: Allowing potential for higher biomass supply results in more biomass use to make electricity and H_2

Biomass is a key resource in all scenarios.

- With the lower biomass supply potential, all available biomass is utilized in all 5 scenarios shown here, including E-RE- (run as a sensitivity to E+RE-).
- With the high biomass supply potential :
  - all available biomass is used in E-B+ and E-RE-B+ cases, which underlines the importance of electrification in reducing reliance on biomass in net-zero pathways.
  - Most of the additional biomass in E+RE-B+, E+RE+B+, and E-RE-B+ is used to produce additional negative emissions via power generation or H_2 production.



Input assumptions that vary between cases		
	E+, E-, E+RE-, E+RE+	E+B+, E-B+, E+RE-B+, E+RE+B+
Biomass potential (by 2050)	0.7 Gt/y (13 EJ)	1.3 Gt/y (24 EJ)

See Annex B for additional discussion of sensitivity cases.

RETURN TO TABLE OF CONTENTS

If no new bioenergy is allowed, more oil and gas are used and direct air capture and sequestration of CO_2 increase to compensate

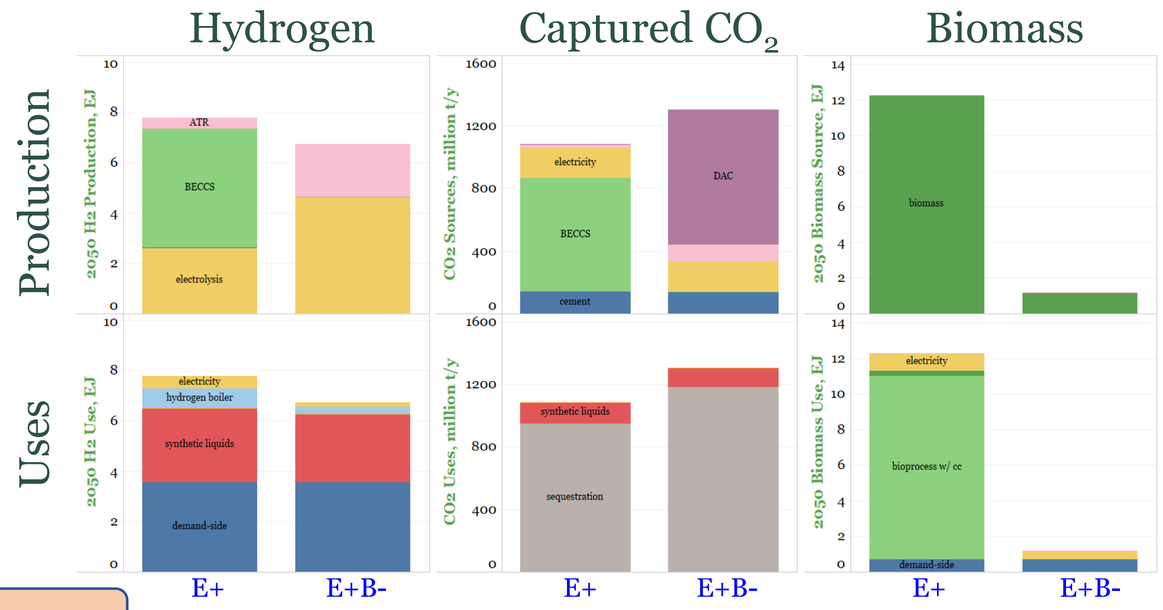
Not allowing new bioenergy removes a key pathway for making net-zero or net-negative emission fuels and leaves only direct air capture (DAC) as an option for achieving negative emissions:

For the E+ case with no new bioenergy (E+B-, upper panel)

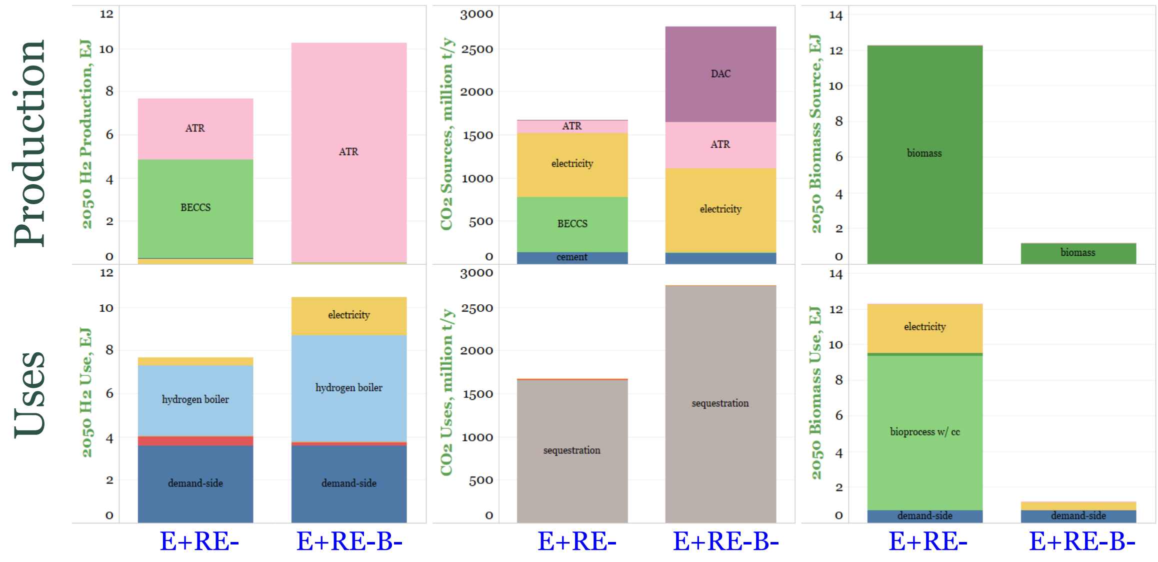
- electrolysis and natural gas reforming with CO_2 capture offset the loss of H_2 production from biomass.
- DAC use increases dramatically to offset the added emissions from greater natural gas use and negative emissions from BECCS. Stored CO_2 increases.
- 30-yr NPV of energy-supply system costs increase ~5%.

For E+RE- with no new bioenergy (E+RE-B-, lower panel)

- More hydrogen is produced and all by natural gas reforming with CO_2 capture. More H_2 is used for power generation and industrial steam generation; less for liquid fuels synthesis.
- DAC deployments starts in the early 2030s and ramps up dramatically by 2050, along with CO_2 capture from gas-fired power plants.
- CO_2 storage nearly doubles relative to E+ RE-.
- 30-yr NPV of energy-supply system cost increases by ~25%.



2050

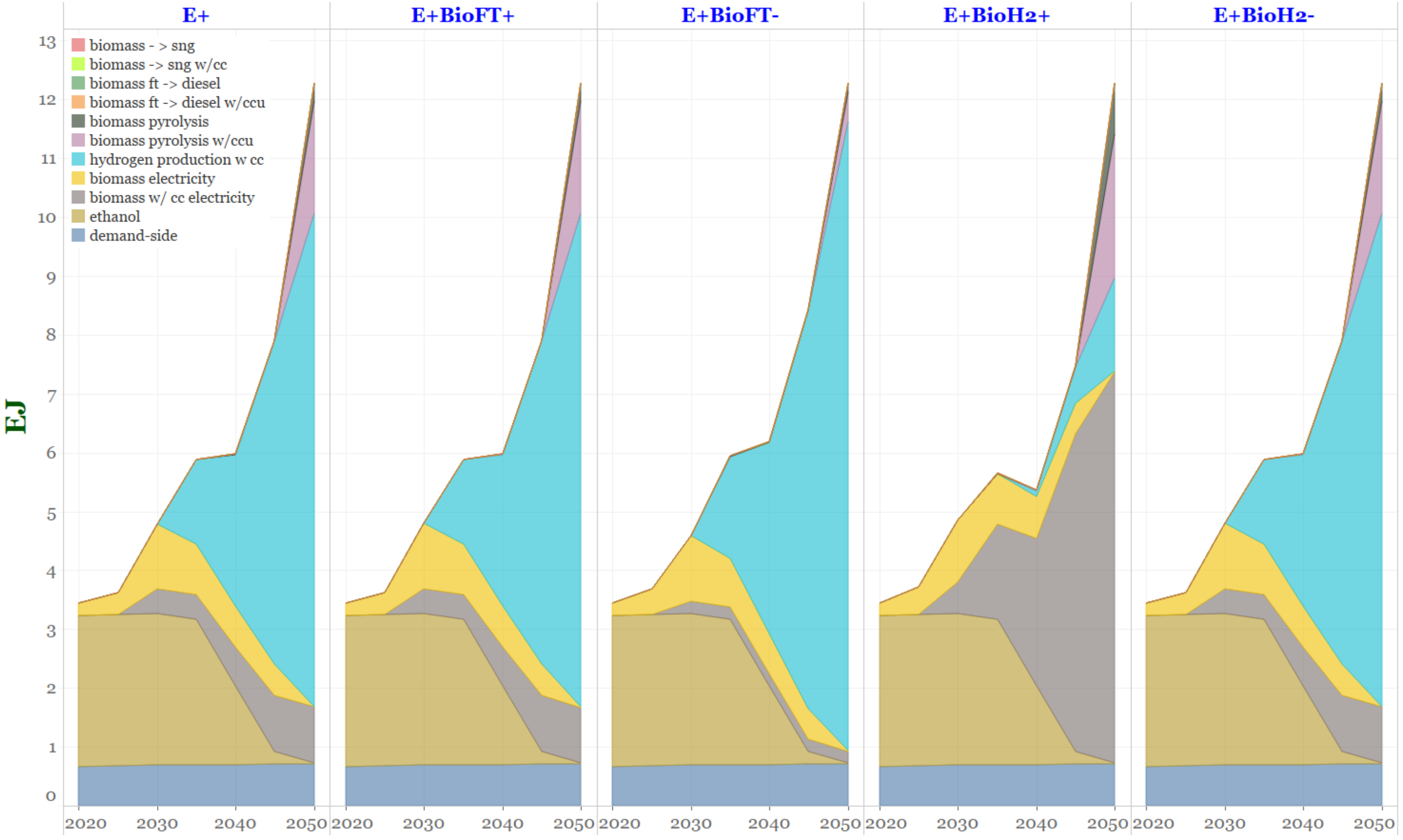


Input assumptions that vary between cases				
	E+	E+ B-	E+ RE-	E+ RE-B-
Biomass potential (increase from today to 2050)	0.7Gt/y	0 Gt/y	0.7Gt/y	0 Gt/y

Higher capital costs for biomass conversion to hydrogen drives more biomass use for electricity, but not for bio-derived liquid fuels

Gasification-based integrated biomass conversion to Fischer-Tropsch fuels or H_2 with CO_2 capture are pre-commercial technologies, with inherently uncertain capital costs for future commercial-scale plants. Sensitivity runs tested the impact of 50% higher and 20% lower assumed capital costs for these technologies:

- Neither higher nor lower biomass-FT costs impacted results, because other routes to liquid fuels are less costly for meeting liquid fuel demands within carbon emission constraints.
- A similar result is observed with lower capital costs for biomass-H_2 with CO_2 capture.
- But with higher costs for biomass-H_2, biomass use shifts away from H_2 production to electricity generation with CO_2 capture. Notably, biomass-FT technology is still not deployed even in this case.
- The 30-yr NPV of energy-supply system costs are similar for all cases shown here



See Annex B for additional discussion of sensitivity cases.

Input assumptions that vary between cases					
$\$/kW_{out,HHV}$ in 2050	E+	E+ BioFT+	E+ BioFT-	E+ BioH2+	E+ BioH2-
BECCS-H_2 capital cost	2700	2700	2700	4050	2160
Biomass FT capital cost	3962	5984	3172	3962	3962

RETURN TO TABLE OF CONTENTS

Spatial downscaling and analysis of bioenergy production and use in the E+ pathway

Summary of this section

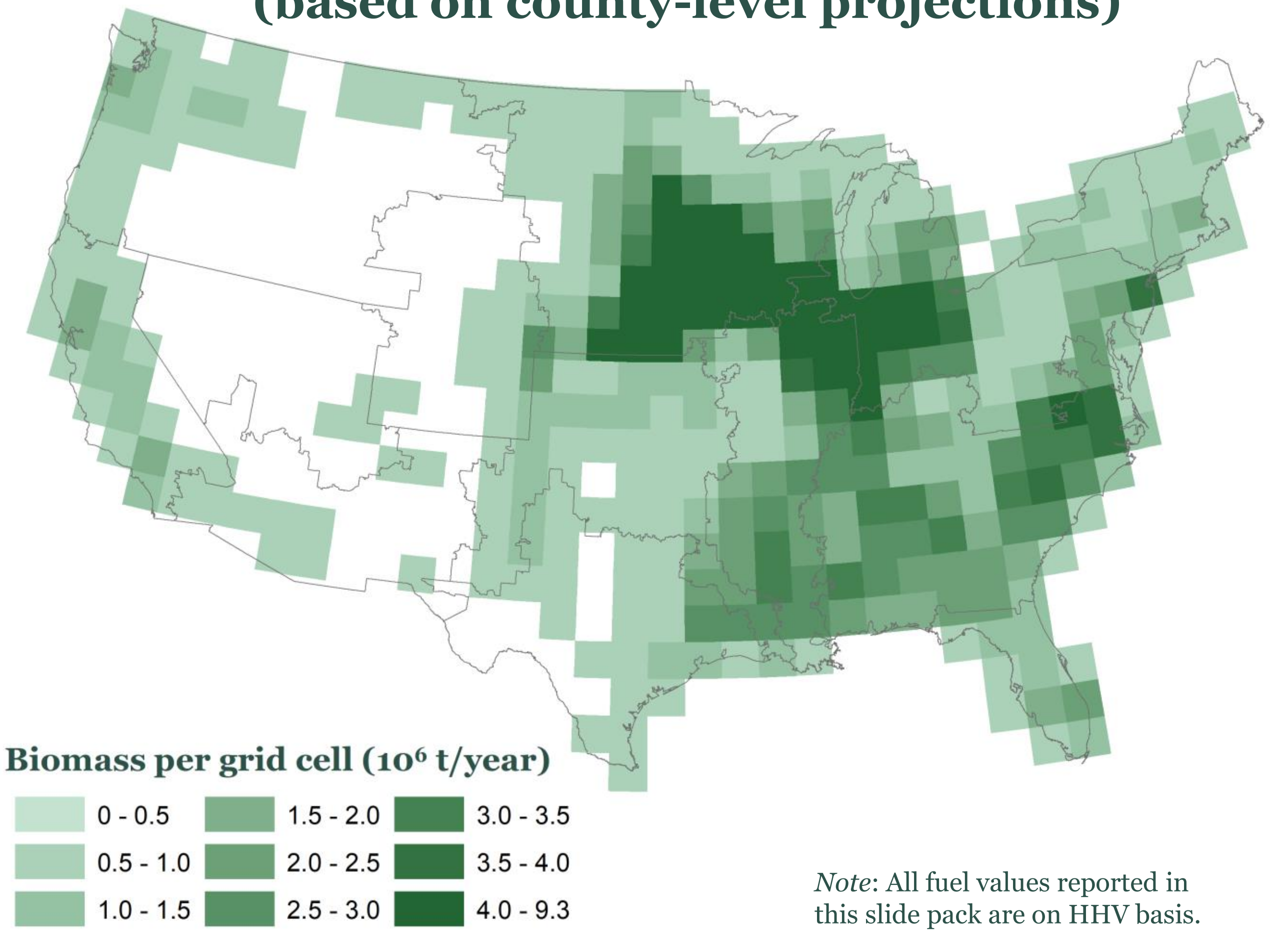
- For the E+ pathway, the geographic distribution of agricultural and forestry residues used for energy is based on county-level projections from the "Billion Ton Study". Land transitioned from growing corn for ethanol to growing perennial grasses or equivalent for energy is assumed to be distributed among counties in proportion to their corn production level in 2018.*
- Transporting biomass long distances to conversion facilities is costly, so our downscaling approach uses the county-level biomass supply estimates to establish 100 mile x 100 mile cells, within each of which all available biomass is assumed to be used in conversion facilities located in that cell. Most bioconversion facilities, regardless of technology, are assumed to have an input capacity of 0.7 million t_{dry}/y of biomass.
- Bioconversion capacity within a given RIO modeling region is deployed first in cells within that region that have the highest biomass supply density (as a surrogate for lowest biomass feedstock cost), and facilities that capture CO_2 are sited near CO_2 storage reservoirs or pipelines (see CO_2 pipeline maps later).
- Facilities are located primarily in the upper Midwest and in the Southeast, corresponding to the spatial distribution of biomass resources.
- Cumulative investment in bioconversion facilities is ~$810 billion (2018$) nationwide by 2050, and farmer revenues from sale of biomass are more than double today's revenues for corn sold into ethanol production.
- See Annex H for details of the bioenergy downscaling analysis.

* The average rain-fed harvestable yield (t/ha/y, dry basis) of perennial energy grasses on former corn-growing land assumed in the modeling here is about ¾ of today's U.S. average whole-plant yield for corn. Conceptually, therefore, the biomass assumed to be supplied from converted corn-growing lands could equivalently be whole-corn-plant biomass with ¼ of the material left on the field for soil maintenance purposes.

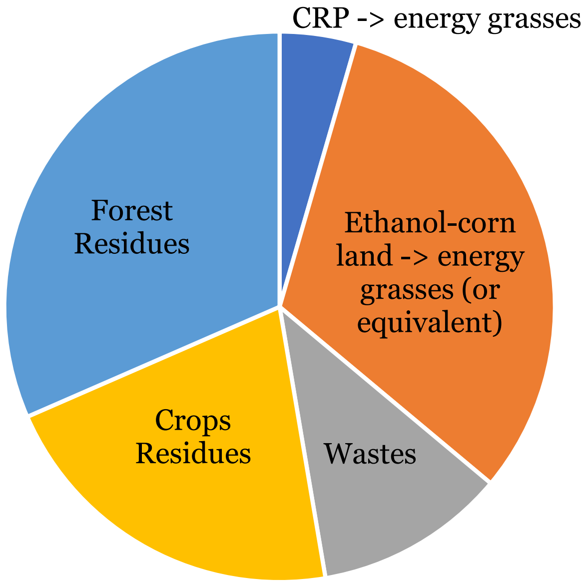
RETURN TO TABLE OF CONTENTS

E+ Scenario: Biomass supply with no increase in land use for energy. Midwest and Southeast are largest sources.

2050 biomass availability, 100 x 100 mi cells (based on county-level projections)

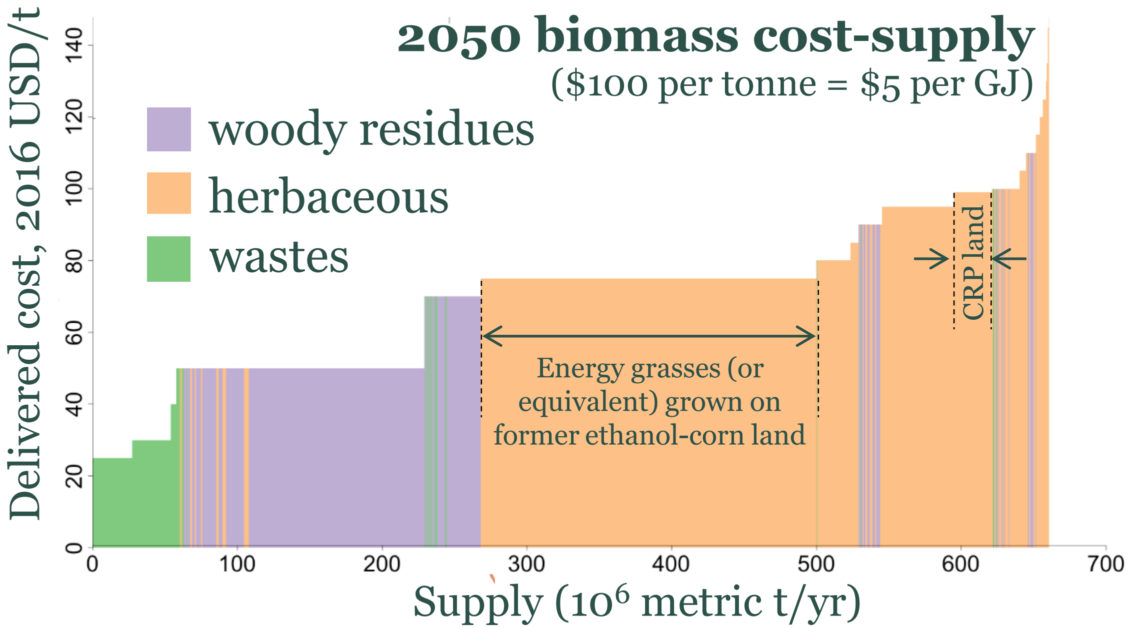


2050 supply by resource (13 EJ total)



2050 biomass cost-supply

(\$100 per tonne = \$5 per GJ)



Note: All fuel values reported in this slide pack are on HHV basis.

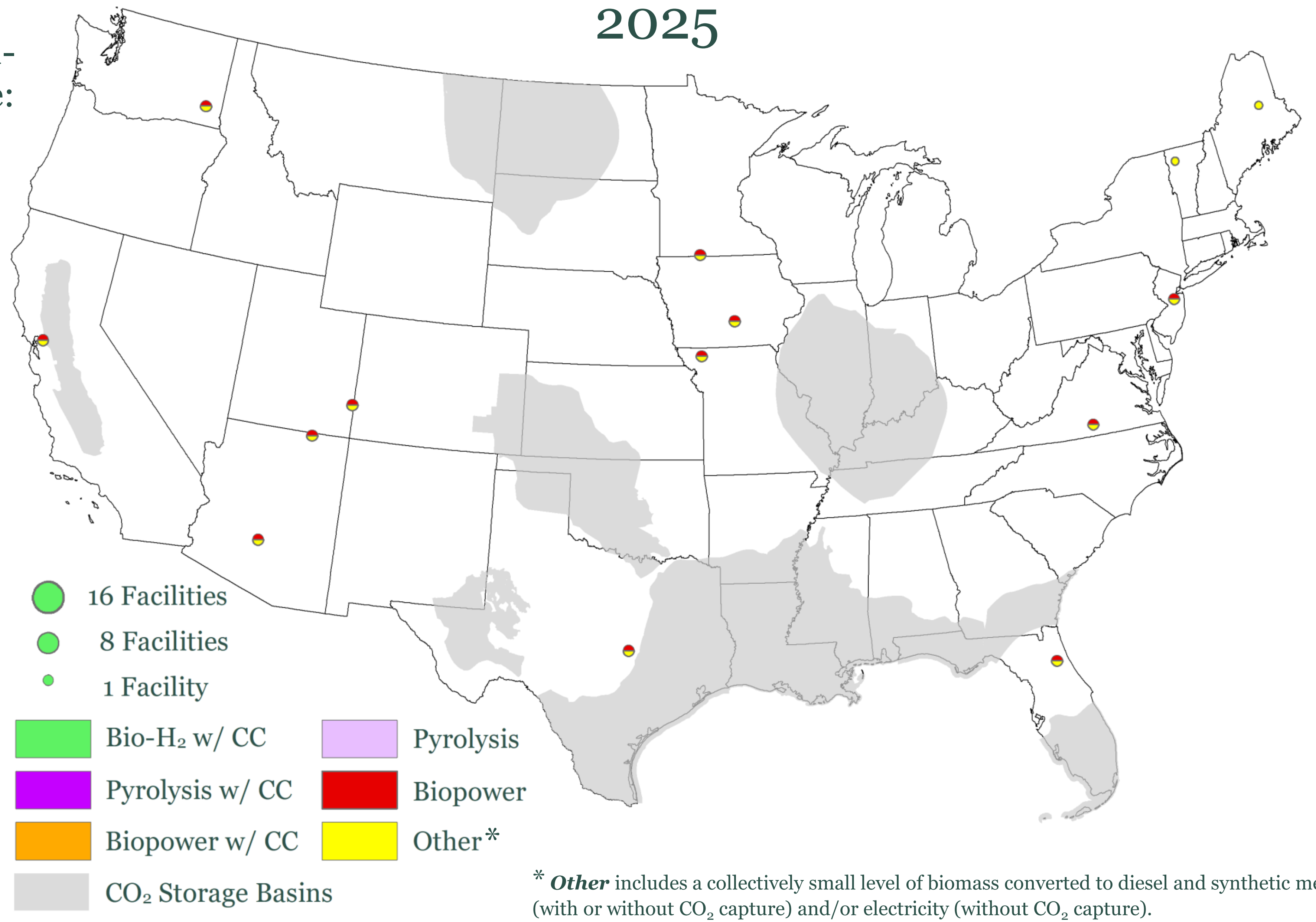
PRINCETON UNIVERSITY

andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 44 million t
- 0.9 EJ



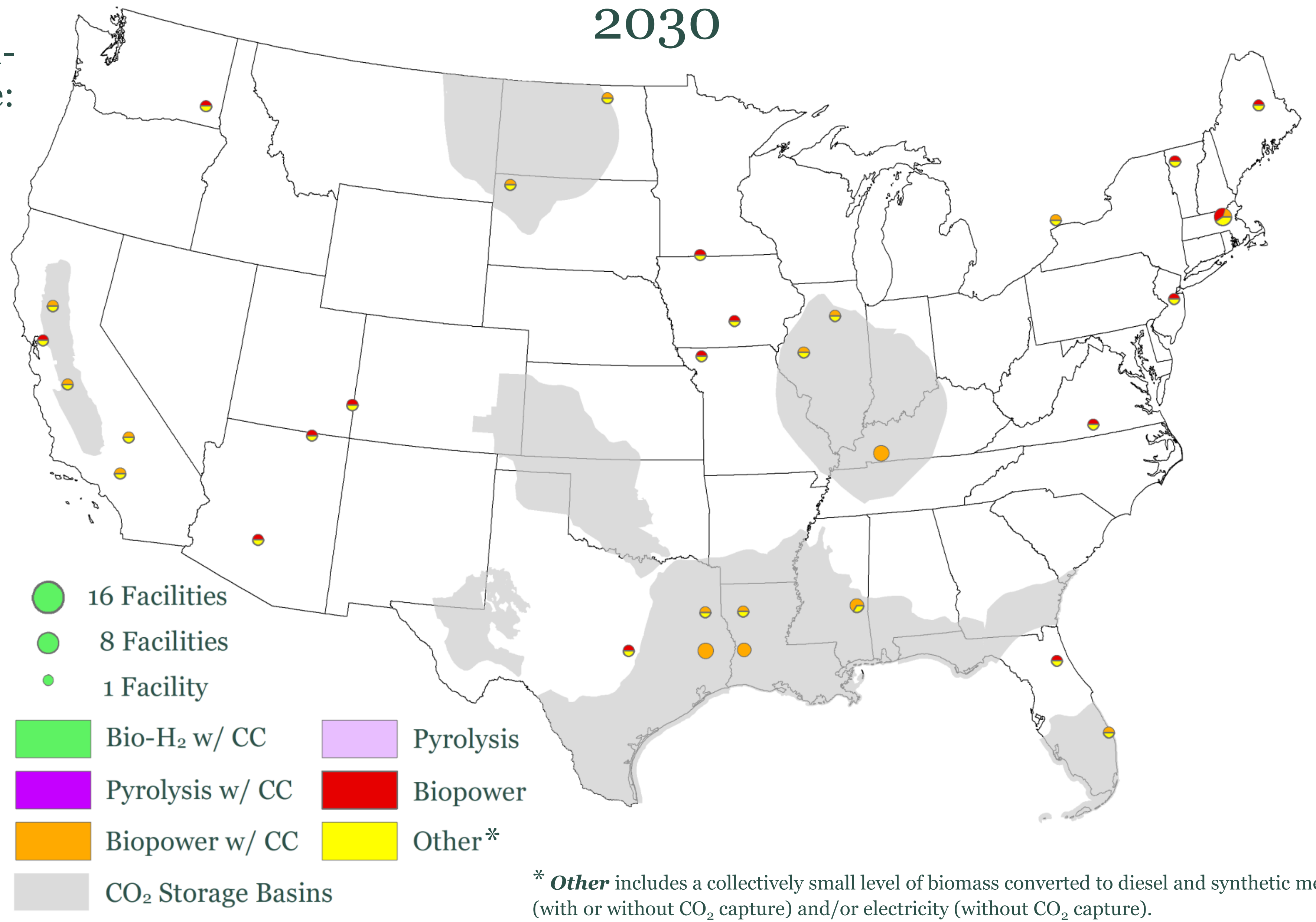
* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 79 million t
- 1.6 EJ



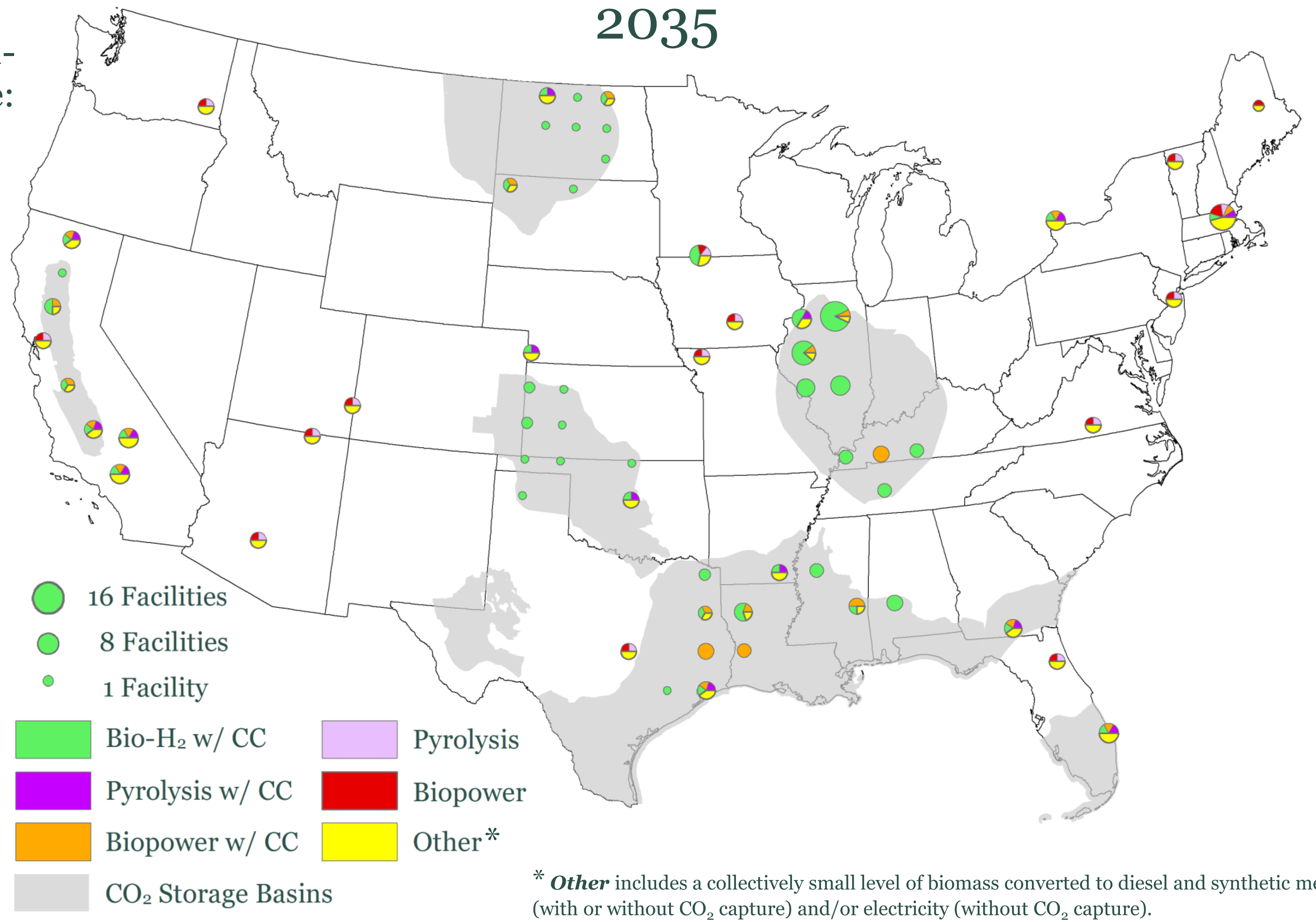
* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 145 million t
- 2.9 EJ



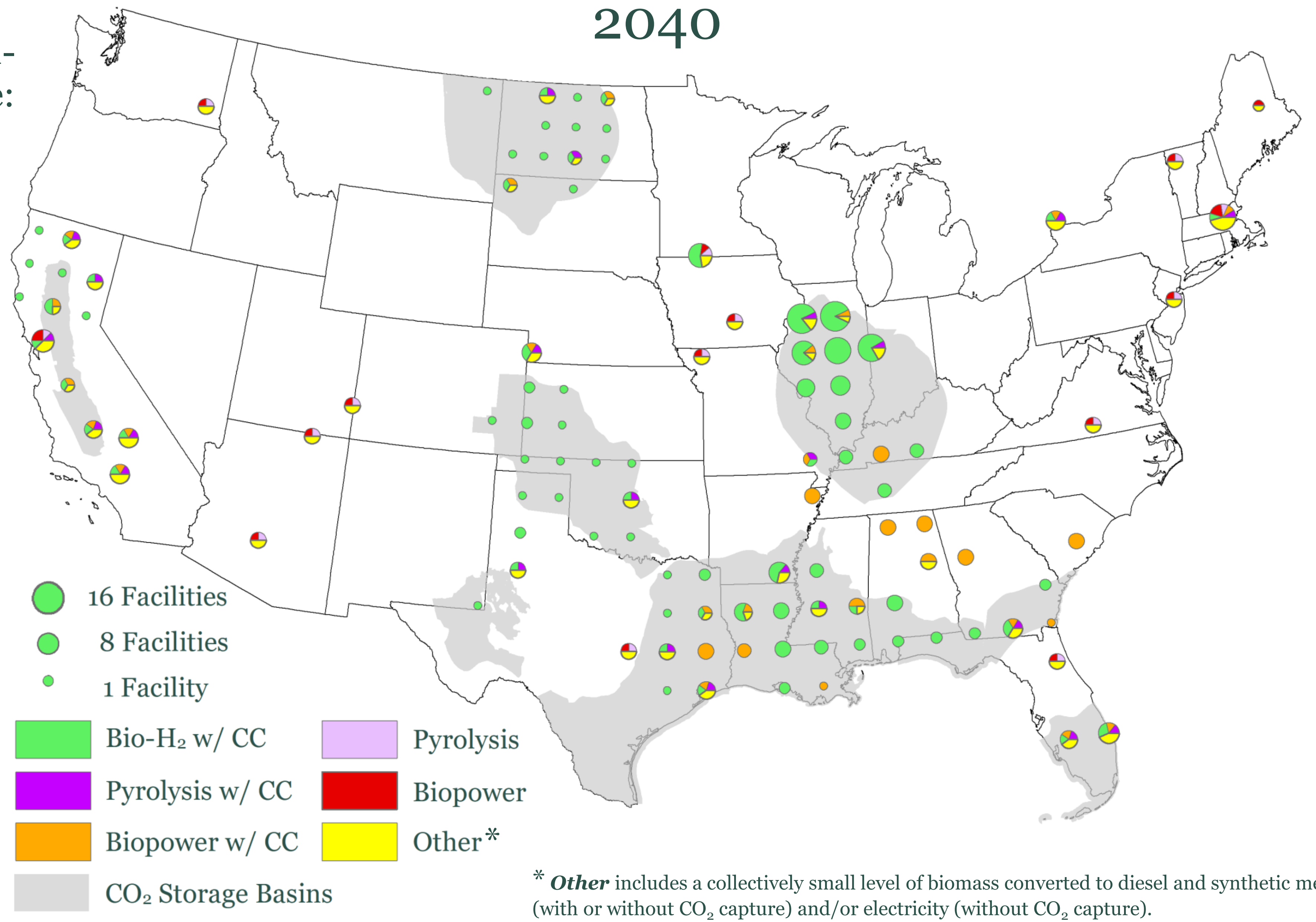
* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 223 million t
- 4.4 EJ



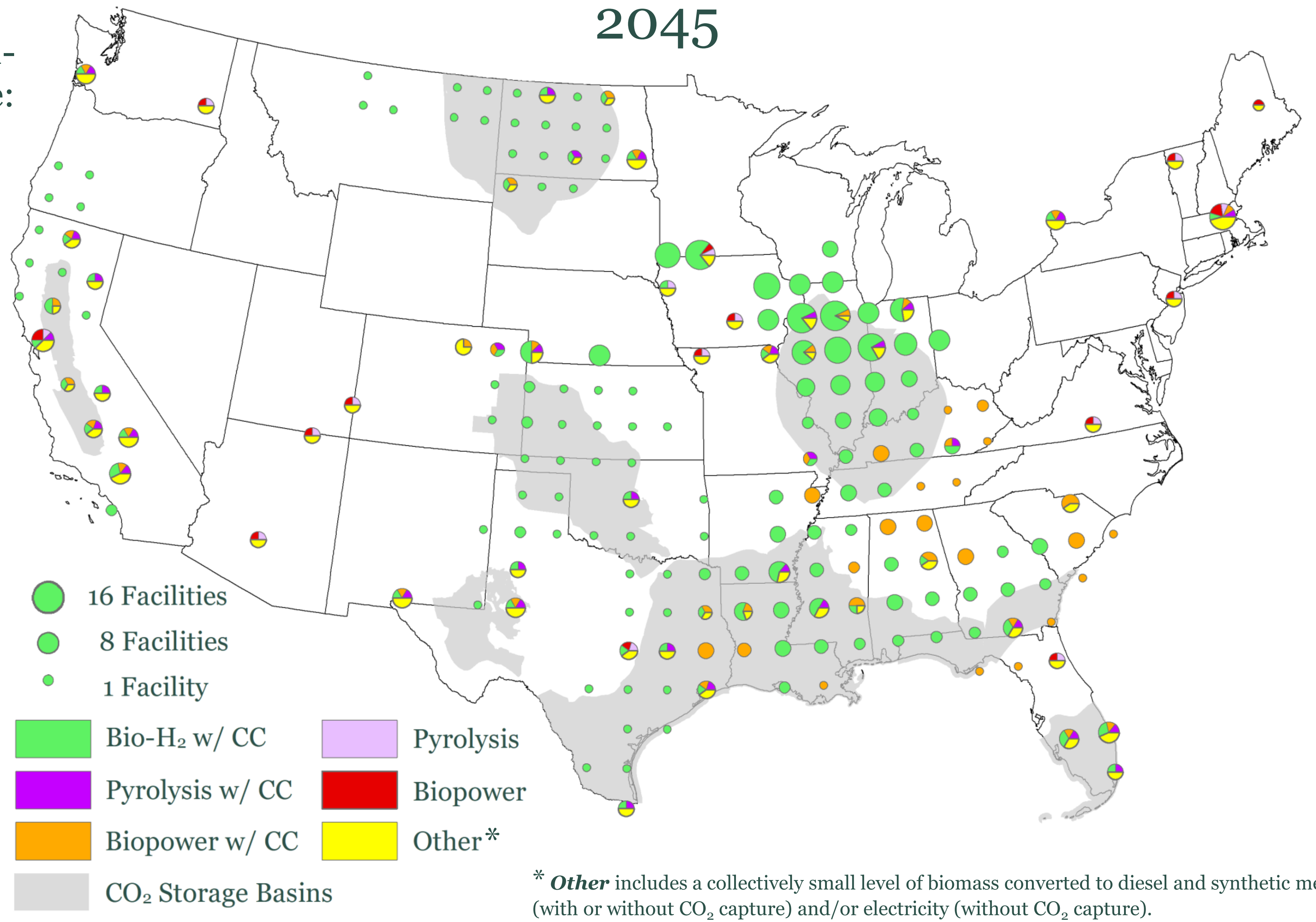
* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 375 million t
- 7.4 EJ



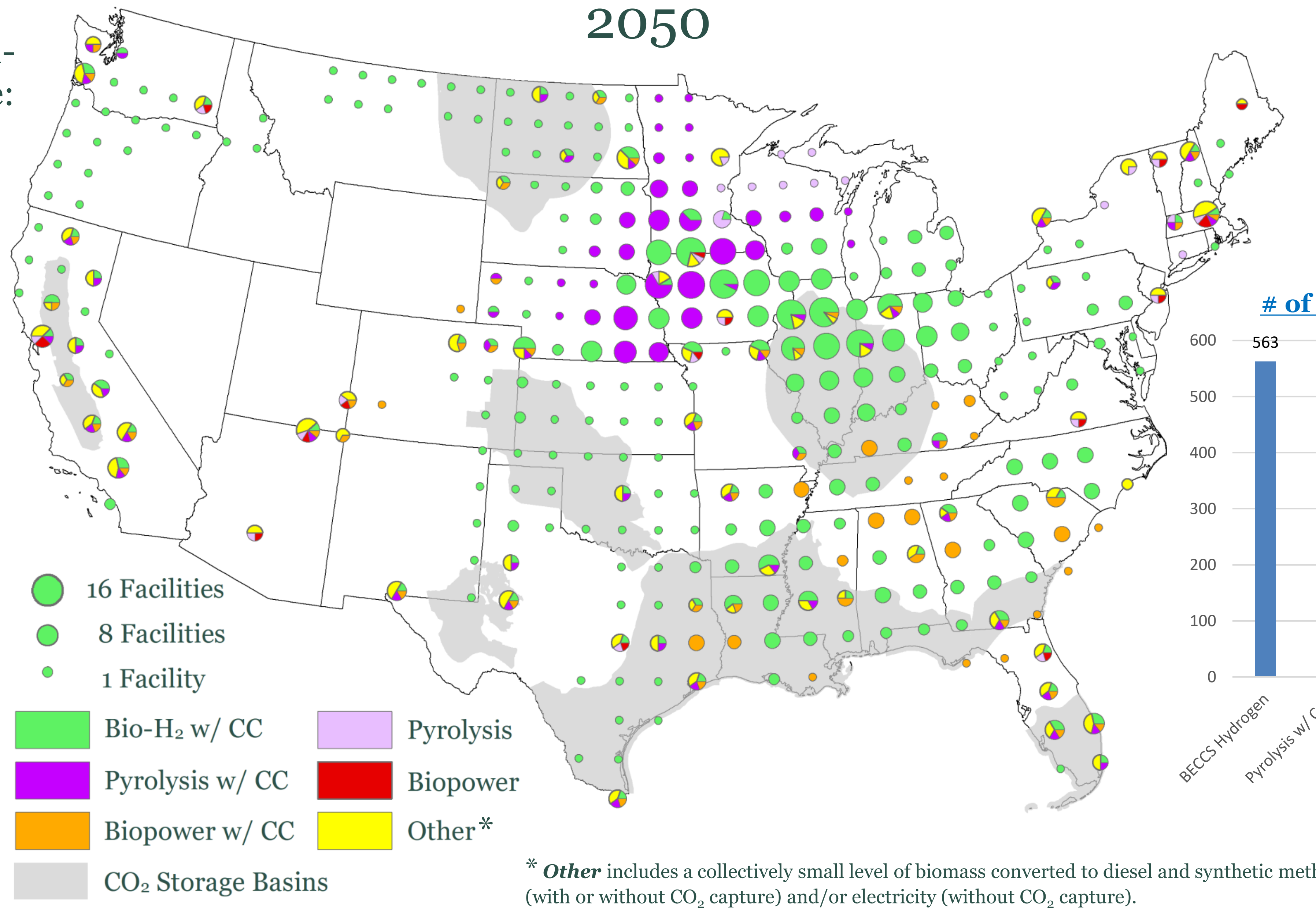
* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

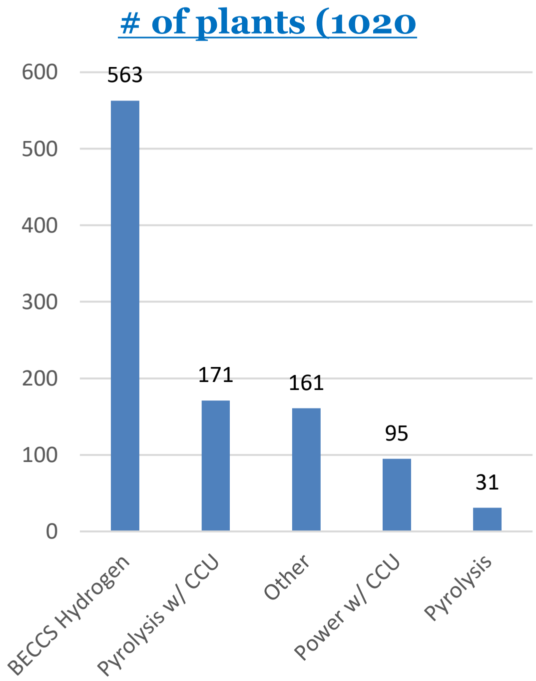
PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

Evolution of the bioconversion industry, E+ scenario

Total annual non-food biomass use:
- 618 million t
- 12.2 EJ



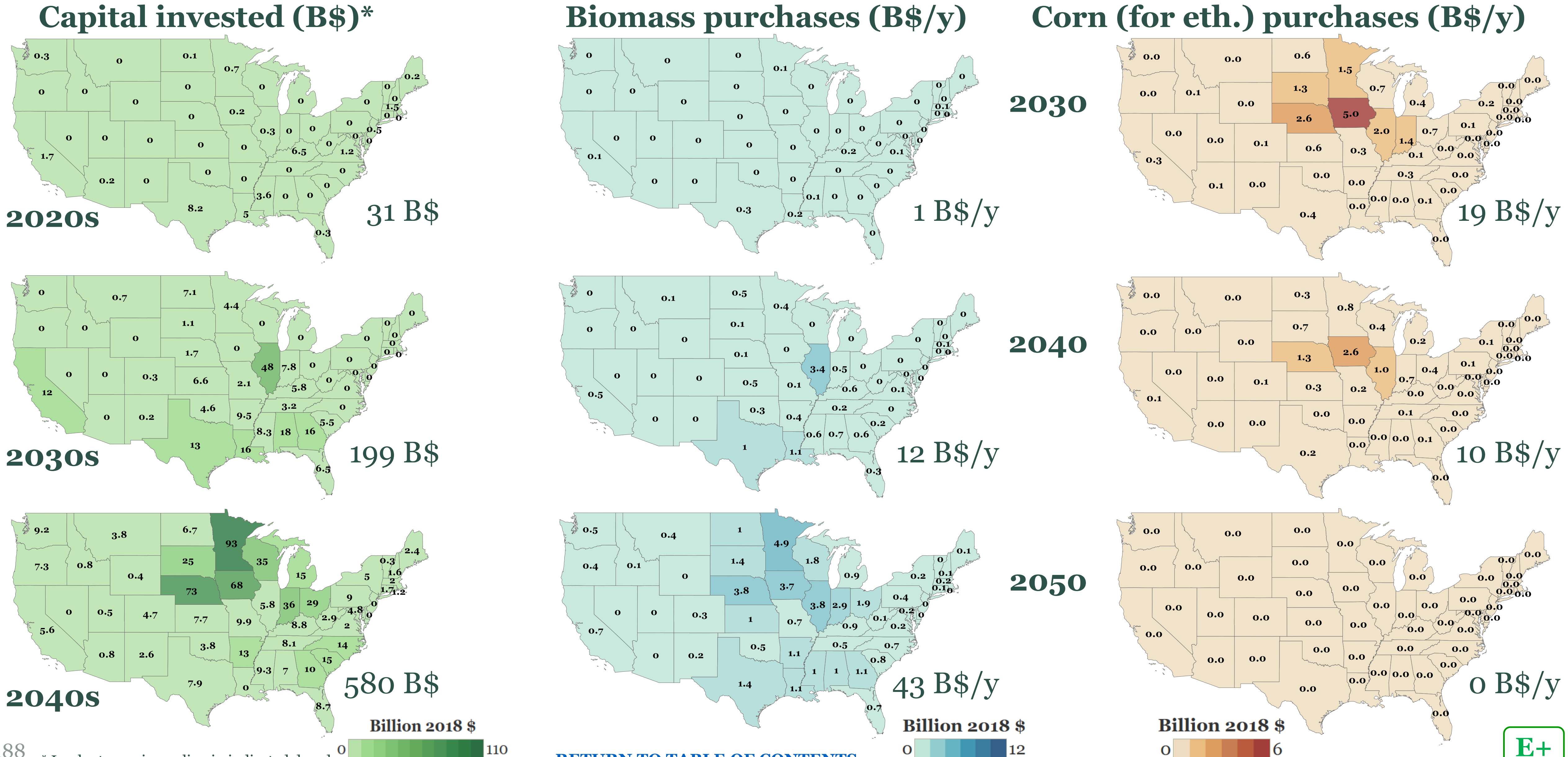


* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

PRINCETON UNIVERSITY

RETURN TO TABLE OF CONTENTS

810 B$ capital invested in bioconversion by 2050, largely in Midwest and Southeast. Biomass purchases grow, displacing corn for ethanol.



* In plants coming online in indicated decade.

[RETURN TO TABLE OF CONTENTS]

E+

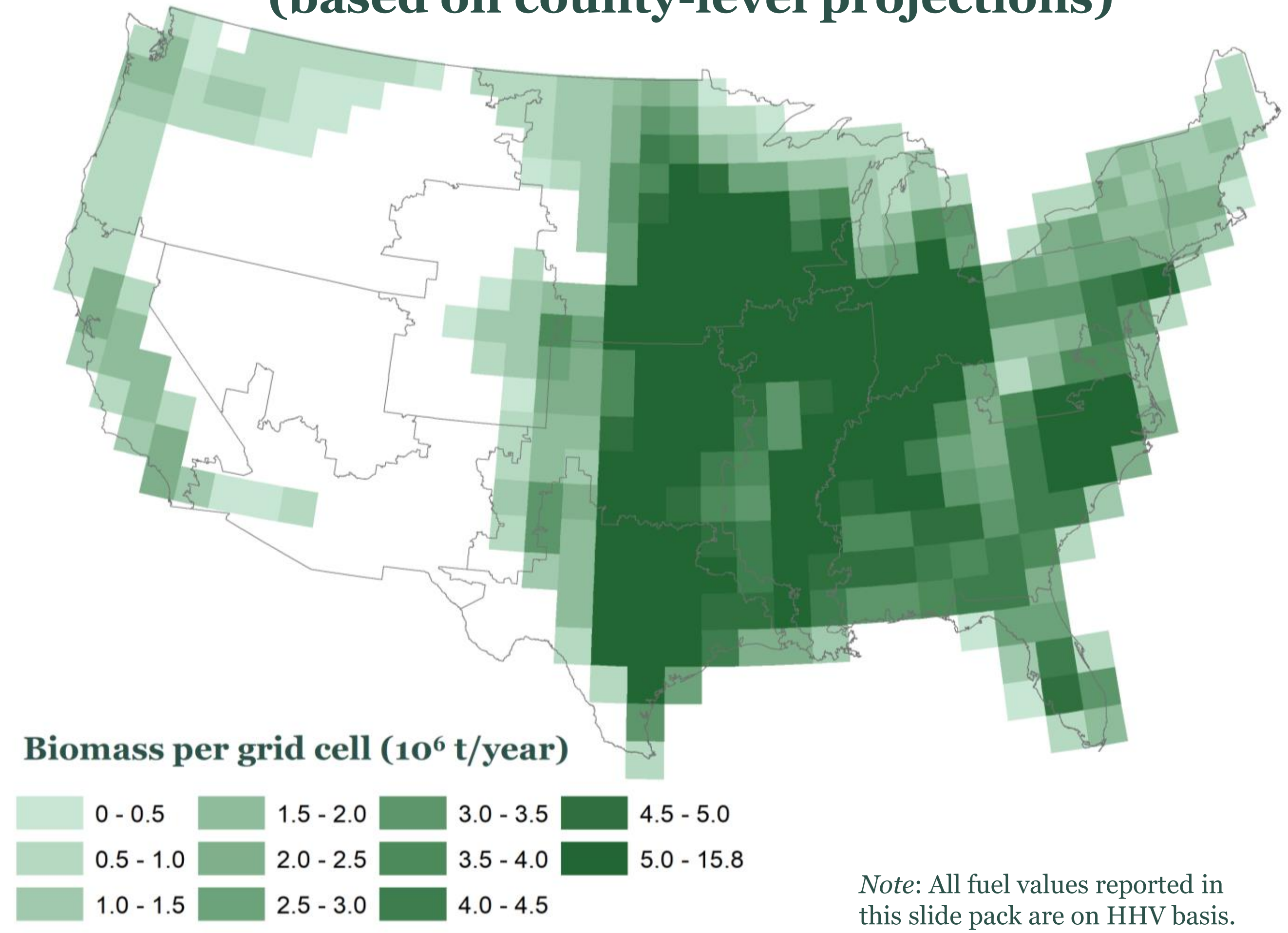
Spatial downscaling and analysis of bioenergy production and use in the E-B+ pathway

Summary of this section

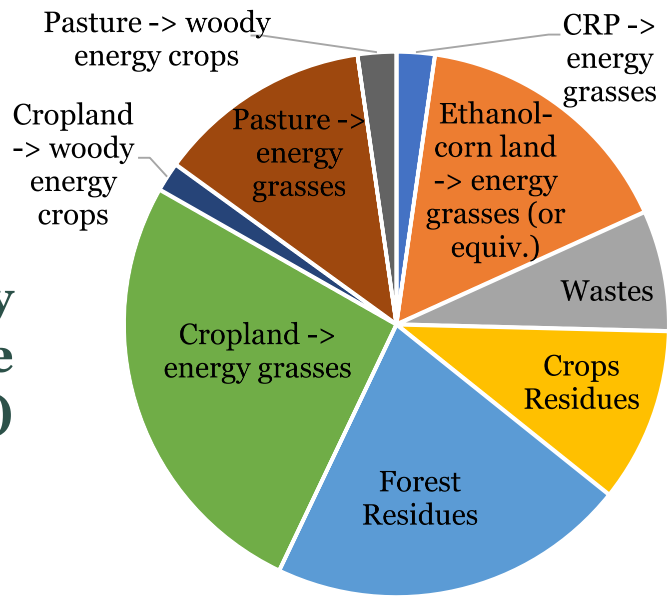
- For the E- B+ pathway, the geographic distribution of biomass supplies, including dedicated energy crops grown on converted crop or pasture land, is based on county-level projections from the "Billion Ton Study". Additionally, production of dedicated energy grasses on lands converted from growing corn for ethanol is assumed to be distributed among counties in proportion to their corn production level in 2018.
- The same downscaling methodology and assumptions are used as for the E+ case reported above.
- Cumulative investment in bioconversion capacity by 2050 totals $1.6 trillion nationwide.
- Farmer revenues from sale of biomass for energy are more than quintuple today's revenues for corn sold into ethanol production.
- See Annex H for details of the bioenergy downscaling analysis.

E- B+ Scenario: Biomass supply is nearly doubled via conversion of some pasture and cropland to energy crops.

2050 biomass availability, 100 x 100 mi cells (based on county-level projections)

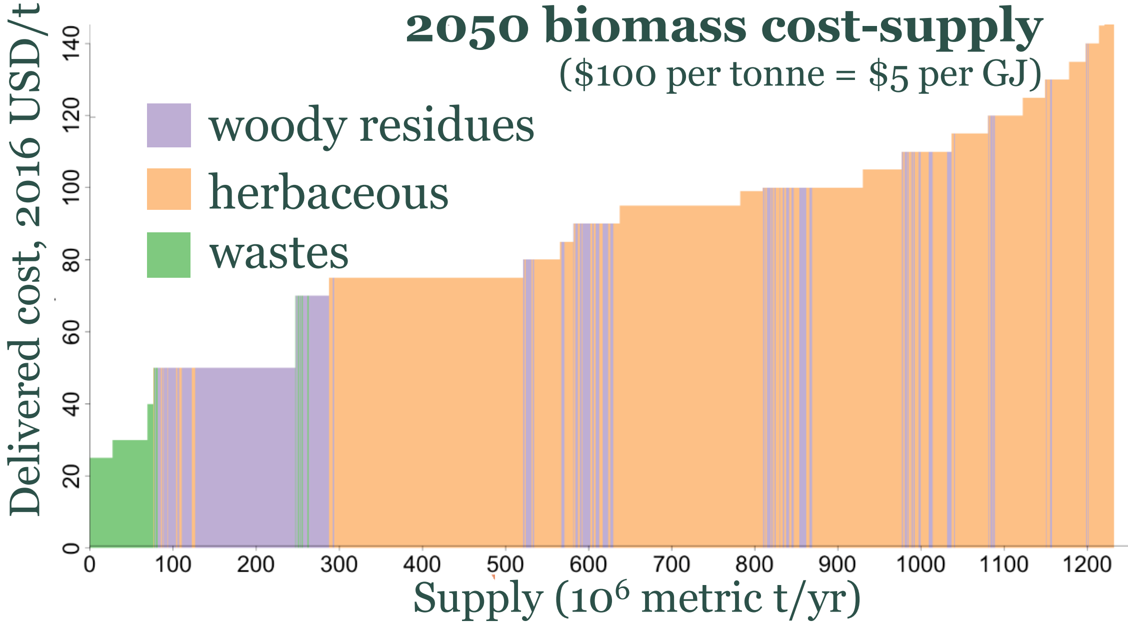


2050 supply by resource (24 EJ total)



2050 biomass cost-supply

($100 per tonne = $5 per GJ)



Note: All fuel values reported in this slide pack are on HHV basis.

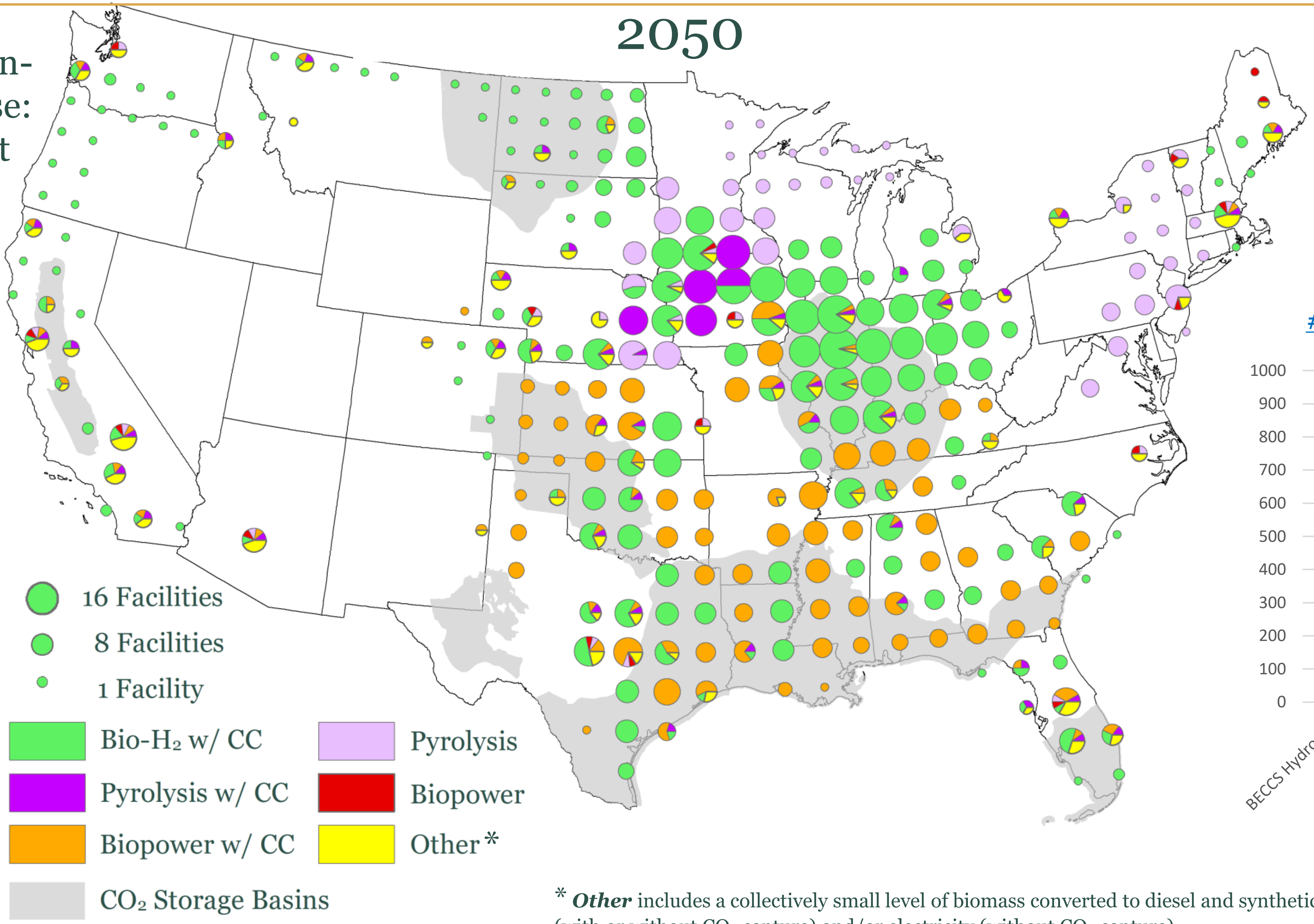
PRINCETON UNIVERSITY

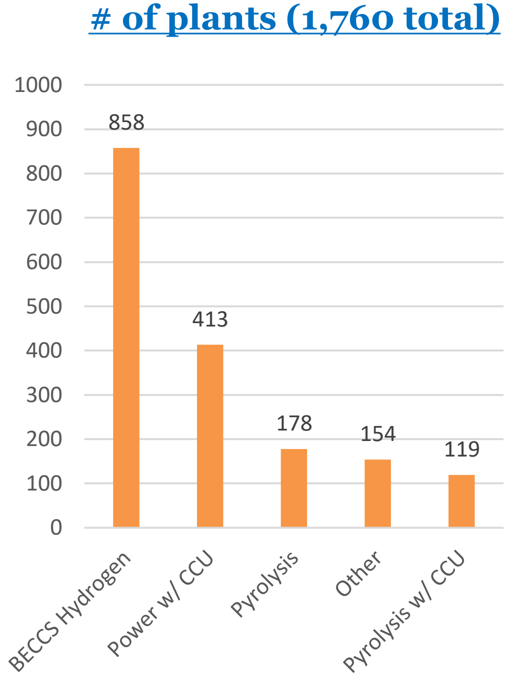
andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

Bioconversion industry, E- B+ scenario

Total annual non-food biomass use:
- 1,153 million t
- 22.8 EJ



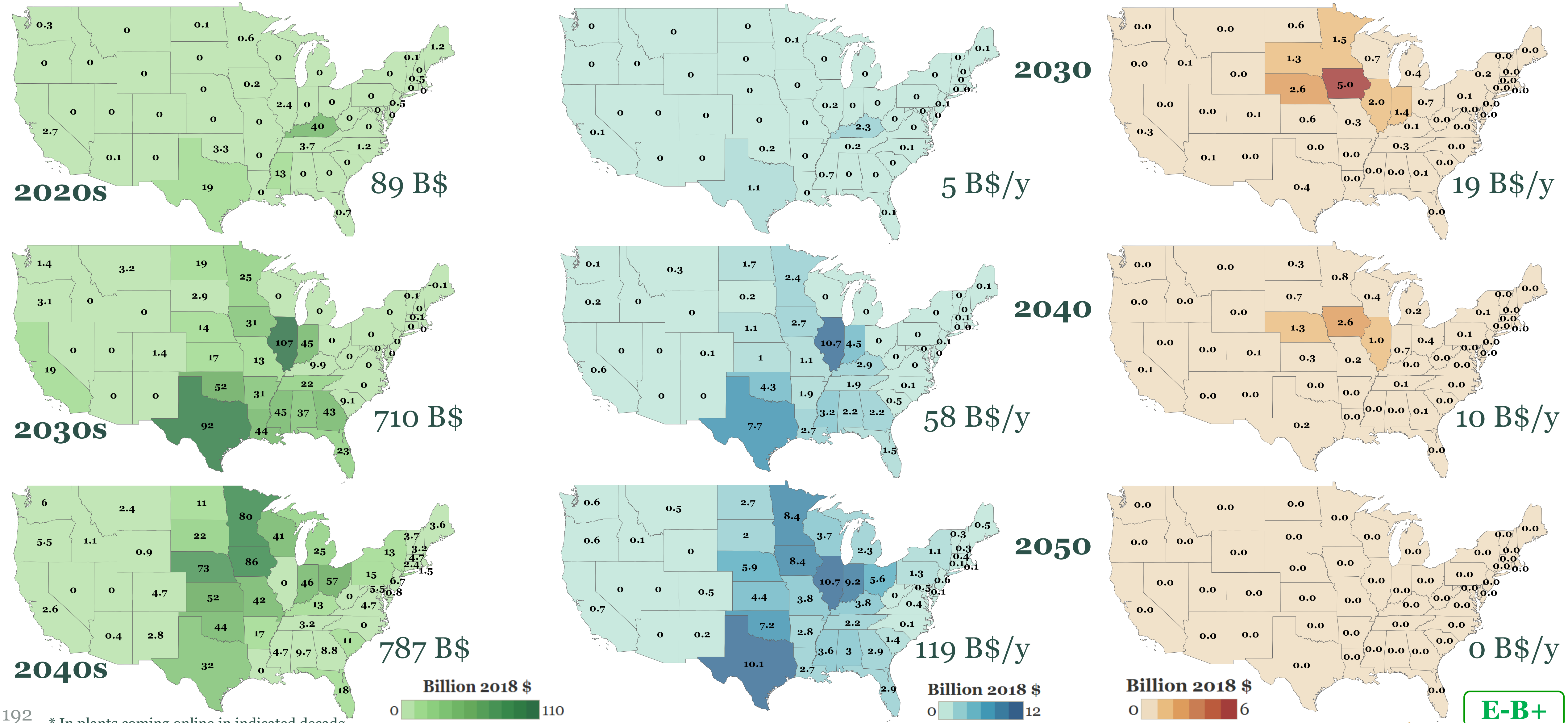


* ***Other*** includes a collectively small level of biomass converted to diesel and synthetic methane (with or without CO_2 capture) and/or electricity (without CO_2 capture).

RETURN TO TABLE OF CONTENTS

1.6 T$ capital invested in bioconversion by 2050, largely in Midwest and Southeast. Biomass purchases grow, displacing corn for ethanol.

Capital invested (B$)* | **Biomass purchases (B$/y)** | **Corn (for eth.) purchases (B$/y)**



* In plants coming online in indicated decade.

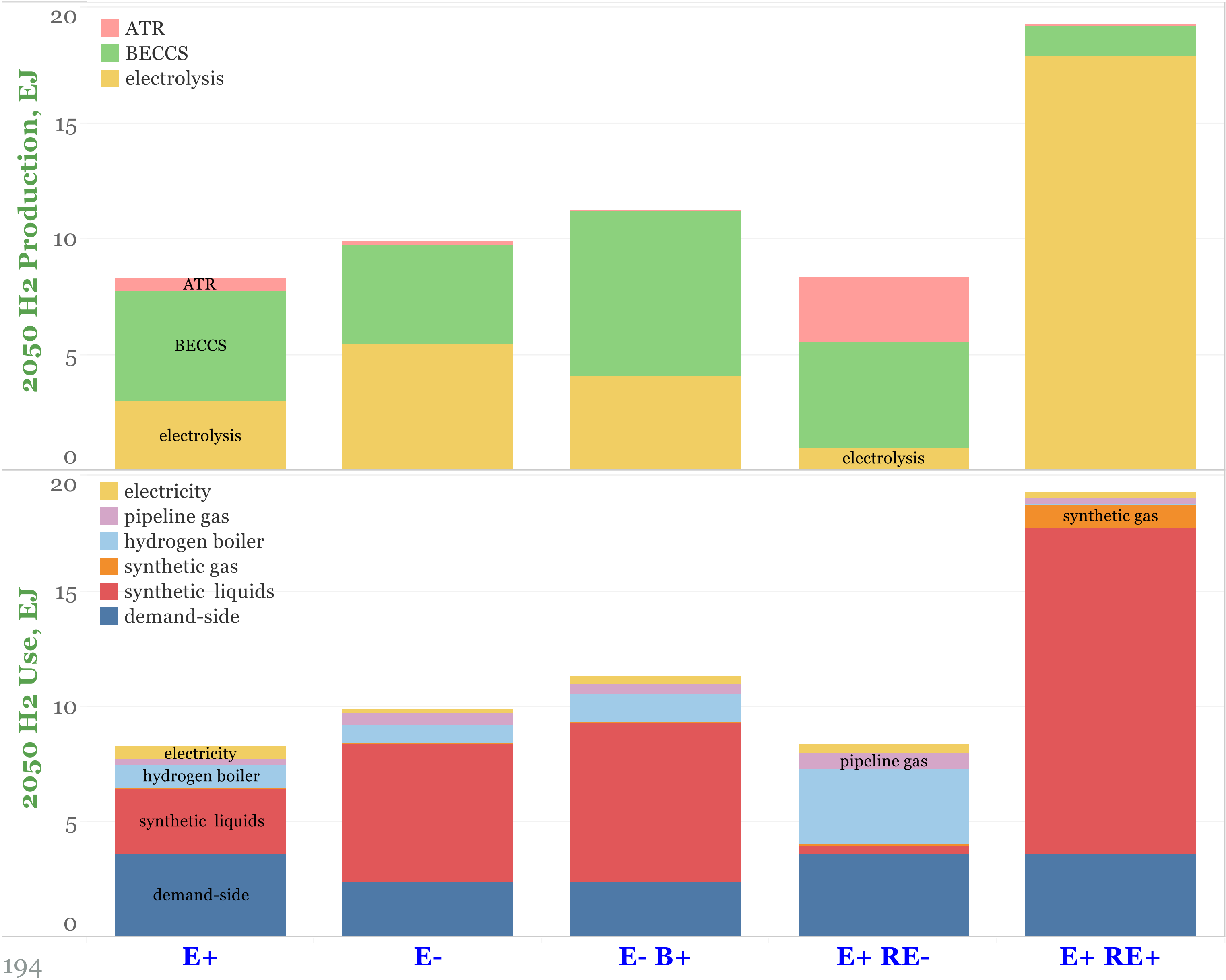
E-B+

Hydrogen production and use

Summary of this section

- In the net-zero models, H_2 can be made by reforming natural gas (without or with CO_2 capture), gasifying biomass (with CO_2 capture), or electrolyzing water. E+, E-, and E-B+ all favor H_2 from a mix of biomass and electrolysis. H_2 from natural gas is prominent in E+RE-, because electrolysis is less cost competitive given more limited wind and solar capacity. In E+RE+, electrolysis dominates by 2050 because fossil fuel use is disallowed and most biomass is converted into pyrolysis oils used for petrochemicals production.
- As a final energy carrier, H_2 is used in fuel cell trucks and for producing ammonia and other chemicals, direct reduction of iron, and industrial heating. As an intermediate energy, H_2 is an input to synthesis of hydrocarbon fuels, and a small amount supplements natural gas use in gas turbine power generation.
- H_2 systems begin expanding substantially only starting in the mid-2030s, reaching total H_2 volumes in 2050 in the E+ pathway more than six times H_2 flows in the U.S. today. In E+RE+, H_2 flows are more than twice as large again, with most H_2 being combined with captured CO_2 to synthesize hydrocarbon fuels.
- Many industrial H_2 users would likely produce H_2 onsite, as happens today. Distributed users might be served by regional pipeline networks and/or truck delivery, as is also the case in some regions today. Vignettes of notional future industry-serving regional H_2 pipelines are sketched to illustrate.
- Design and mapping of future H_2 systems was not done (except for biomass H_2, as described earlier) with as high a resolution as some other features of the net-zero pathways, but coarse (14-region) analysis indicates possible future geographic distribution of this industry.
- See Annex L for additional details relating to hydrogen in the net-zero pathways.

58 to 136 Mtpa of H_2 are produced in 2050; volume-equivalent (at pipeline pressure) to 0.8x to 2.2x today's U.S. natural gas use



H_2 sources

ATR = autothermal reforming of natural gas with CO_2 capture.

BECCS = biomass gasification to H_2 with CO_2 capture (negative net emissions).

Electrolysis = water splitting using electricity.

H_2 uses

Electricity = H_2 burned in gas turbines in high "hythane" blend with CH_4 (60% limit by energy).

Pipeline gas = H_2 used for "hythane" blend in CH_4 pipelines (7% limit by energy).

H_2 boiler = industrial steam generation.

Synthetic gas = CH_4 synthesis from H_2 and CO_2.

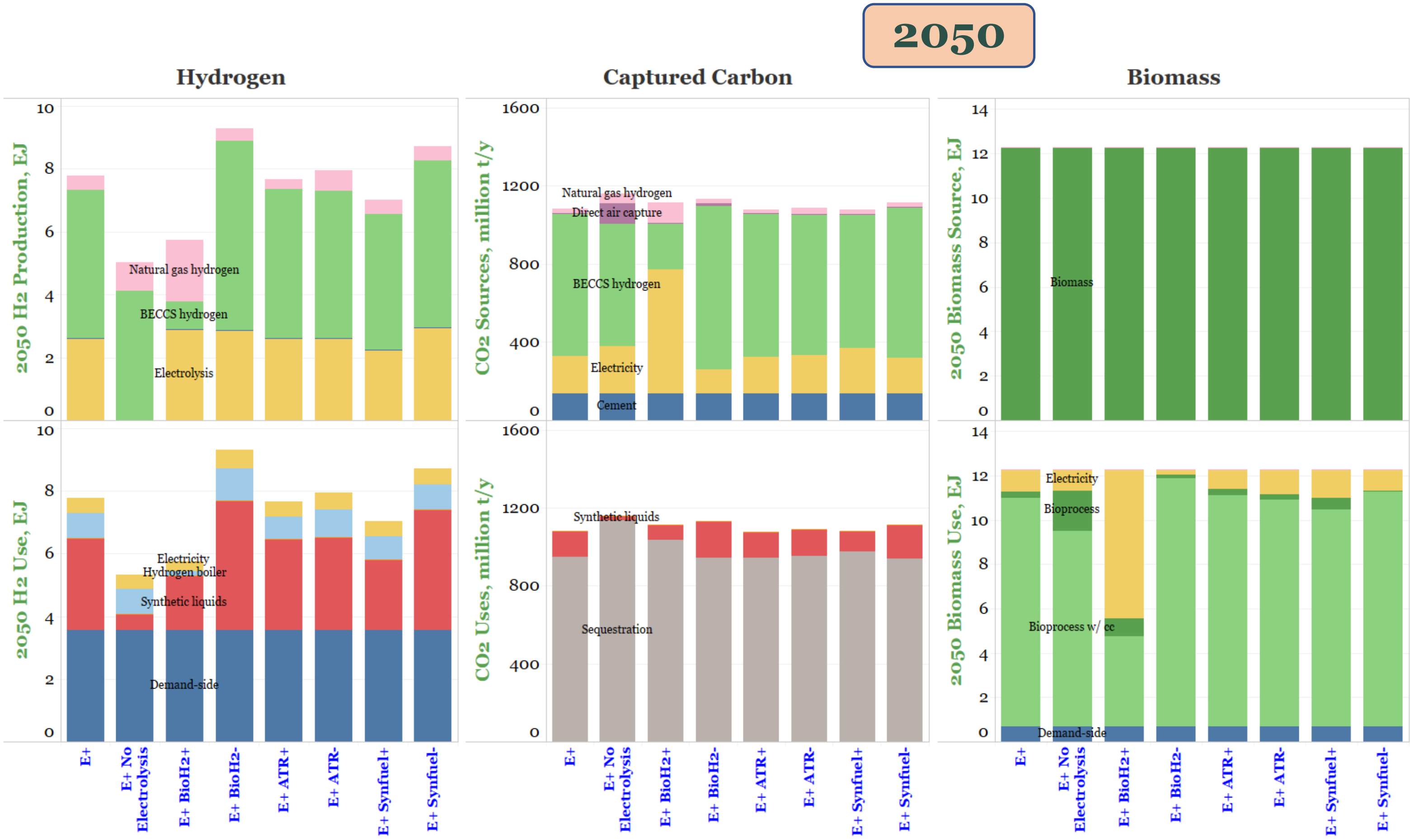
Synthetic liquids = Fischer Tropsch fuels from H_2 + CO_2.

Demand side = H_2 used in transport and for production of chemicals, direct-reduced iron, and process heat in various industries.

Note: All fuel values reported in this slide pack are on HHV basis.

Sensitivity model runs on E+: Cost/availability of technologies for H_2 production and related fuels synthesis impacts results.

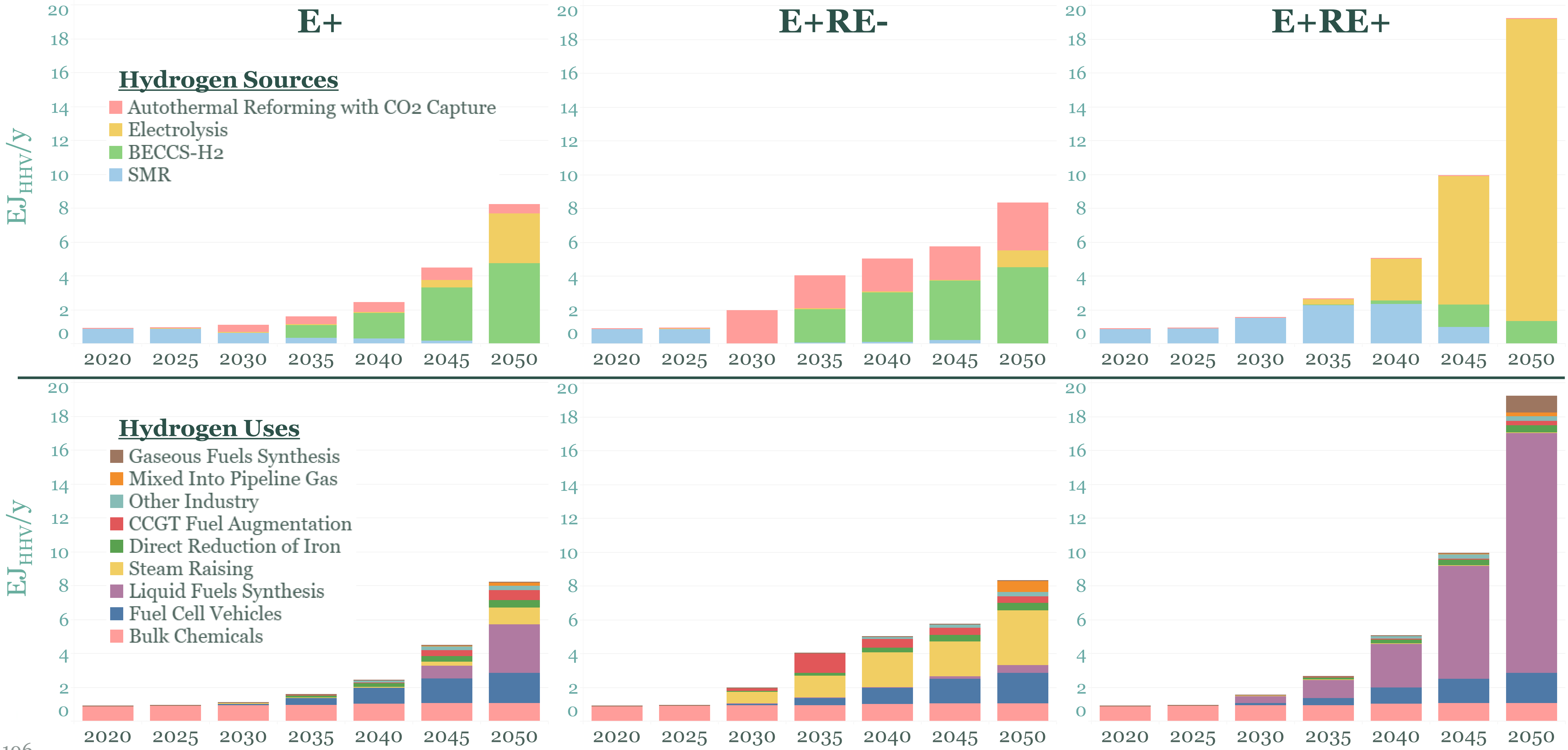
- If electrolysis is disallowed, total H_2 produced is 35% lower, while H_2 from natural gas (ATR-CCS) doubles. Synthetic liquids production is much lower. Direct air capture is deployed to offset residual emissions from greater ATR and use of more petroleum fuels.
- Higher bio-H_2 capital cost drives biomass use from H_2 production to electricity generation with CO_2 capture. More gas is used for H_2 production, and synthetic liquids output falls modestly.
- Results are insensitive to different ATR costs.
- Higher FT synthesis cost reduces output of H_2 and synthetic liquids by ~25%. Lower FT synthesis cost increases H_2 from biomass and via electrolysis.
- NPV of total energy-supply system costs (2020-2050) are about the same for all cases shown.
- See Annex B for additional details.



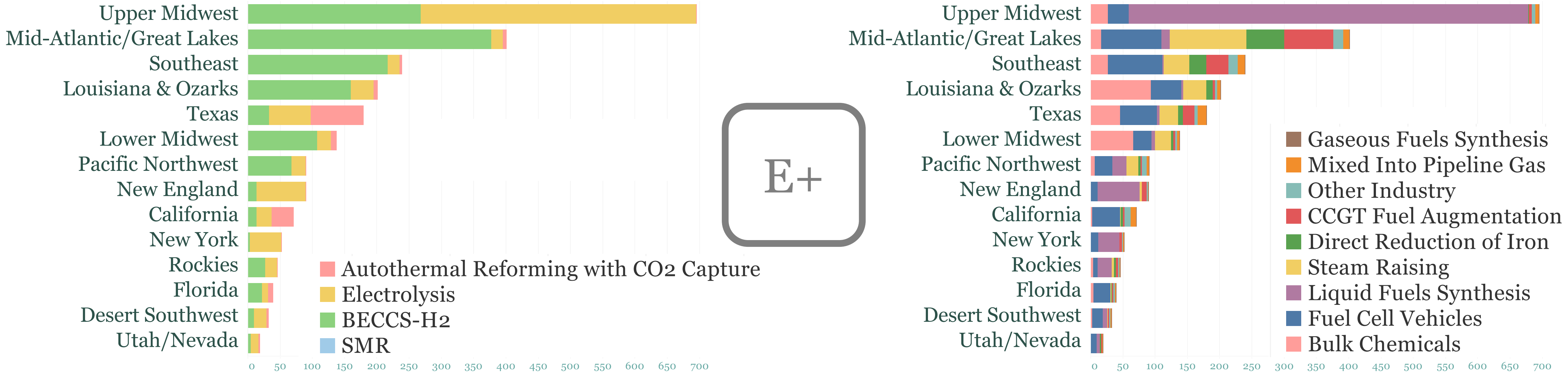
Input assumptions that vary between cases, installed capital cost in 2050 (2016$)

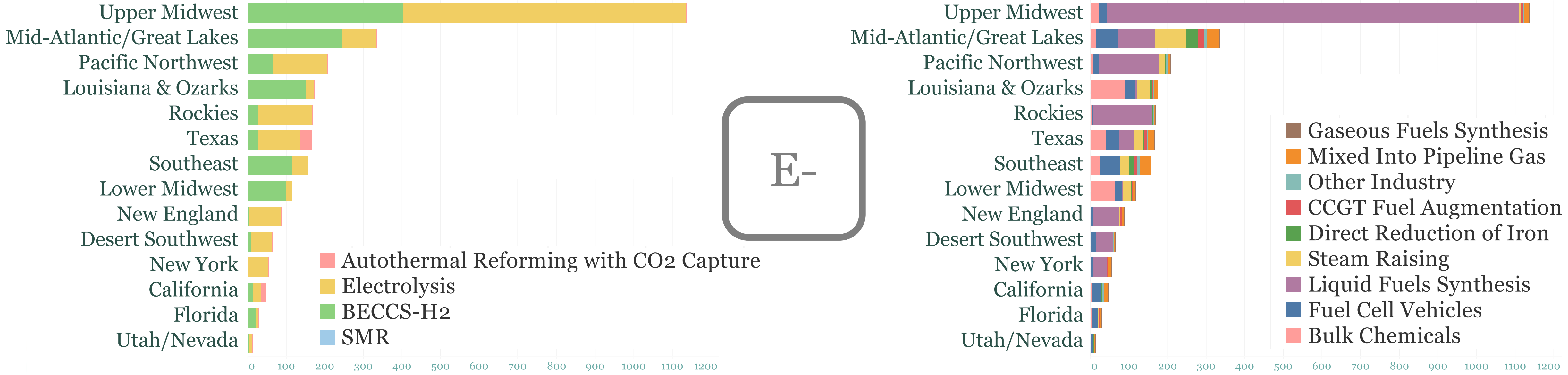
$\$/kW_{H2}$ (HHV)	E+	E+ No Electrolysis	E+ BioH2+	E+ BioH2-	E+ ATR+	E+ ATR-	E+ Synfuel+	E+ Synfuel-
BECCS-H_2	2700	2700	4050	2160	2700	2700	2700	2700
ATR-CCS (H_2 from nat. gas)	814	814	814	814	1221	651	814	814
FT (Fischer-Tropsch) synth.	1155	1155	1155	1155	1155	1155	1732	924
Electrolysis	420	not allowed	420	420	420	420	420	420

Growth accelerates after 2030. Mix of H_2 sources and uses varies by pathway. Total is largest by far in E+RE+.



H_2 sources and uses vary by region for different net-zero pathways. 2050 results compared here for E+ and E-.



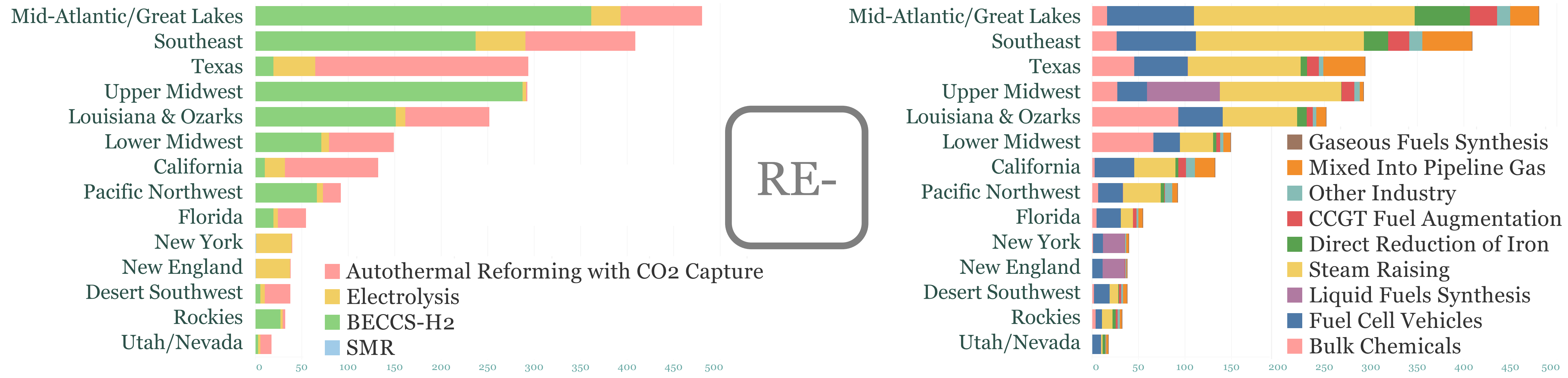


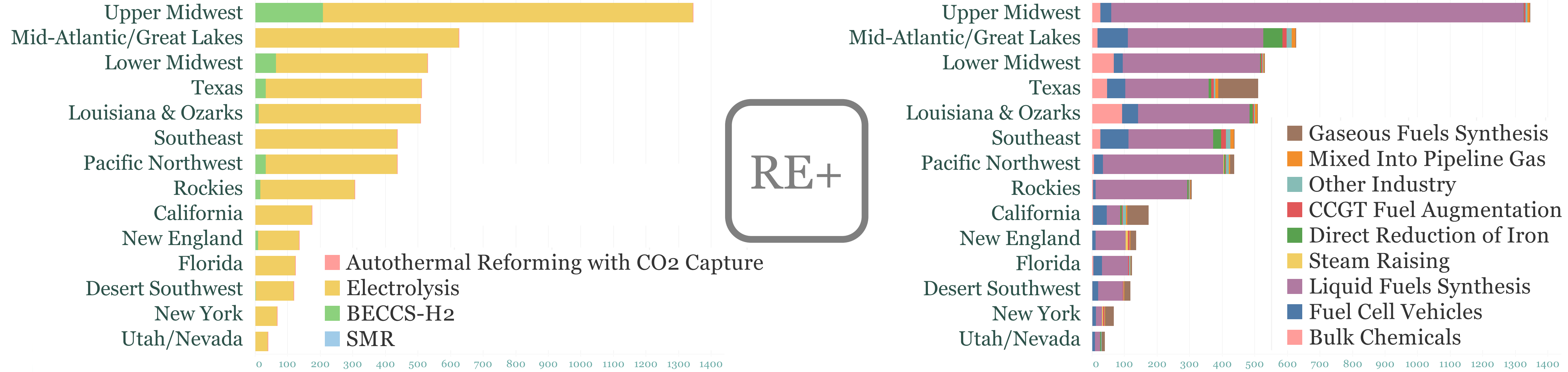
H_2 production (TWh)

RETURN TO TABLE OF CONTENTS

H_2 utilization (TWh)

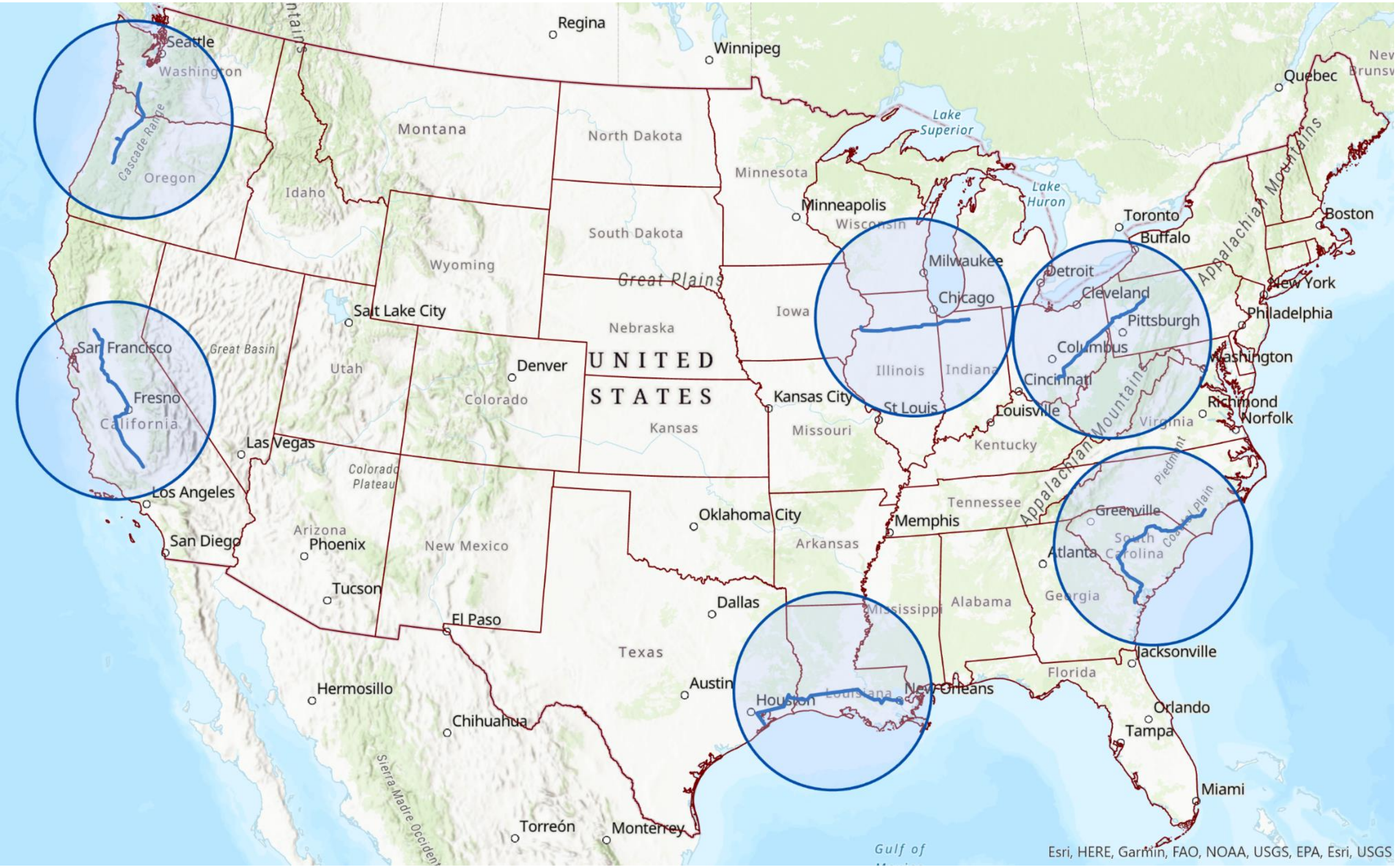
H_2 sources and uses vary by region for different net-zero pathways. 2050 results compared here for E+RE- and E+RE+.





H_2 production (TWh) RETURN TO TABLE OF CONTENTS **H_2 utilization (TWh)**

Notional views of potential H_2 production and use clusters



PRINCETON UNIVERSITY

andlinger center for energy+the environment

RETURN TO TABLE OF CONTENTS

High Meadows Environmental Institute

Carbon Mitigation Initiative

Industrial H_2-using clusters operate today in U.S. and elsewhere. Here, Air Products & Chemicals Gulf Coast H_2 infrastructure.

- A total of about 2,500 km of H_2 pipelines are in service in the US today
- The most significant H_2-using clusters today are on the Gulf Coast

Source: *[Air Products & Chemicals, 2012](#).*

Air Products H_2 Plants - USGC	
Capacity	1.2+ BSCFD
No. of Plants	22
Pipeline Length	~ 600 miles