Insights from DOE Roads to Removal Analysis:

Impacts of carbon-negative hydrogen from biomass

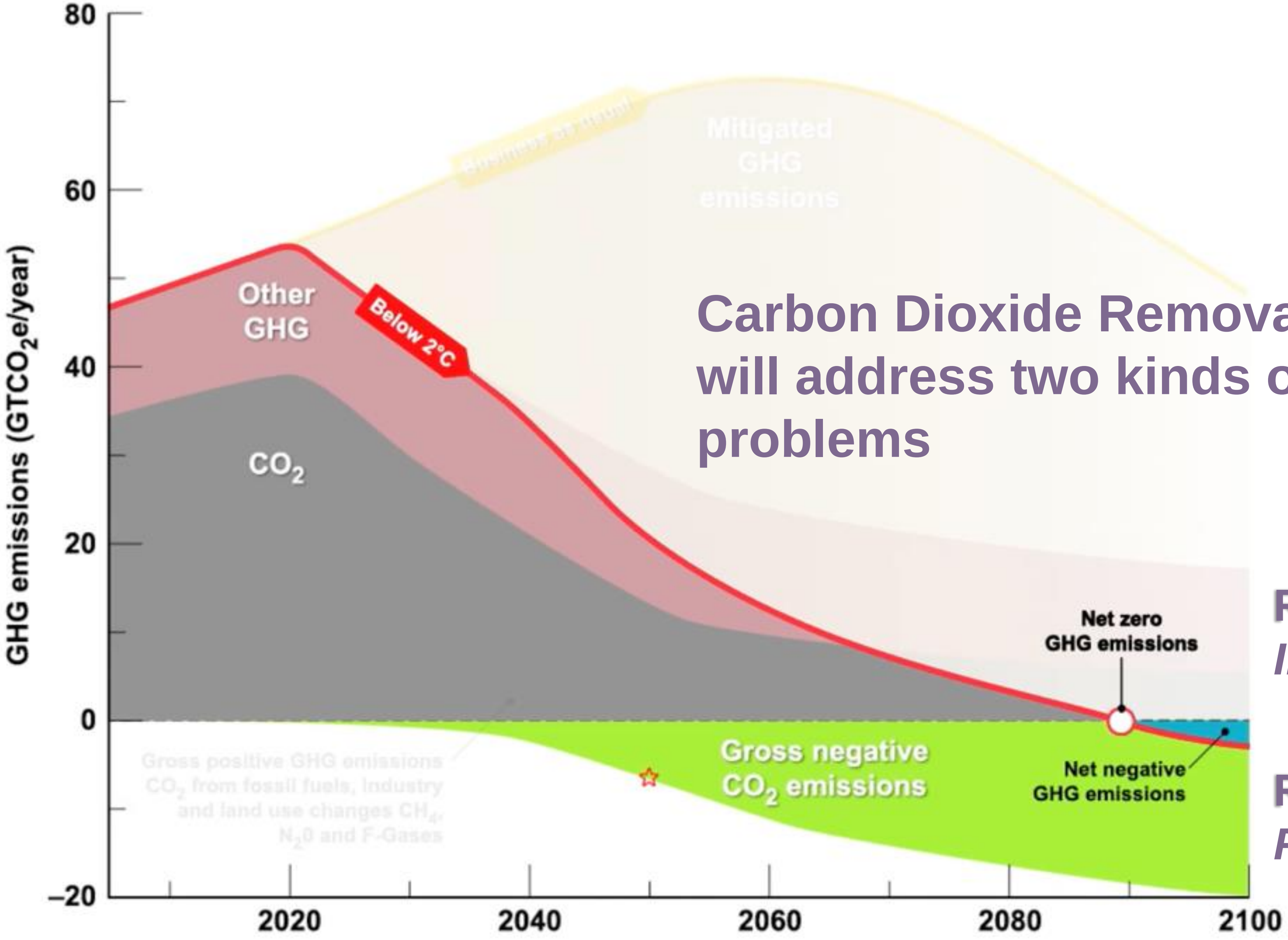
June 21, 2023

Carbon Negative Hydrogen Workshop

Sarah Baker, Wenqin Li (LLNL), Joe Sagues (NC State), Mathhew Langholtz, Chad Hellwinckel, Ingrid Busch (ORNL), Mark Wright, (IA State), Jerome DuMortier (University of Indiana), Alvina Aui (LLNL), Phil Robertson (Michigan State), Sinead Crotty (Yale)

Lawrence Livermore National Laboratory

Carbon Dioxide Removal (CDR) will address two kinds of problems



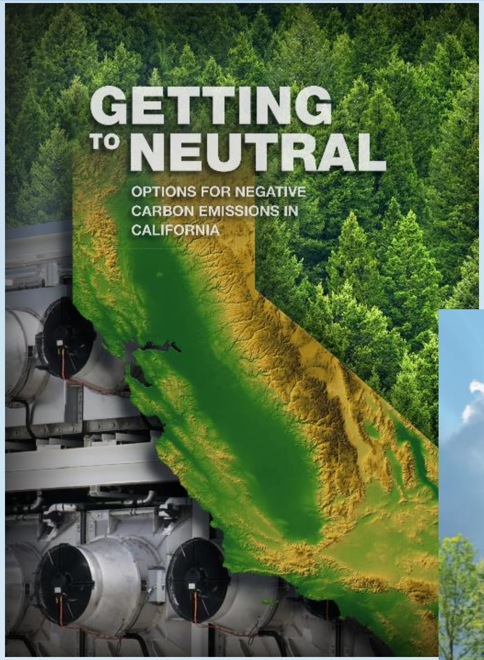
Source: Jérôme Hilaire Mercator Institute

Reductions
In Emissions

Removals
From the Air

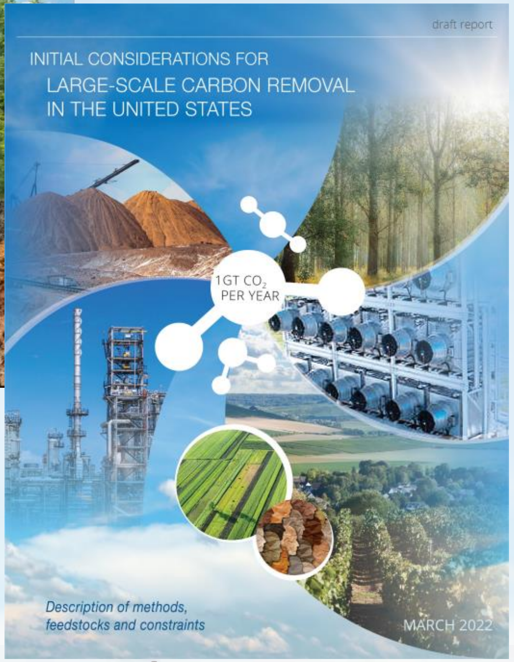
Carbon Removal Assessments

How much CO_2 removal and storage can we accomplish in the USA? What will it cost?

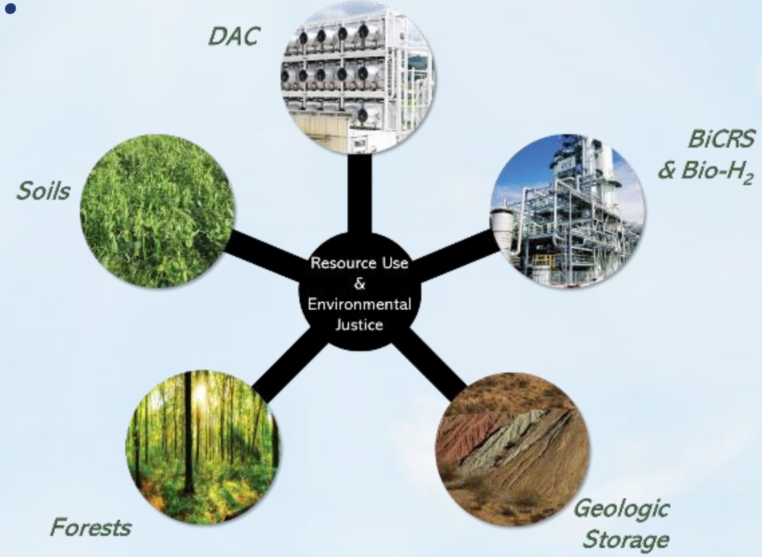


125 Mt by 2045

5-6 Mt/yr by 2030



>1 Gt/yr by 2050?

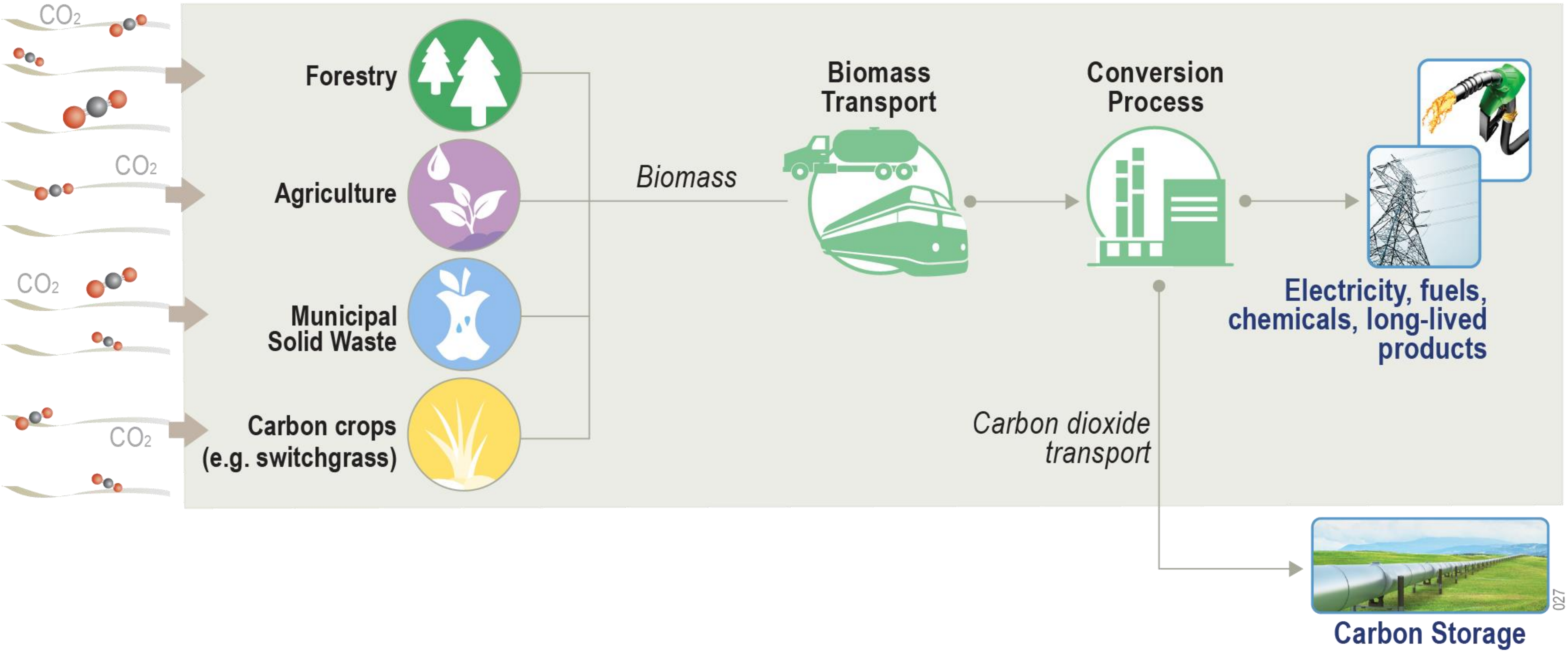


THE LLNL CARBON INITIATIVE
Anticipating the threat and preparing DOE for the next major phase of climate mitigation technology

Roads to Removal

Project Team

Biomass Carbon Removal and Storage (BiCRS)



BiCRS Biomass Supply, Conversion, and Impacts

Currently Available Waste Biomass

CURRENT AVAILABILITY

Location
Amount
Price

MID CENTURY POTENTIAL, INCLUDING PURPOSE-GROWN CARBON CROPS

Biomass potential in **2050**

Biomass/ Technology Suitability Criteria

Feedstock, product, scale dependent TEA

BILT-Biocarbon Infrastructure Logistics and Transportation for CO_2 Removal

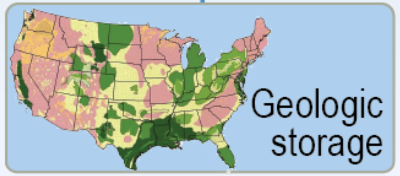
Facility size, type, location, product type to minimize cost/ton CO_2

Biomass location, amount, price, soil carbon from 3 approaches:

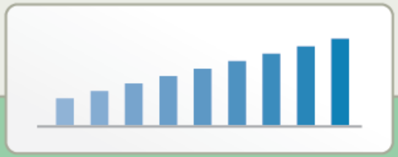
1) Baseline (primarily waste biomass outside of current use)

2) Zero cropland change (baseline + carbon crops on non-cropland)

3) Maximum biomass potential (baseline + carbon crops due to market response on agricultural lands)



Including biomass and CO_2 transport and storage costs



BiCRS CO_2 supply curves

Regional opportunities

Energy Equity and Environmental Justice (EEJ)

We did not analyze

- Gaps to implementation
- Avoided or reduced emissions
- Policy
- Infrastructure needed to support co-products (including H_2 infrastructure)

Biomass Carbon Removal and Storage (BiCRS) Feedstocks

FEEDSTOCK CATEGORIES

Agriculture

- Corn stover ▲
- Wheat, barley, oat, rice straw ▲
- Sorghum stubble ▲
- Cotton residue ▲
- Sugarcane bagasse ▲
- Non-citrus residue ▲
- Cotton gin trash ▲
- Tree nut residue ▲
- Citrus residues ▲
- Rice hulls ▲
- Sugarcane trash ▲
- Hog, cow manure ●

Forestry

- Hardwood, softwood, mixed wood residue ▲
- Other forest residue ▲
- Primary, secondary mill residue ▲
- Western forest restoration ●
- Hardwood whole trees ▲
- Mixed and softwood small diameter trees ▲

MSW

- Construction and demolition waste ▲
- Paper and paperboard (long dash)
- MSW wood ▲
- Non-citrus residue ▲
- Food waste ■

Biogenic Point Source CO_2 Emissions

- Landfill Biogas ♦
- Wastewater Biogas ★

Carbon Crops

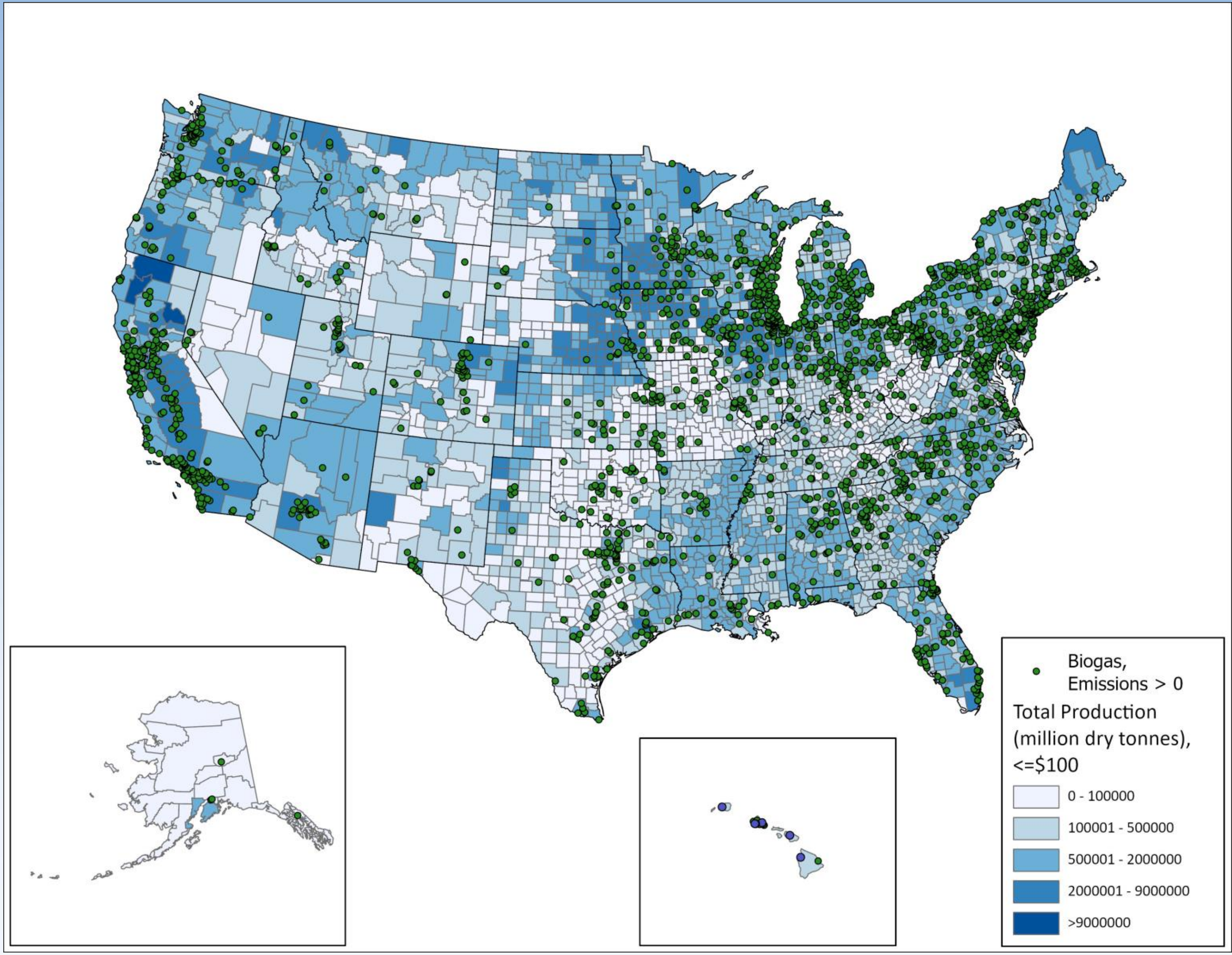
- Switchgrass ❖
- Willow ❖
- Poplar ❖

Legend

- Feedstock Categories (blue)
- Feedstock (light green)
- CO_2 Emissions (orange)
- Midcentury only (dark green)
- — Reports & Academic Literature
- ▲ DOE 2016 Billion Ton Rpt
- ■ National Wet Waste Inventory Rpt
- ● FIA Evalidator
- ♦ EPA Databases
- ★ JBEI BioSiting
- ❖ New Analysis

U.S. Biomass Assessment Results, Mid Century

Biomass Assessment Approach (2050)	Annual Bone Dry Tonnes @ $100/tonne	Commodity Price Change
Baseline	**494 million tonnes**	0
Zero Cropland Change	**637 million tonnes**	0
Maximum Potential	**967 million tonnes**	10-20%



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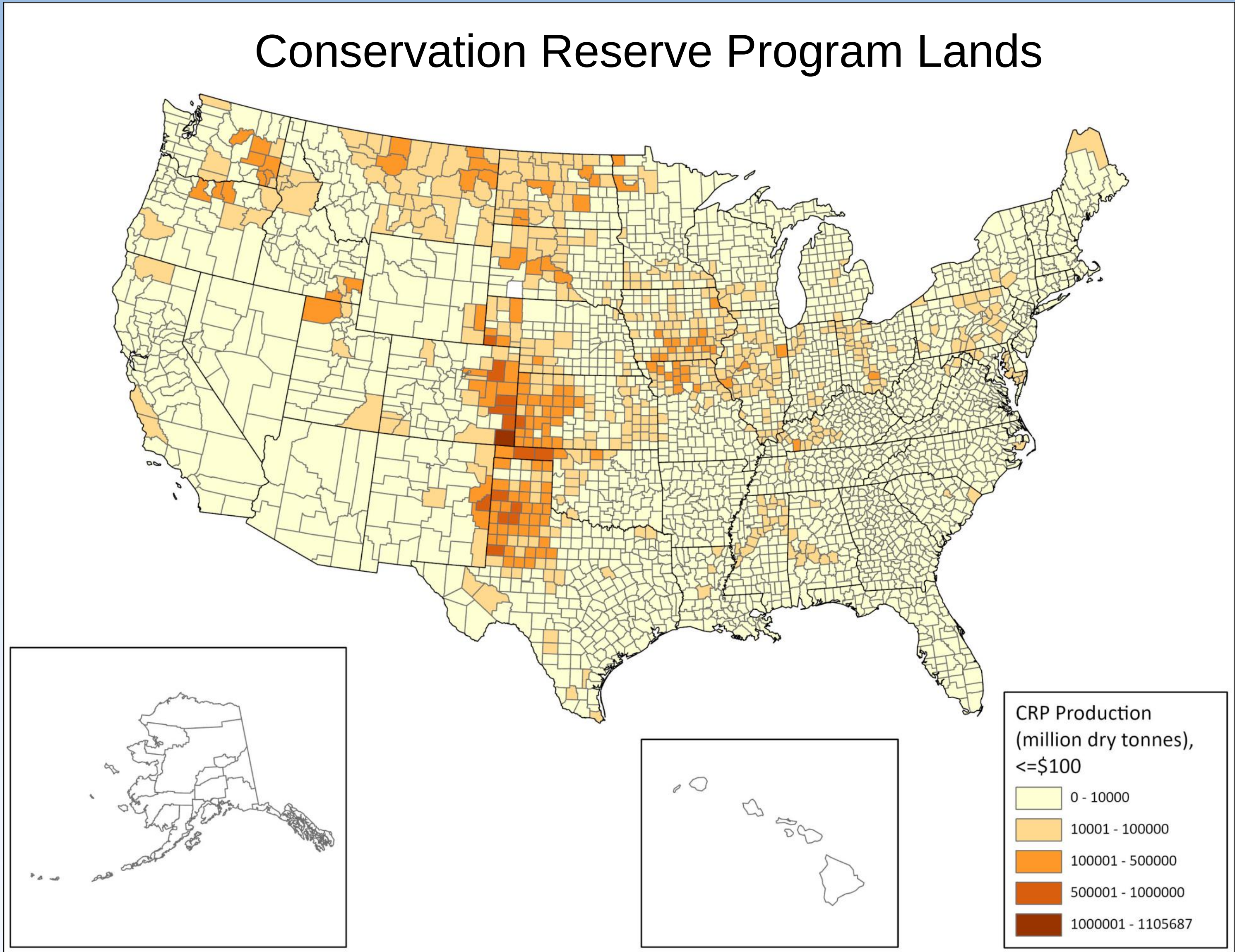

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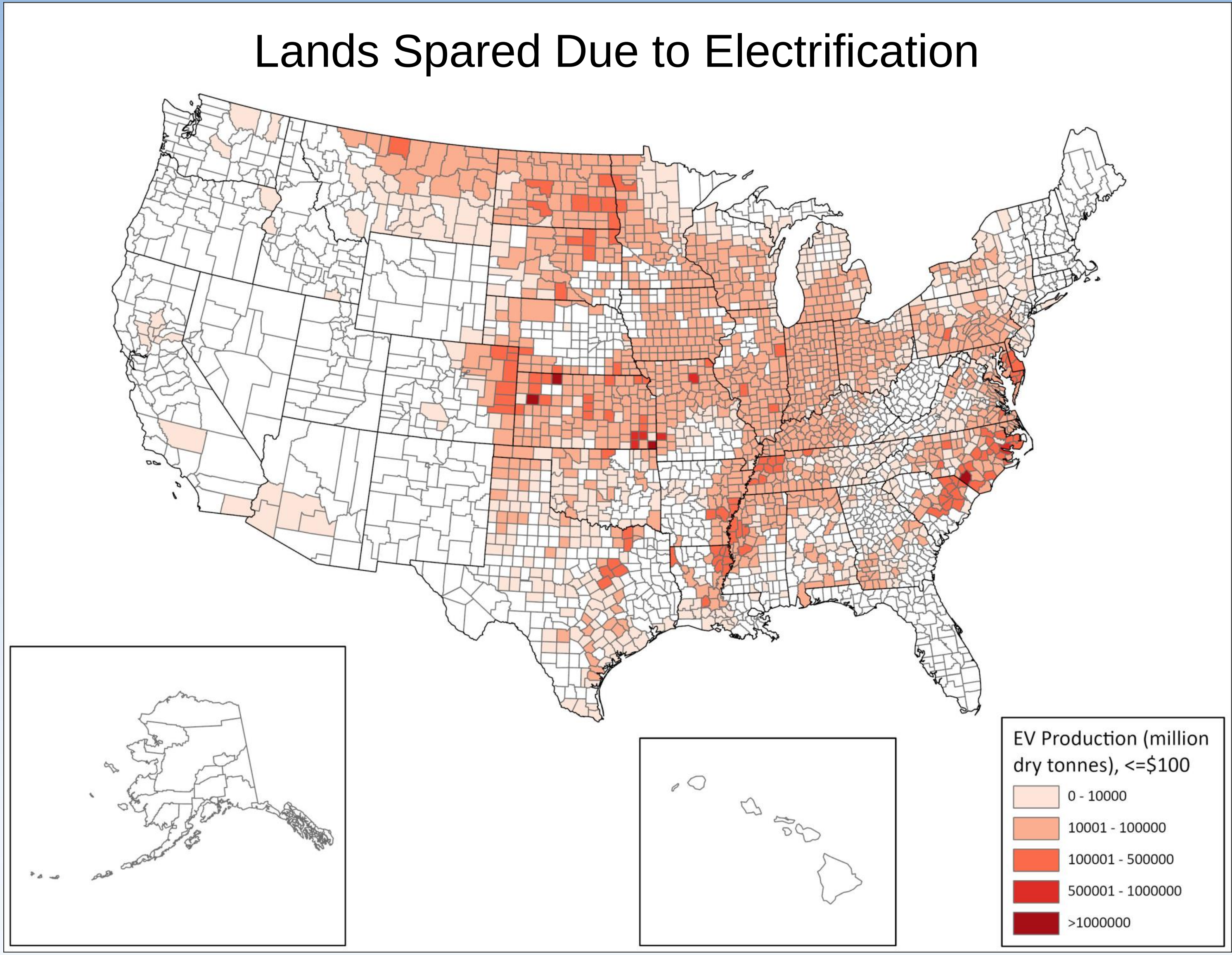

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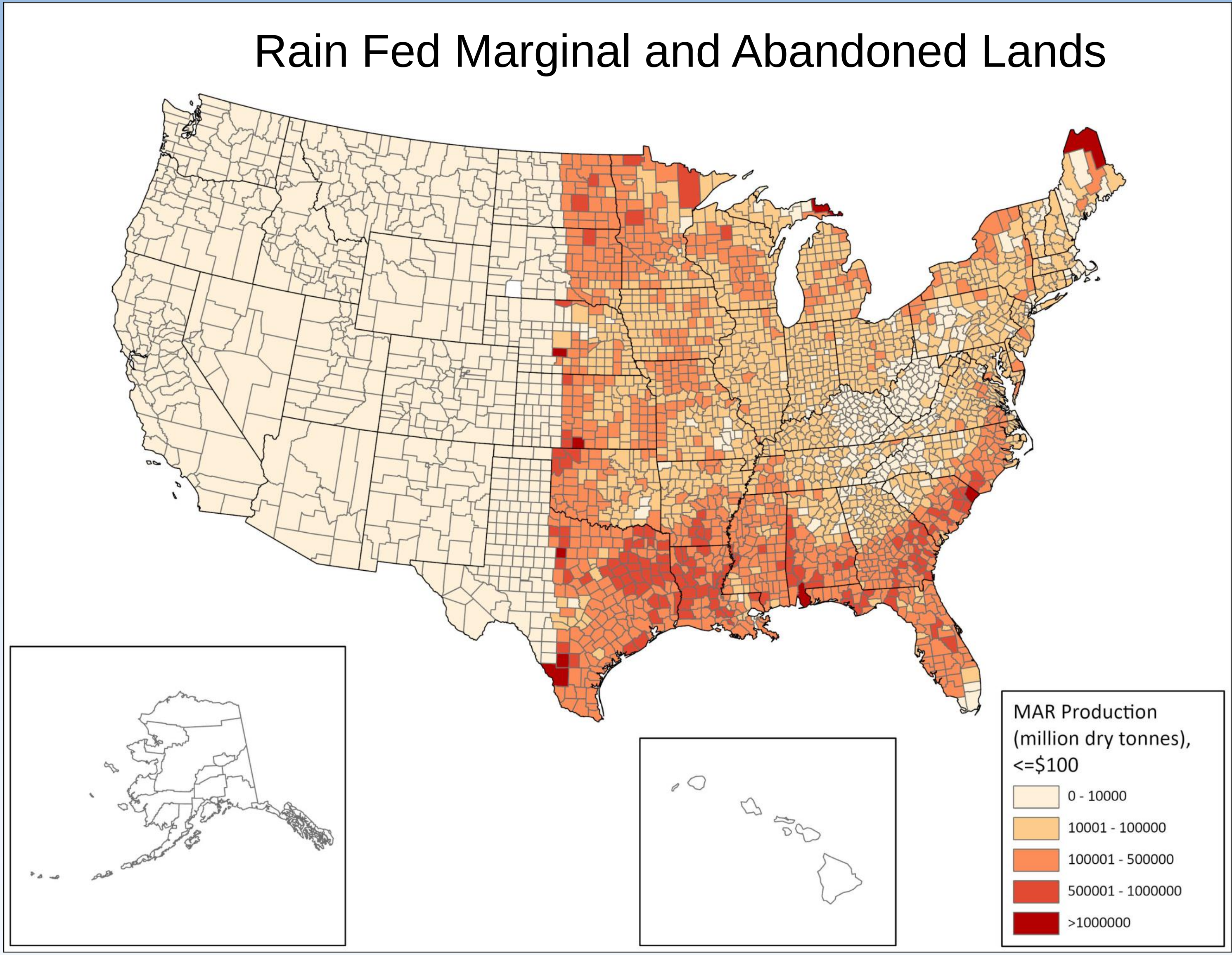

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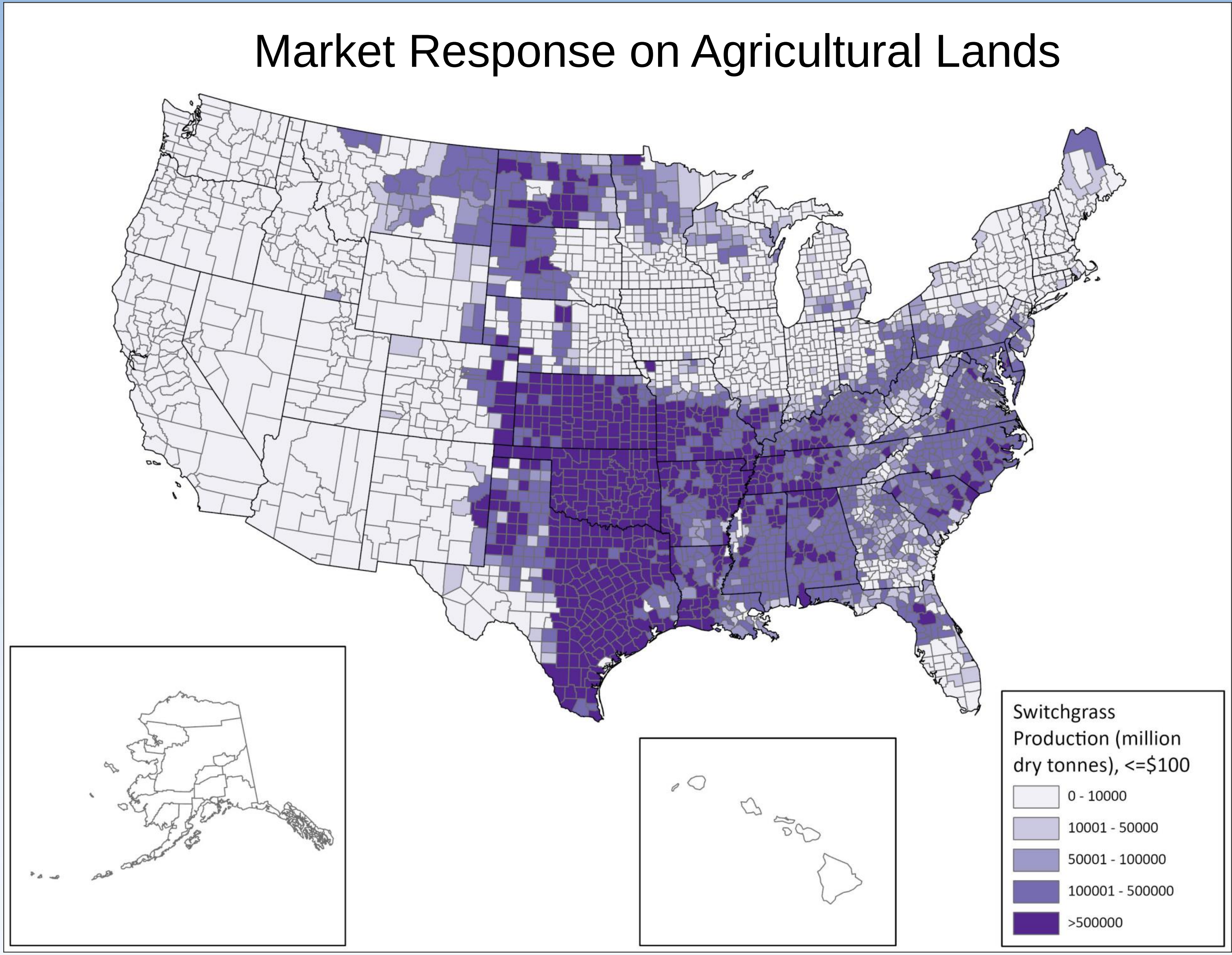

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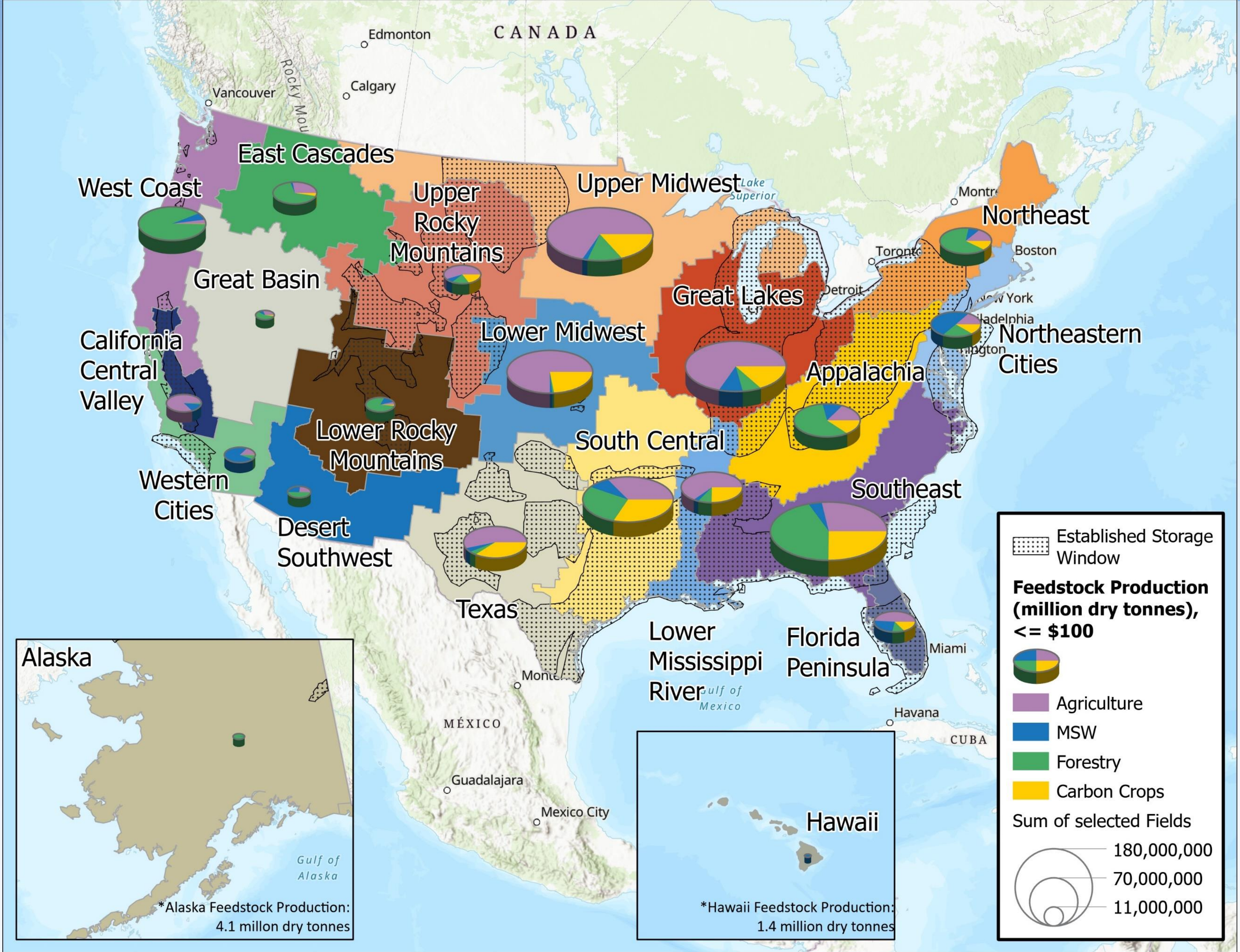
Biomass in Each U.S. CO_2 Removal Region-

Zero Cropland Change



We Analyzed 27 Unique BiCRS Pathways

BIOCARBON SOURCES

Dry Biomass
- Agriculture
- Forestry
- Dry MSW

Carbon crops

Wet Biomass
- Wet MSW
- Manure

Biogenic Industrial Emissions

Landfills, wastewater treatment facilities, manure digesters

BIOMASS CONVERSION TECHNOLOGIES

- Gasification
- Pyrolysis
- Combustion
- Liquefaction
- Fermentation
- Anaerobic digestion
- Sawmill

BIOPRODUCTS

- Hydrogen
- Liquid fuels
- Heat & power
- Methane
- Chemical co-products

BIOCARBON SINKS

- CO_2 Capture and sequestration
- Biochar sequestration
- Long-lived products
  - Polymers
  - Lumber
  - Construction materials

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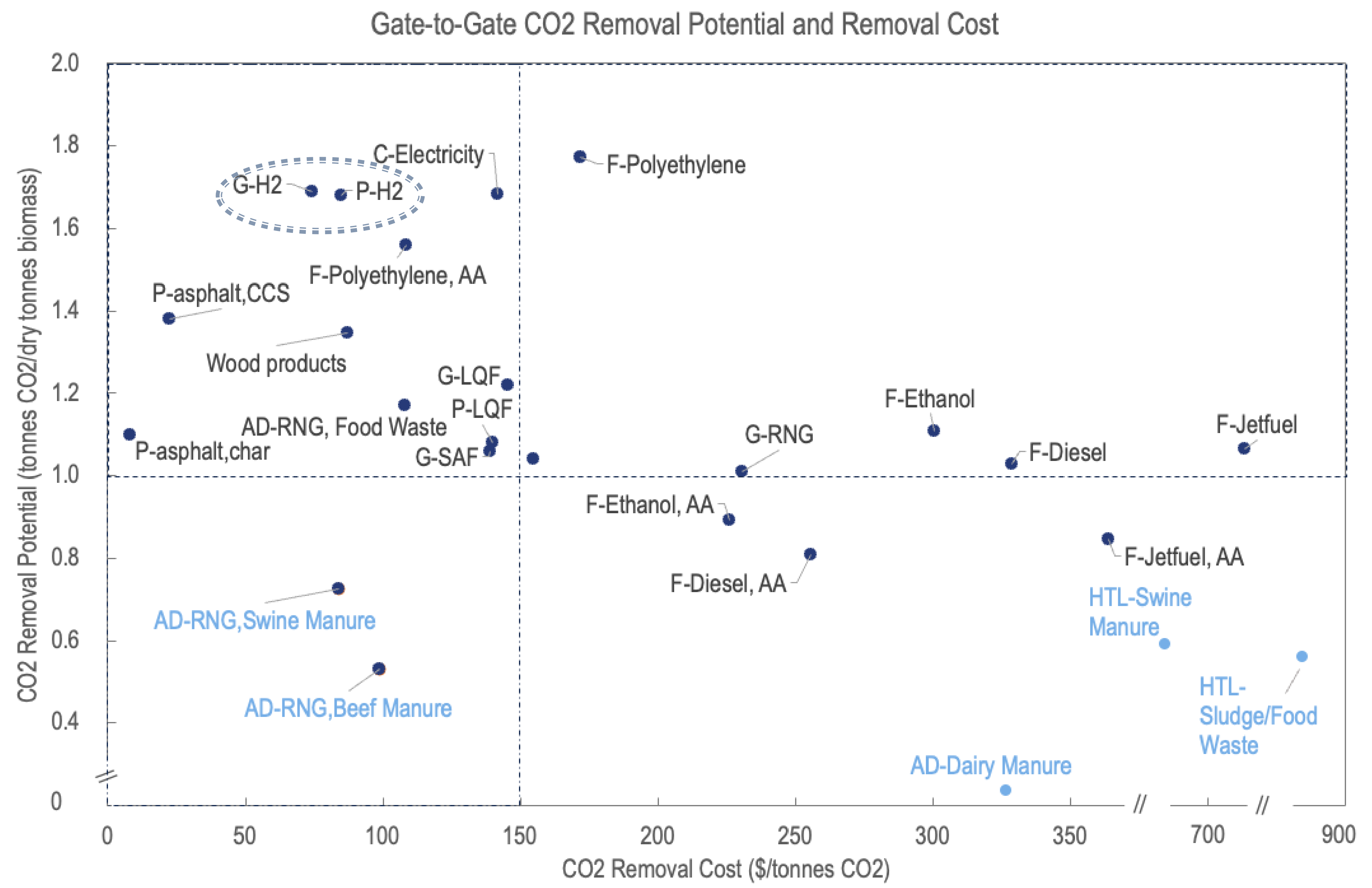
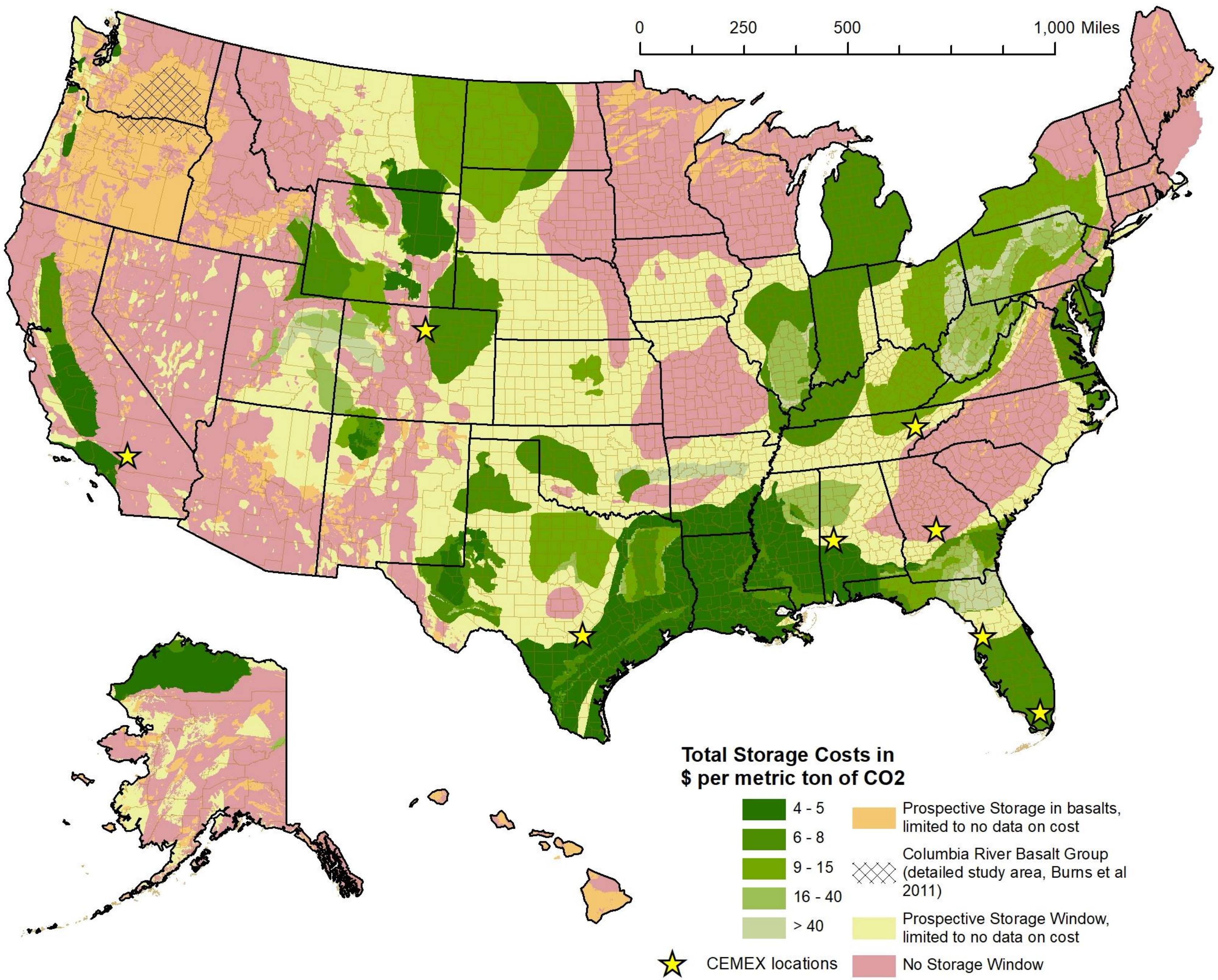


Gate-to-Gate CO2 Removal Potential and Removal Cost
CO2 Removal Potential (tonnes CO2/dry tonnes biomass)
CO2 Removal Cost ($/tonnes CO2)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
0
50
100
150
200
250
300
350
700
900
C-Electricity
G-H2
P-H2
F-Polyethylene
F-Polyethylene, AA
P-asphalt,CCS
Wood products
G-LQF
P-LQF
AD-RNG, Food Waste
P-asphalt,char
G-SAF
G-RNG
F-Ethanol
F-Diesel
F-Jetfuel
F-Ethanol, AA
F-Diesel, AA
F-Jetfuel, AA
AD-RNG,Swine Manure
AD-RNG,Beef Manure
HTL-Swine Manure
HTL-Sludge/Food Waste
AD-Dairy Manure

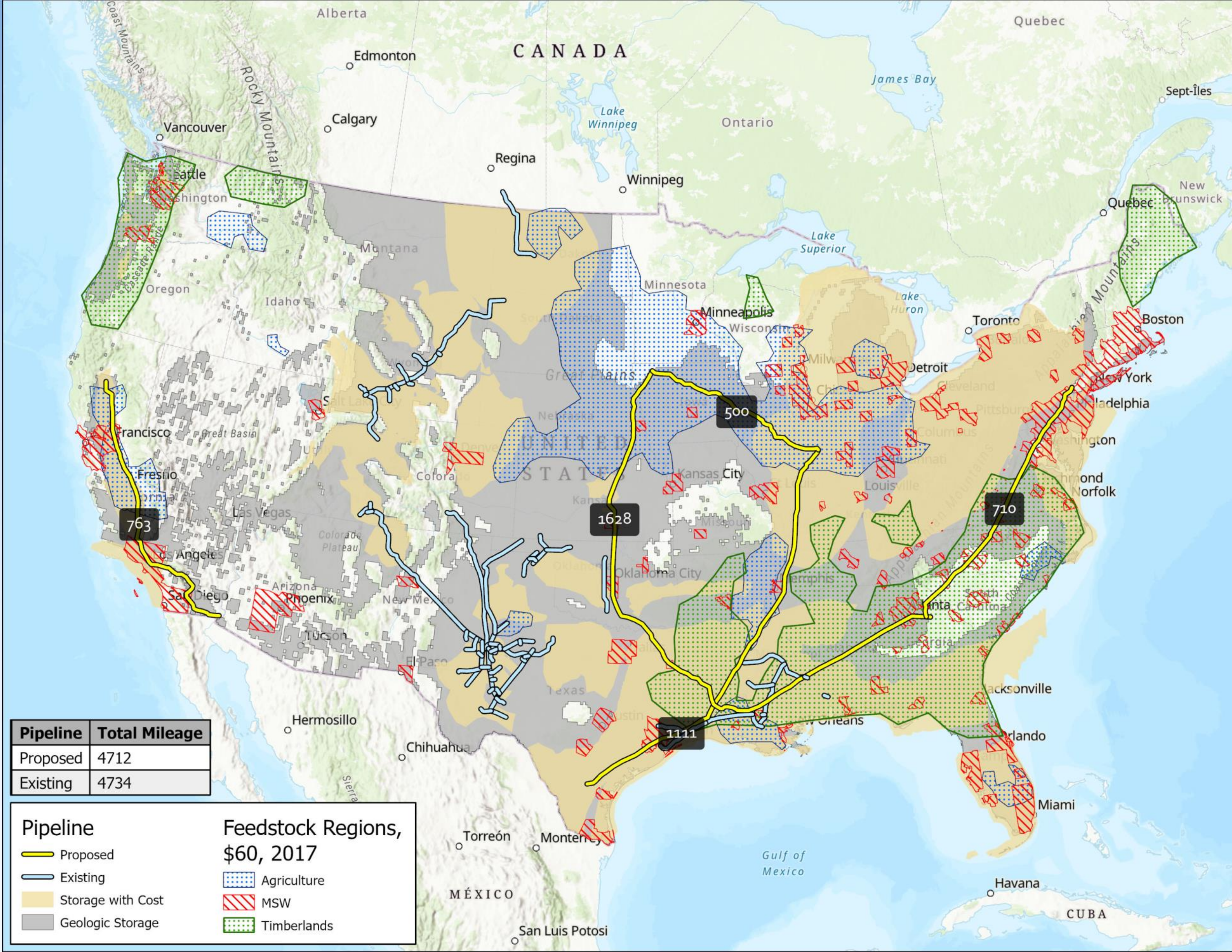
US Geologic Storage:

Extensive, but not co-located with all biomass



Sue Havorka

Minimal CO_2 Trunk Line



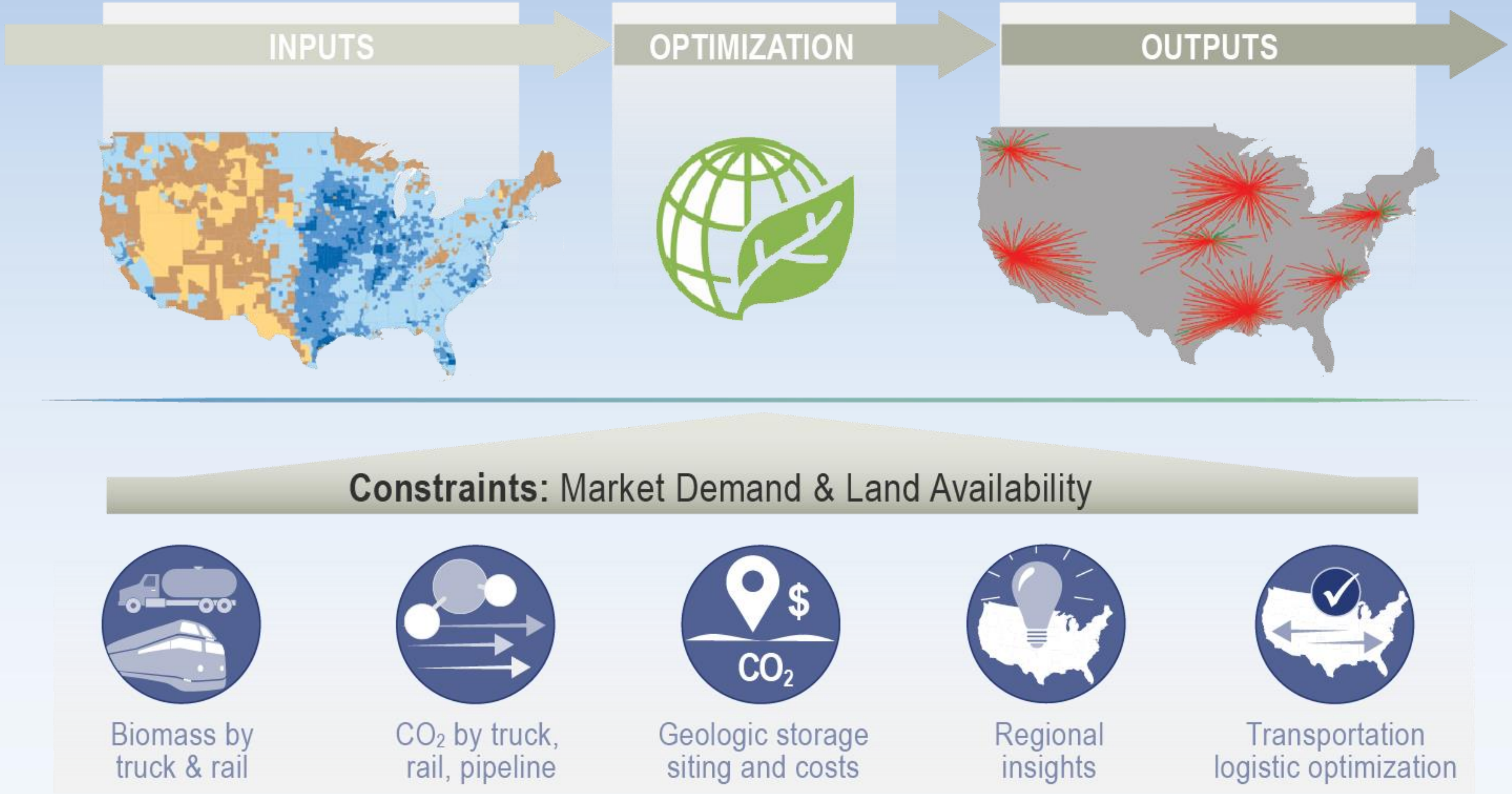
Pipeline	Total Mileage
Proposed	4712
Existing	4734

Implementation of BiCRS: Biocarbon Infrastructure, Logistics, and Transportation

BIOMASS INFRASTRUCTURE, LOGISTICS AND TRANSPORT

INPUTS

- Spatial biomass distribution
- Facility sizing & siting criteria
- Technology conversion efficiency
- TEA & LCA



OUTPUTS

- Facilities sited
- Biomass consumed
- Product produced
- Carbon removal potential
- Carbon removal cost

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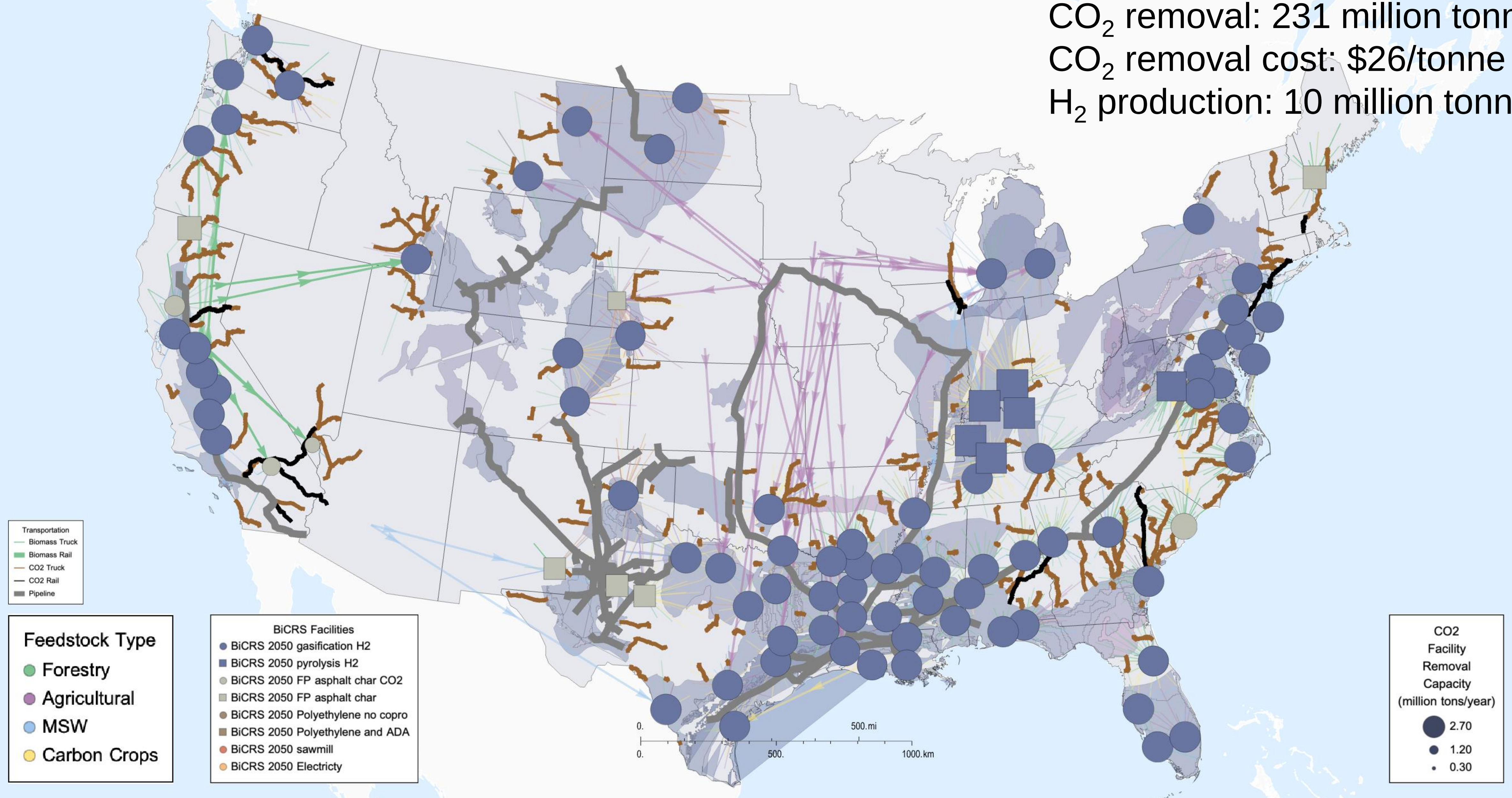
Ingrid Busch

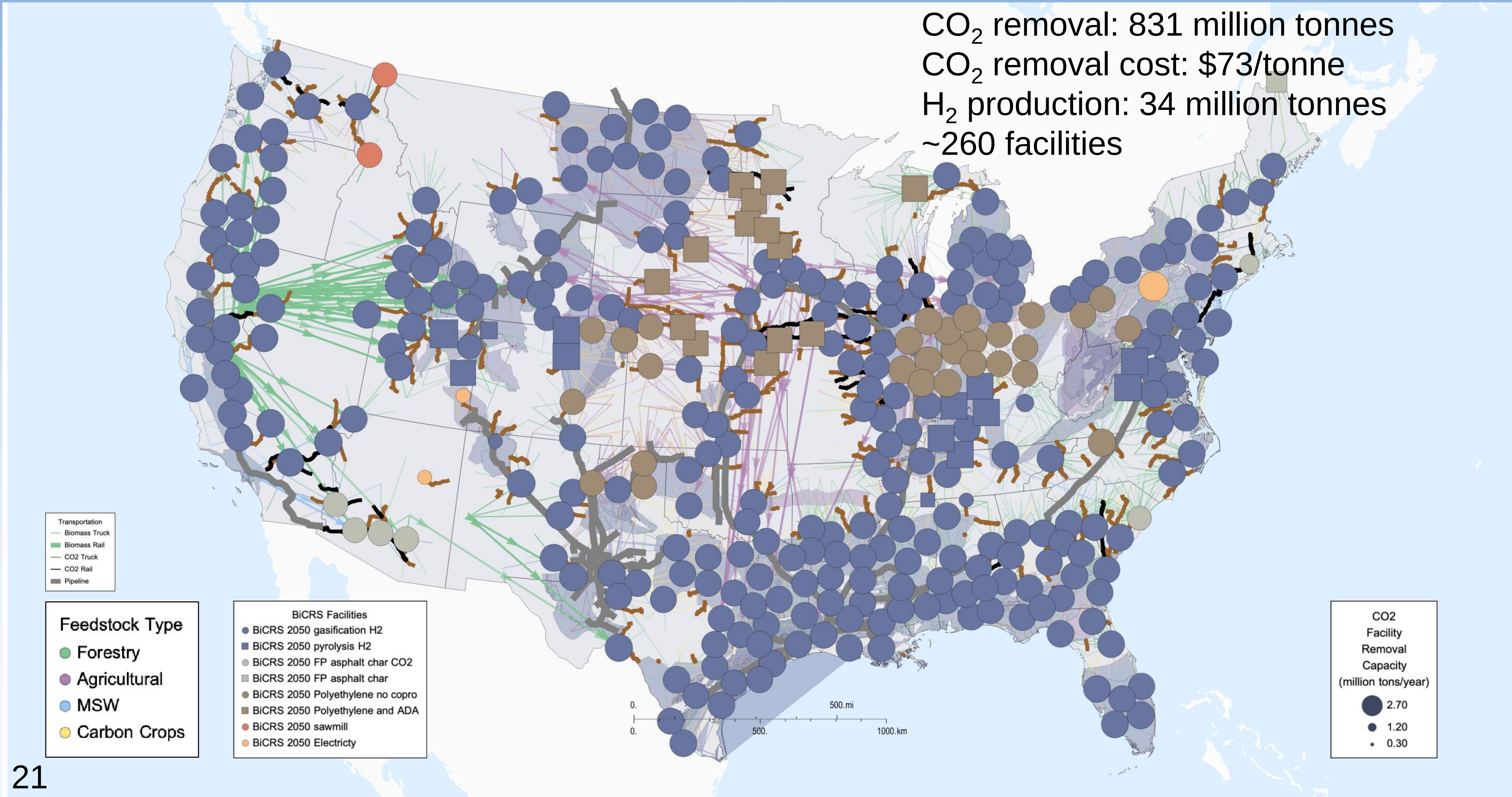
Optmization Results: 25% Removal capacity

CO_2 removal: 231 million tonnes
CO_2 removal cost: $26/tonne
H_2 production: 10 million tonnes



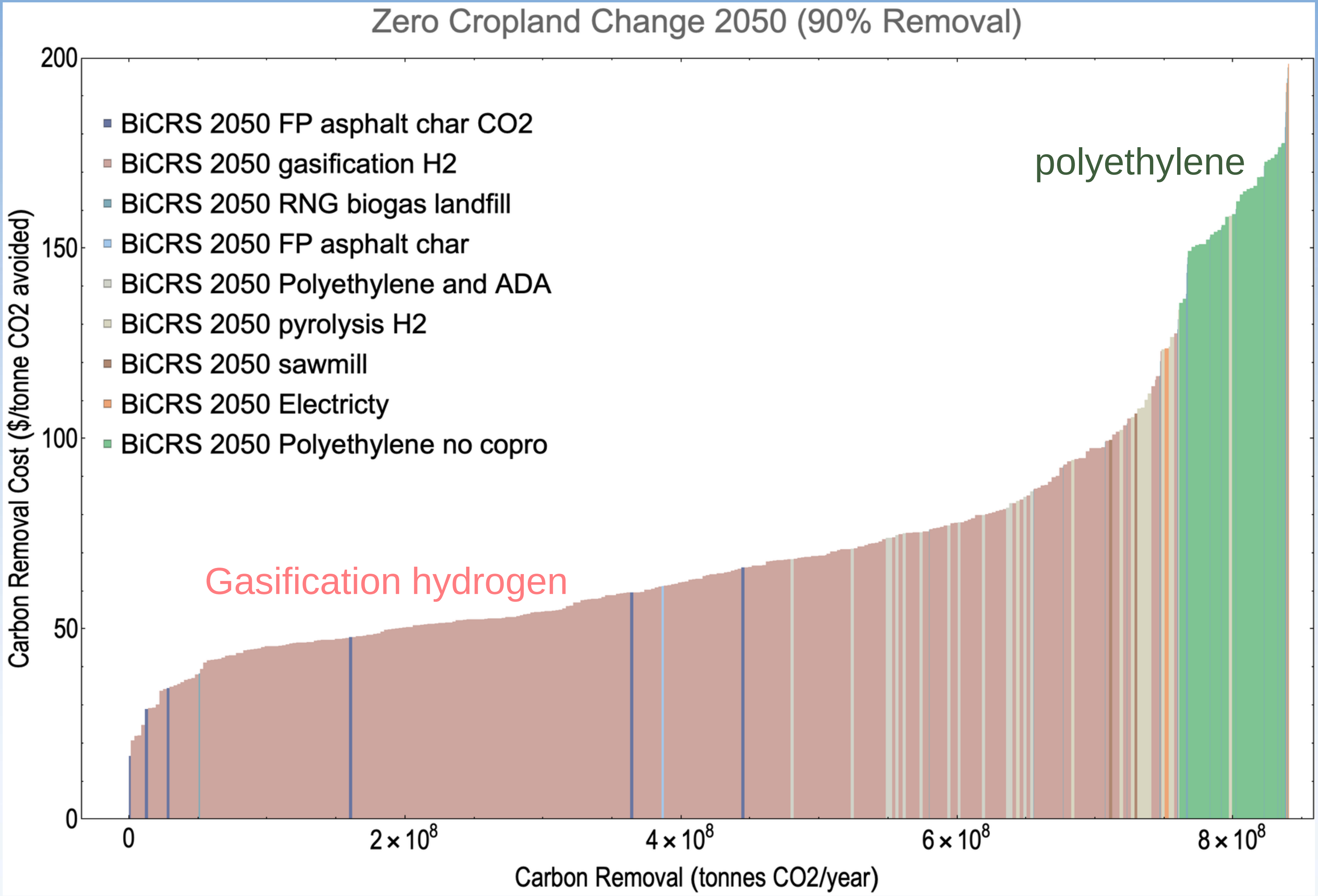
Optmization Results: 90% Removal capacity

CO_2 removal: 831 million tonnes
CO_2 removal cost: $73/tonne
H_2 production: 34 million tonnes
~260 facilities



Optimized Carbon Removal Results:

cost curve dominated by H2 at <$100/ton



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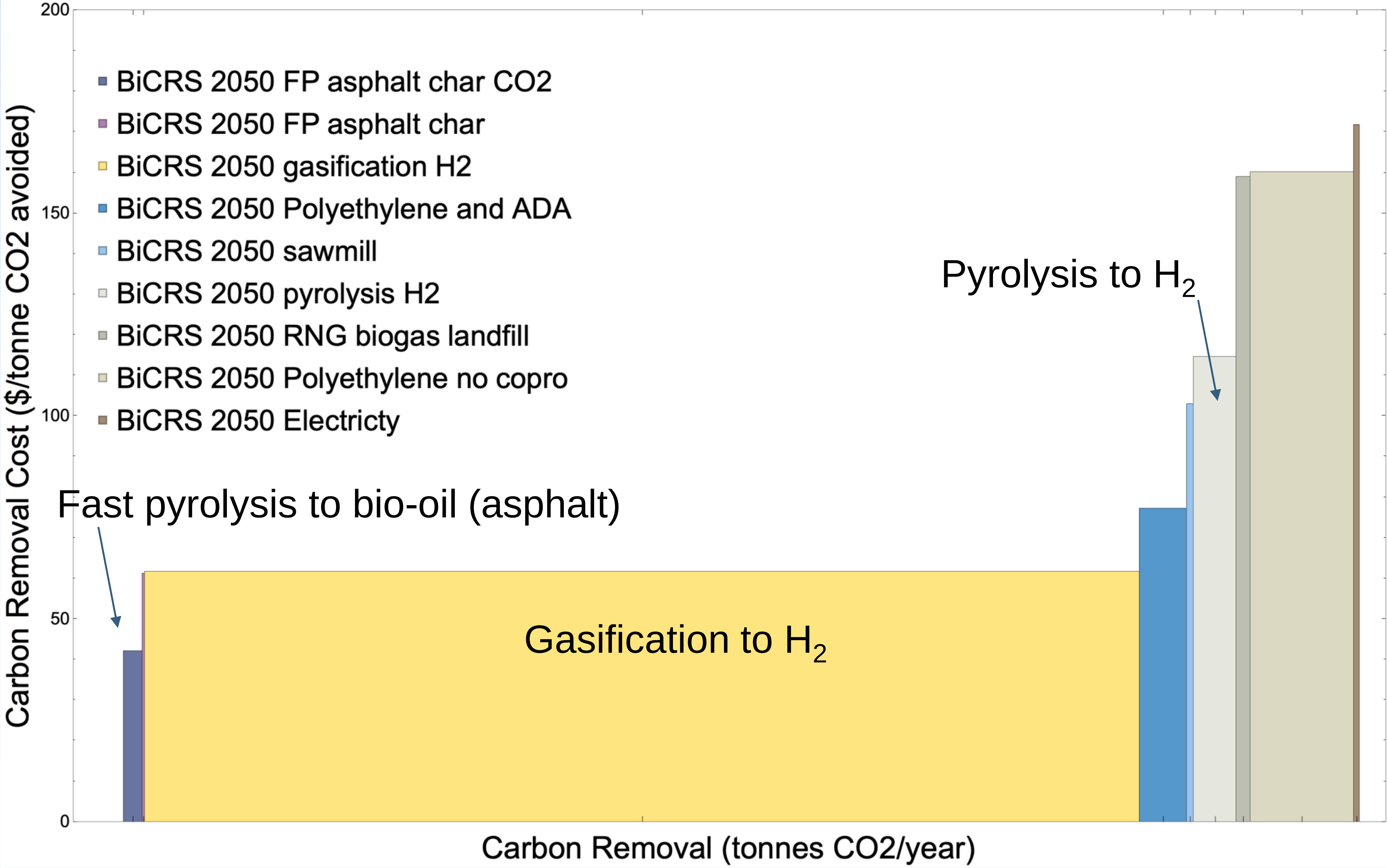
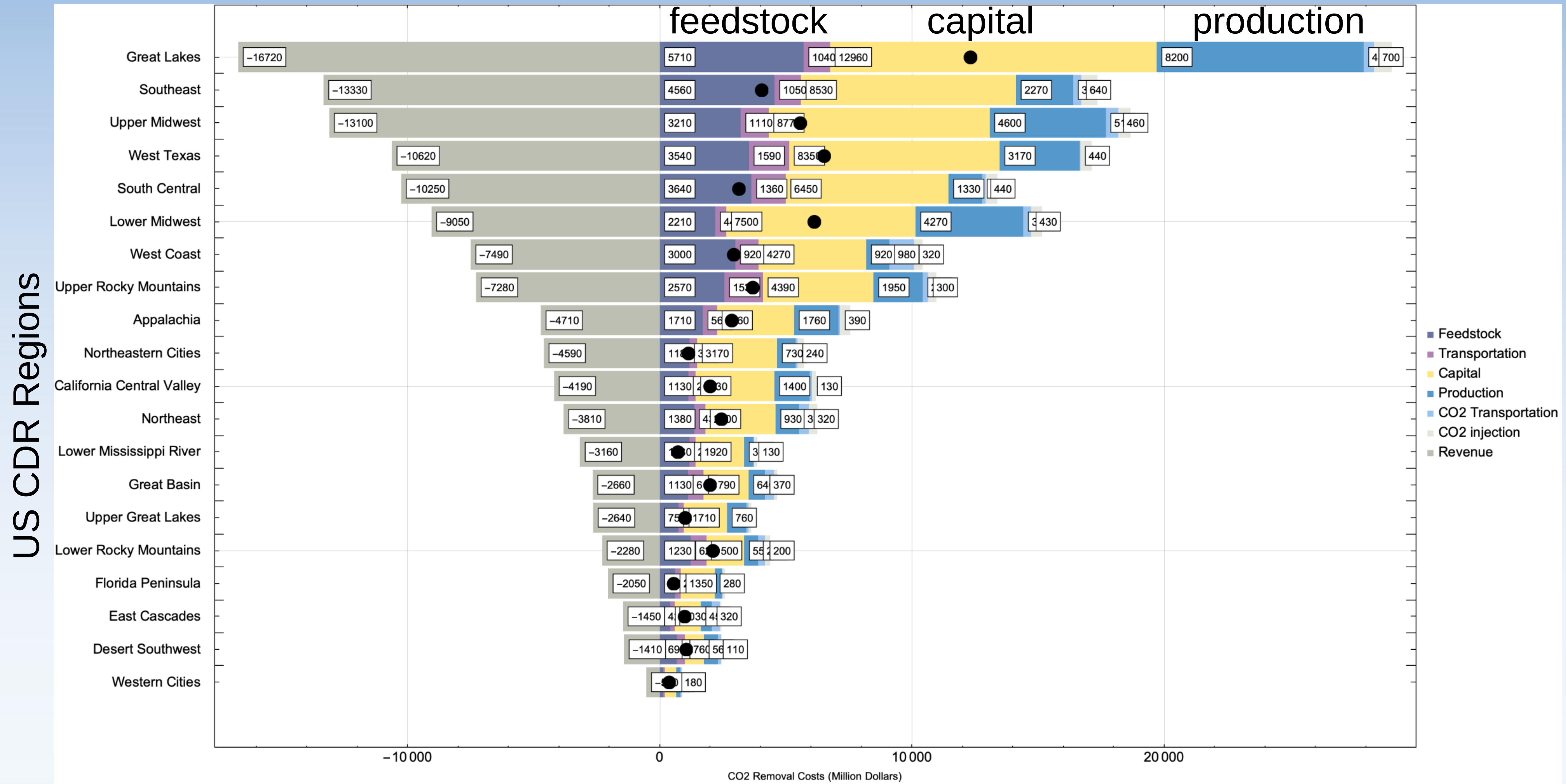
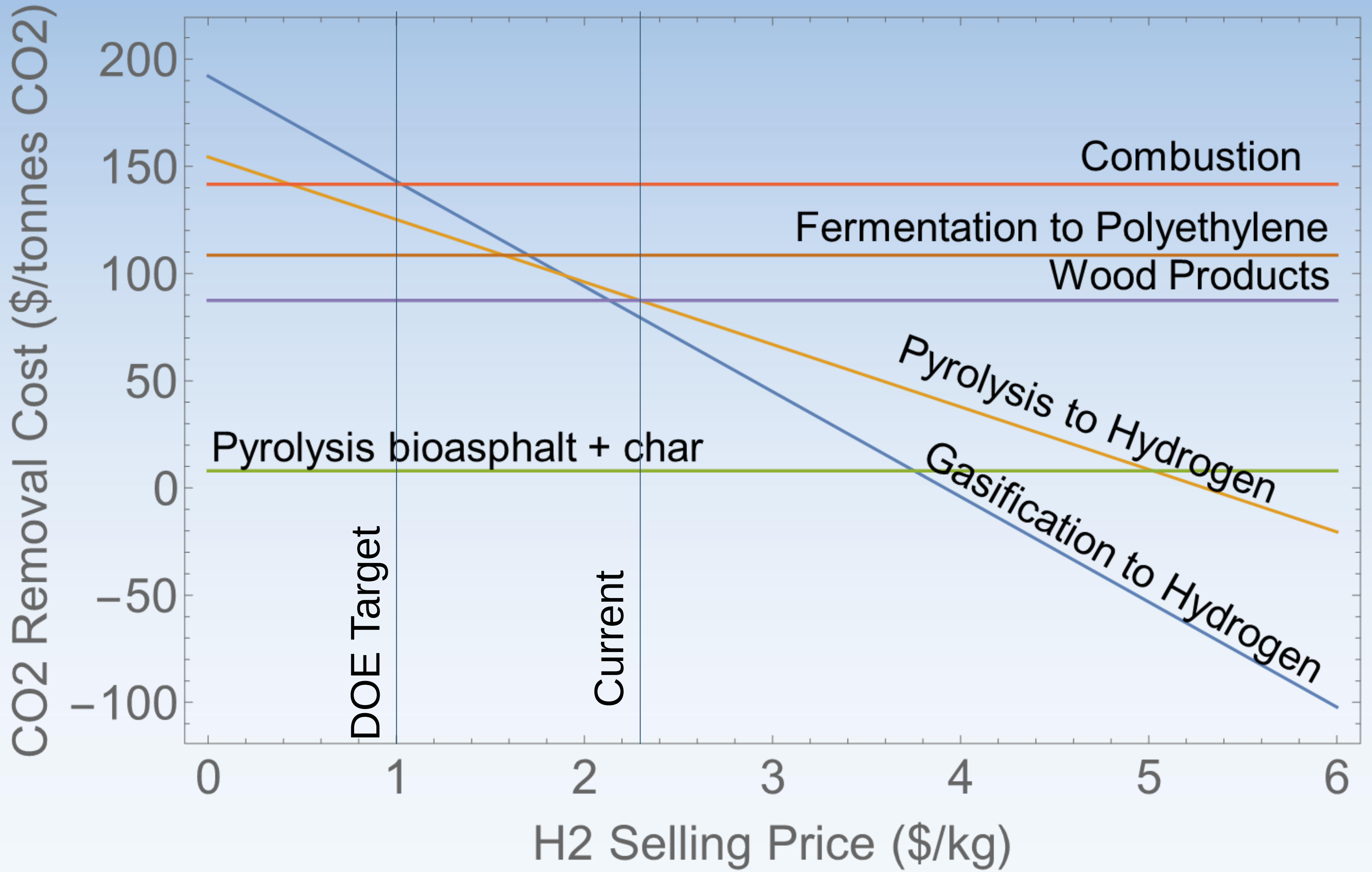


Cost Breakdown by Region- Dominated by Capital, Feedstock, and Production costs



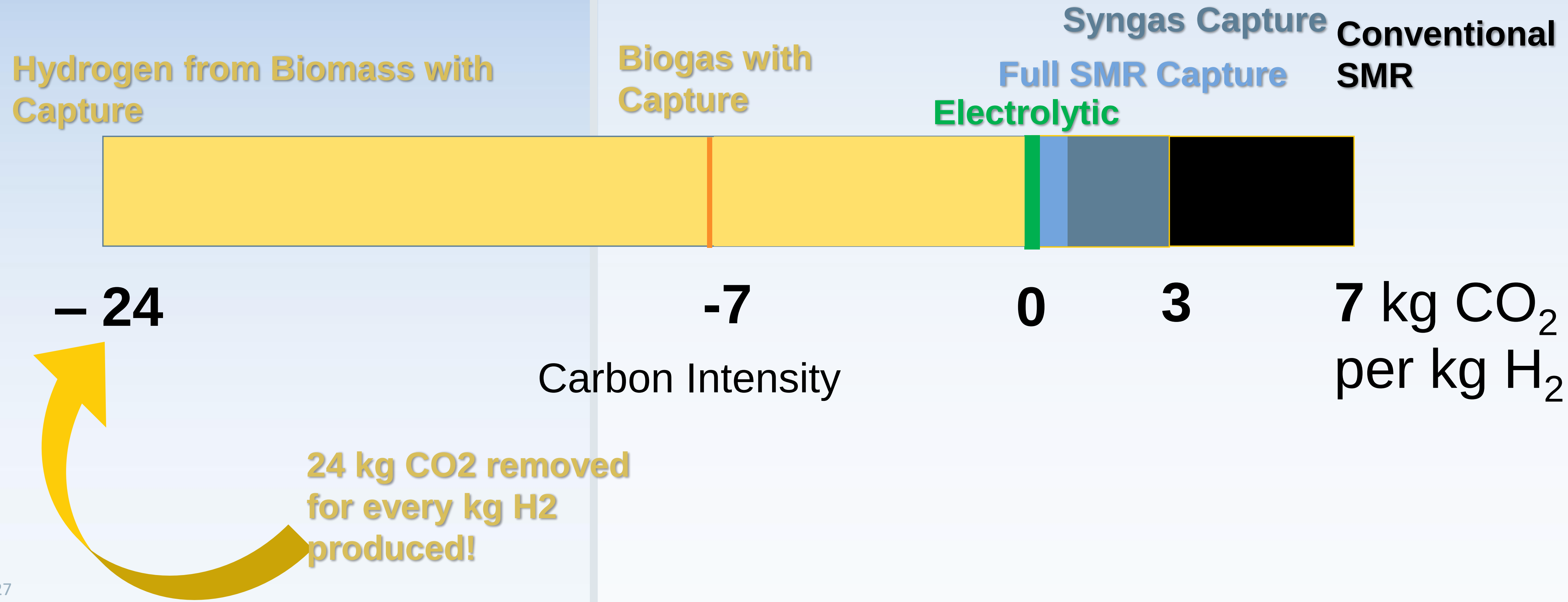
H_2 Prices are Variable… Sensitivity of CO_2 removal cost to H_2 selling price



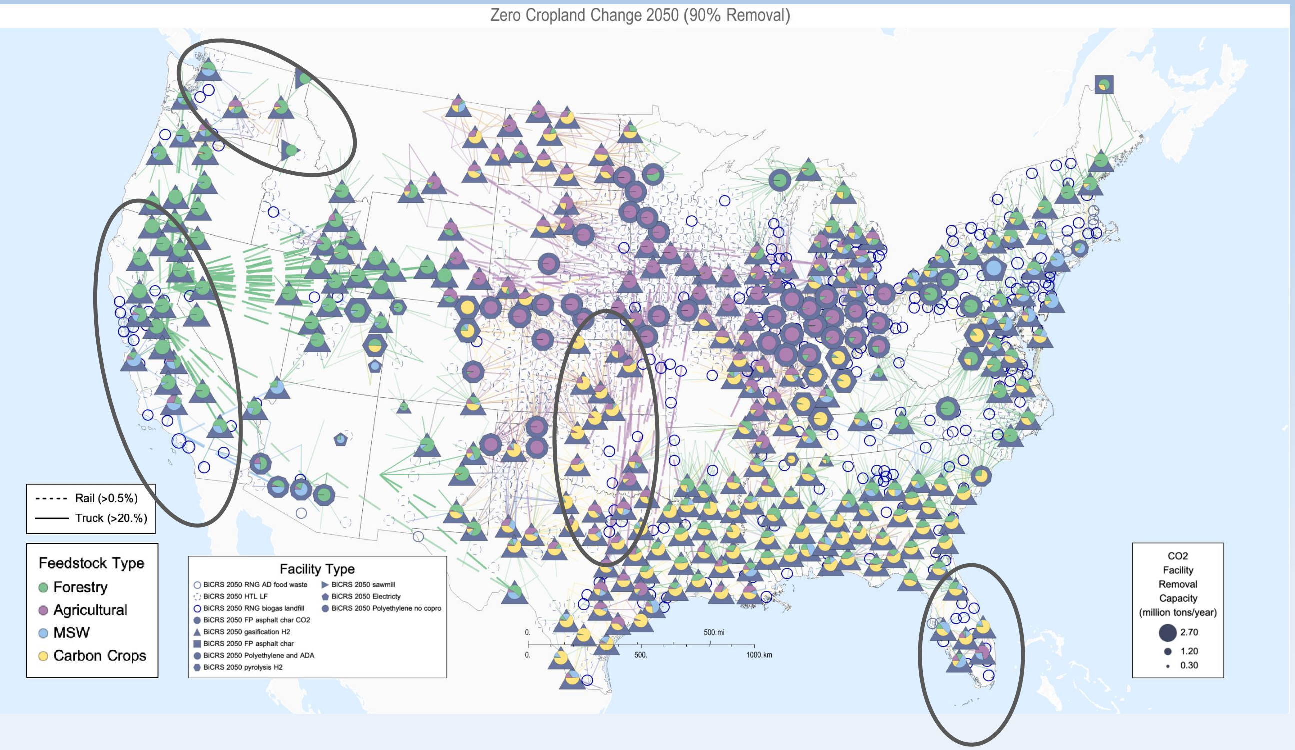
Impact of Optimized BiCRS Pathway on Meeting Projected H_2 Market Demand

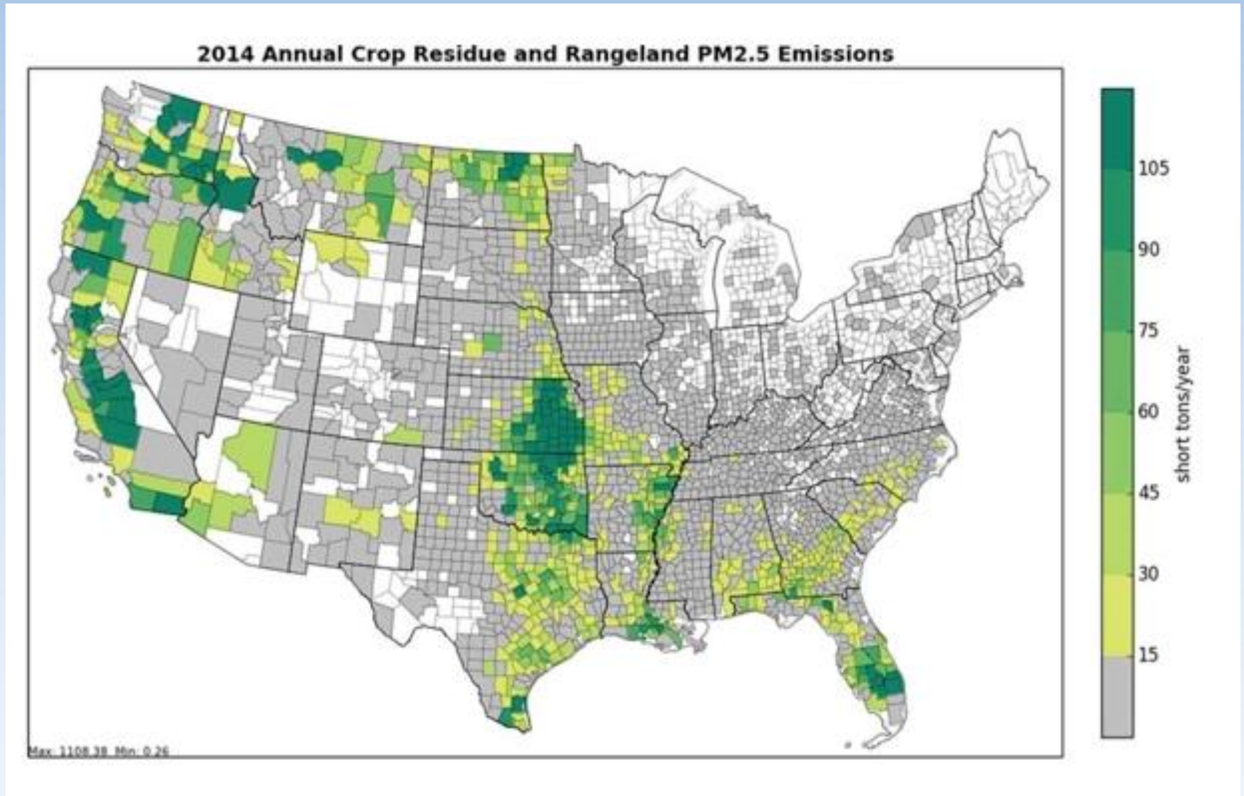
Biomass Assessment Approach (2050)	Feedstock Used million tonnes/year	CO2e removal potential Million tonnes/year	CO2 removal cost $/tonne CO2	H2 Production Million tonnes/year	Projected H2 Market Million tonnes/year
Zero Cropland Change	**532 million tonnes**	831	73	34	50
Maximum Potential	**752 million tonnes**	1163	75	49.5	50

Carbon Intensity of Hydrogen: +7 to – 24 kg CO_2/kg H_2



BiCRS Hydrogen – Opportunity to reduce PM 2.5





Pouliot et al., 2017 https://doi.org/10.1080/10962247.2016.1268982

BiCRS Carbon Negative Hydrogen

- BiCRS H_2 Highest Impact Pathway toward Maximized CO_2 Removal

- U.S. has sufficient biomass resources to provide biomass to BiCRS with zero cropland impacts @ 1 Gigatonne scale CO_2 removal; requires hundreds of biorefineries

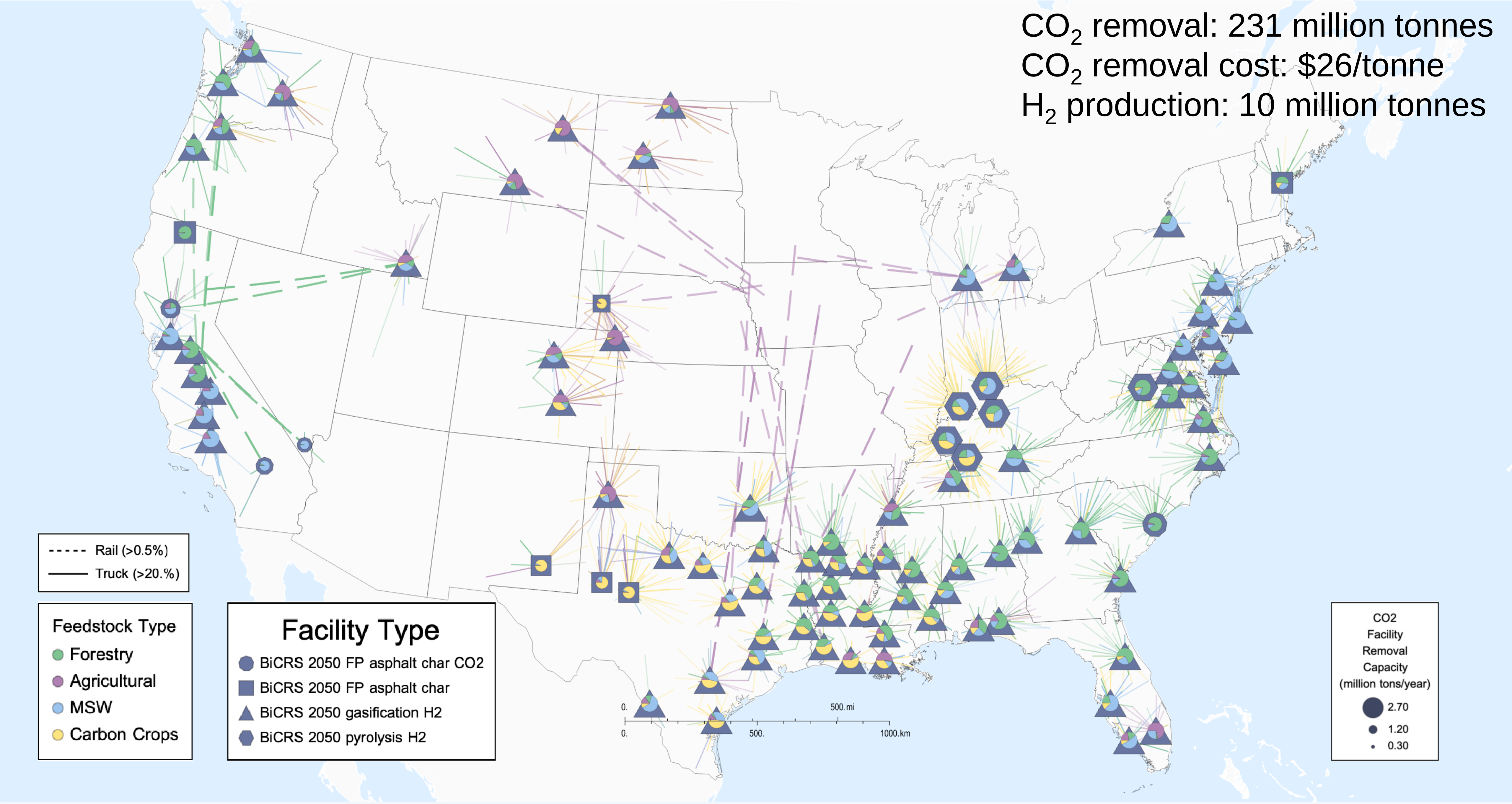
- Most significant cost drivers are feedstock, capex and opex, not CO_2/Biomass transportation, nor geologic storage.

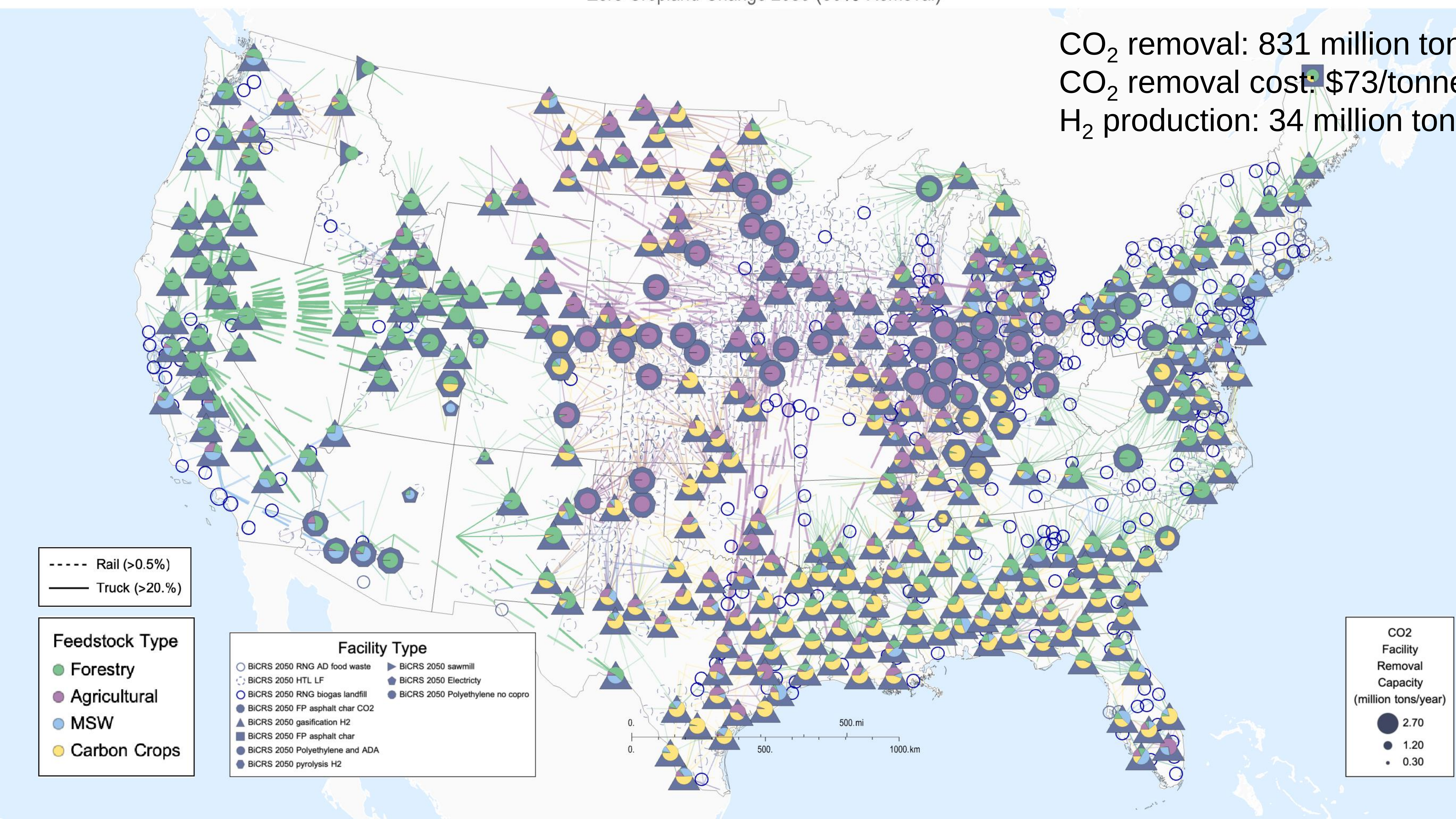
- We provide an optimized solution for one objective- there are many demands on biomass in a decarbonized future…innovation is needed to provide the fuel, products, and CO_2 emissions reduction and removal we will need


Keep a Big Tent
We will need every solution we can find

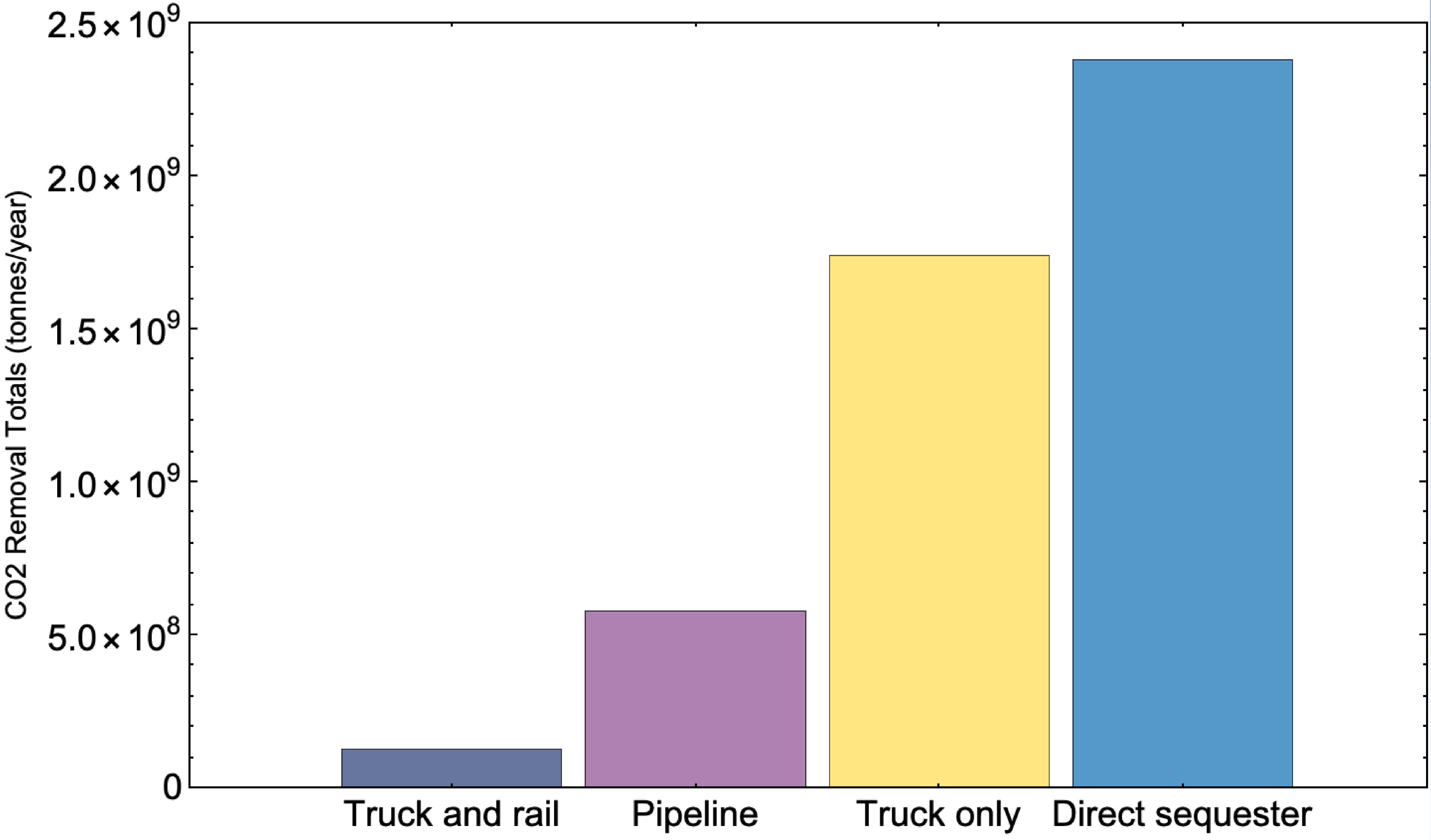
Lawrence Livermore National Laboratory

Zero Cropland Change 2050 (25% Removal)





CO2 removal: 831 million ton
CO2 removal cost: $73/tonne
H2 production: 34 million ton
Rail (>0.5%)
Truck (>20.%)
Feedstock Type
Forestry
Agricultural
MSW
Carbon Crops
Facility Type
BiCRS 2050 RNG AD food waste
BiCRS 2050 HTL LF
BiCRS 2050 RNG biogas landfill
BiCRS 2050 FP asphalt char CO2
BiCRS 2050 gasification H2
BiCRS 2050 FP asphalt char
BiCRS 2050 Polyethylene and ADA
BiCRS 2050 pyrolysis H2
BiCRS 2050 sawmill
BiCRS 2050 Electricty
BiCRS 2050 Polyethylene no copro
0.
500.mi
0.
500.
1000.km
CO2 Facility Removal Capacity (million tons/year)
2.70
1.20
0.30



CO2 Removal Totals (tonnes/year)
2.5×10^9
2.0×10^9
1.5×10^9
1.0×10^9
5.0×10^8
0
Truck and rail
Pipeline
Truck only
Direct sequester

Maximum 5 ktpd facilities, would not allow facilities closer than 50 miles apart

Exclusions	Requirements
Population density of more than 500 people within 1 square mile	Water supply of 12.5k gallons/minute within 20 miles++
Wetlands or open water	Within 200 miles of rail transfer station for biomass and CO_2
Protected lands	Within 200 miles of pipeline transfer station for biomass and CO_2***
Slope greater than 12%	
Landslide hazard	
100-year floodplain	

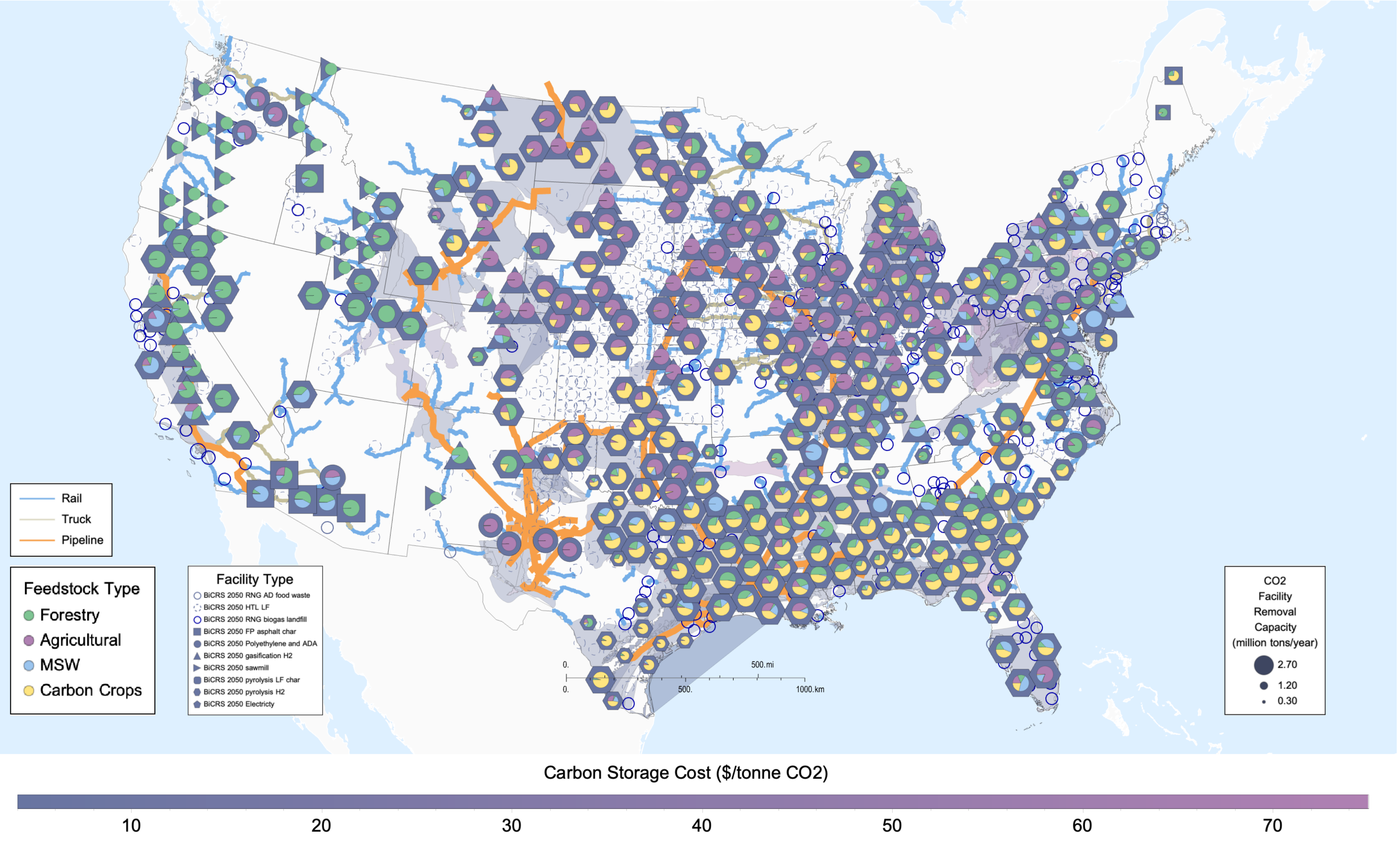
Term	Assumptions
Capital Recovery Factor (CRF)	11.75%
Interest rate	10%
Project life	20 years
Indirect Capital Cost	0.424 * Direct Capital Cost
Capital Scaling Factor	0.7
Fixed Operating Cost	4.5% of total capital cost
Plant Utilization	90%
Cost Year	2022

Product	Units	2025	2050
Electricity	Billion kWh	10,850	11,950
RNG	Billion MJ	34,251	38,220
Gasoline	Billion gallons	134	134
Diesel	Billion gallons	60.7	56.7
Jet fuel	Billion gallons	26.4	34.7
Ethanol	Billion gallons	14.9	16.9
Hydrogen	million tons	12.3	50.0
Bioasphalt binder	Million tons	3.15	7.28
Bio-polyethylene	Million tons	29.1	57.8
Adipic acid	Million tons	3.15	9.92
Acetone	Million tons	2.00	2.51
Nylon	Million tons	0.71	1.41
Lumber	m^3	45,827,900	51,912,700

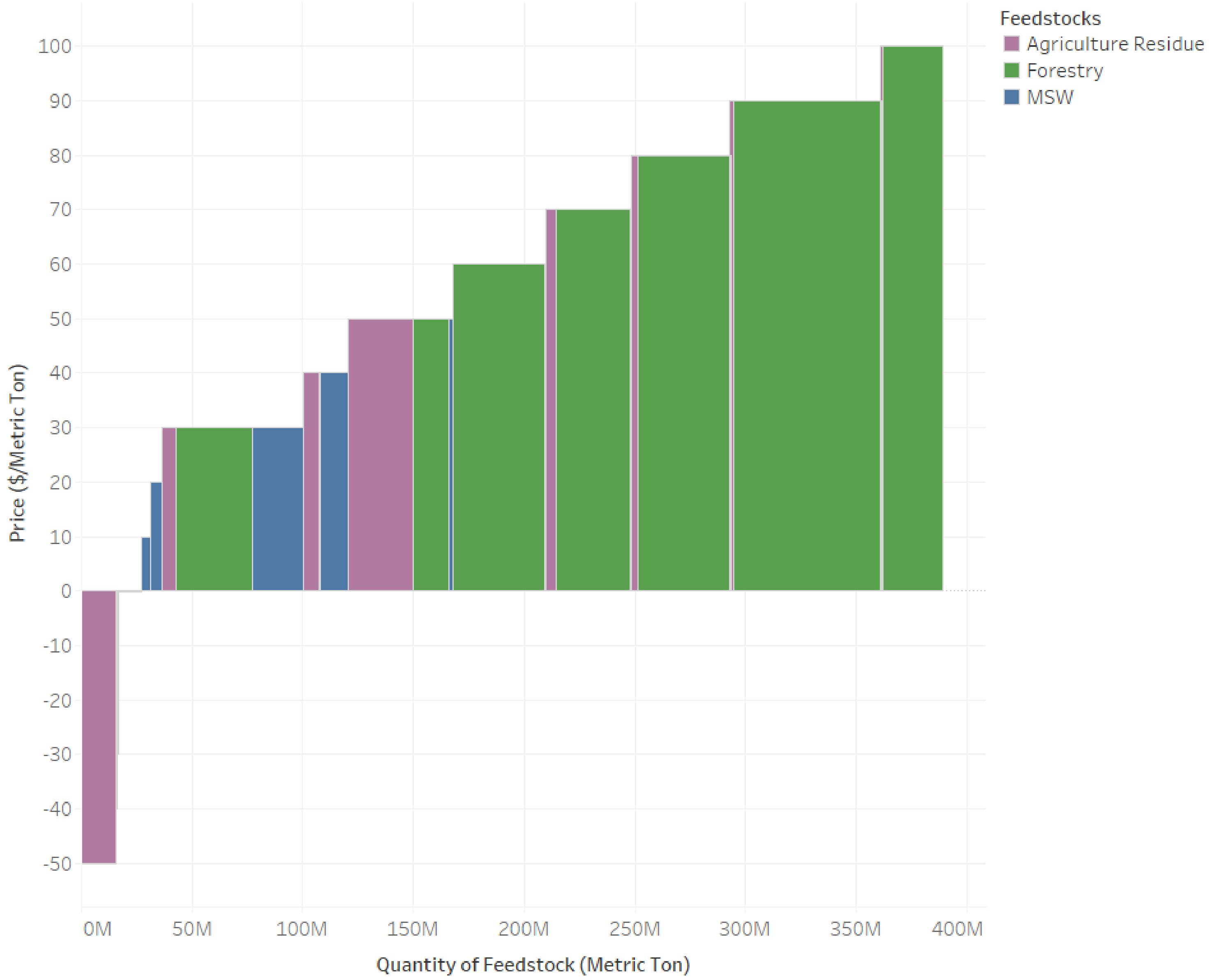
Product prices		
Ethanol	1.624401	$/gal
Biochar	95.43	$/MT
Hydrogen	2.385	$/kg
MEK-2-Butanone	1750.8	$/MT
Lumber/wood products	147	$/m3
Wax co product	0.5	$/GGE
Acetone	1167.502	$/MT
Electricity	0.08	$/kWh
Polyethylene	1208.92969	$/MT
Liquid fuels / Gasoline	2.30263635	$/gal
Diesel	2.44308045	$/gal
RNG	3.98	$/MMBTU
Jet fuel	2.27845381	$/gal
Bioasphalt	152.241986	$/MT
Adipic Acid	1.72	$/kg
sodium syulfate	0.15	$/kg

		Gasification to H2	Pyrolysis to H2	CAPEX plant level: gasification to H2	CAPEX plant level:pyrolysis to H2
	t/d	# facilities	# facilities	MM$/plant	MM$/plant
25%	1000			456	242
	2000			741	393
	3000			984	522
	4000			1203	639
	5000	77	6	1407	745
90%	1000	2	1	456	242
	2000	1	1	741	393
	3000			984	522
	4000	1		1203	639
	5000	260	11	1407	745

Hydrogen Price at $1 per kg (CO2 Pipelines and Storage)

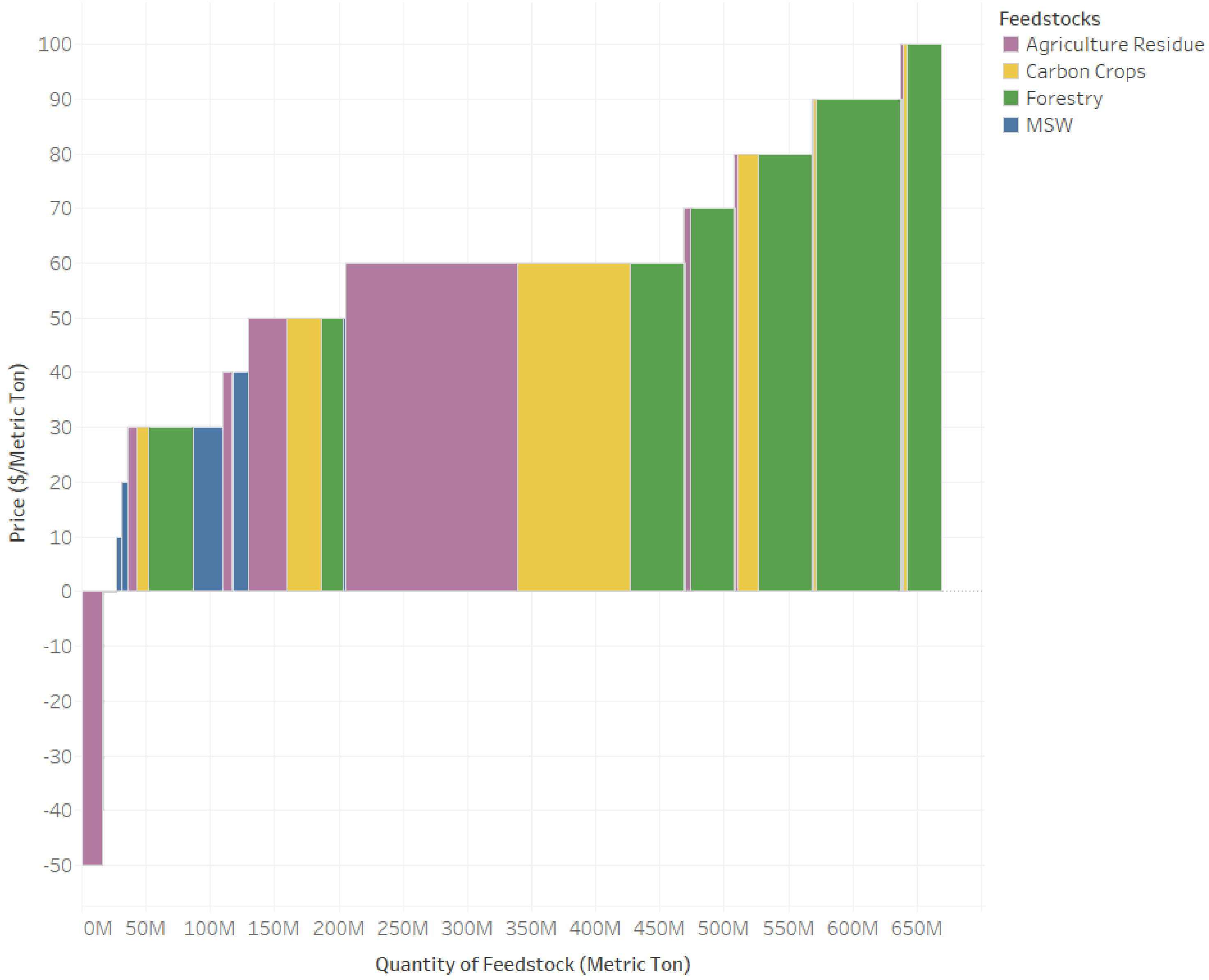


2050 Baseline Biomass Stepwise Supple Curve (up to $100/Metric Ton) for All Feedstocks



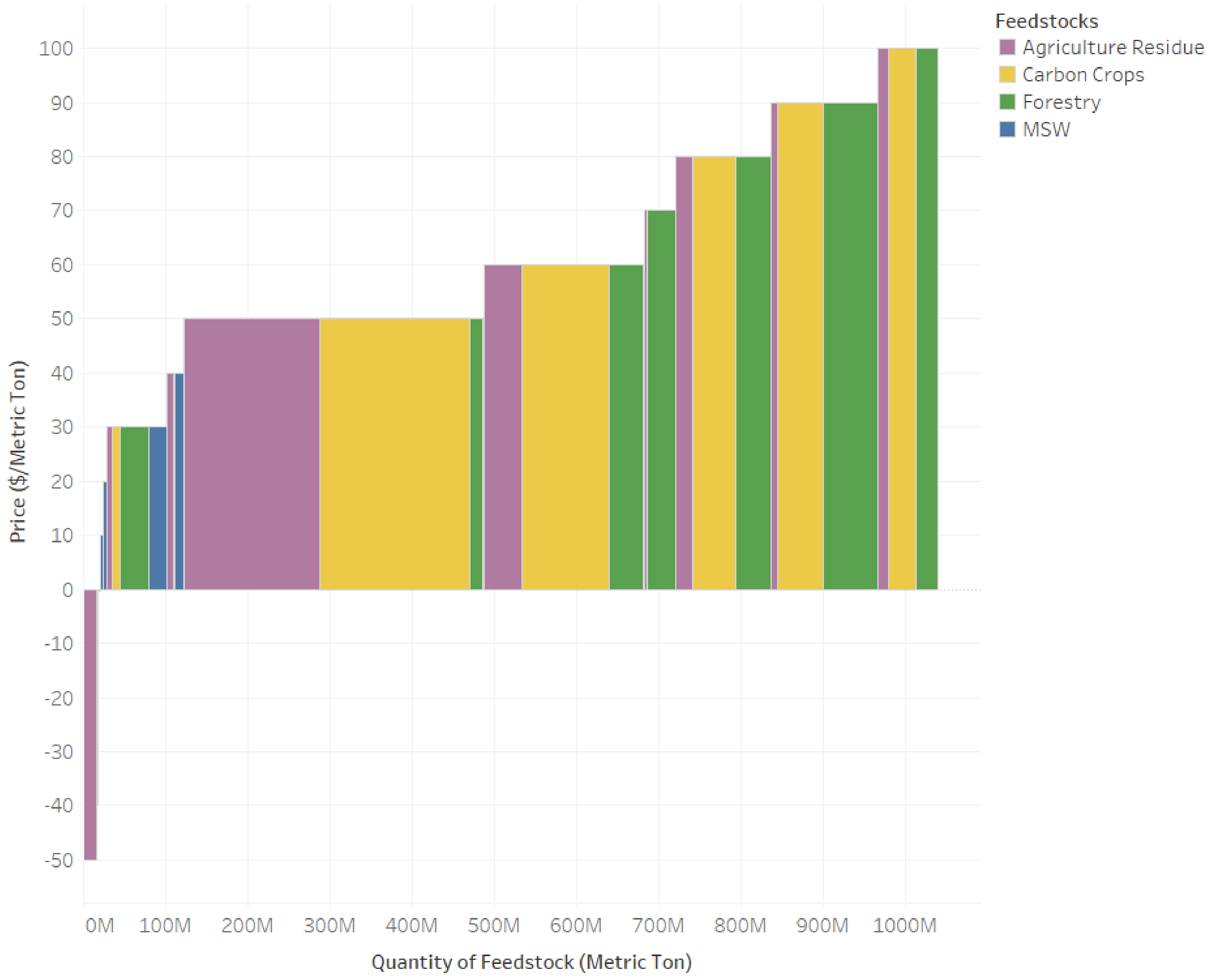
Running Sum of Quantity vs. sum of Price Value. Color shows details about Feedstocks. Size shows sum of Quantity. Details are shown for Price and Feedstocks. The data is filtered on Quantity, which ranges from 1 to 116874972.54.

2050 Minimum Cropland Change Biomass Stepwise Curve (up to $100/Metric Ton) for All Feedstocks

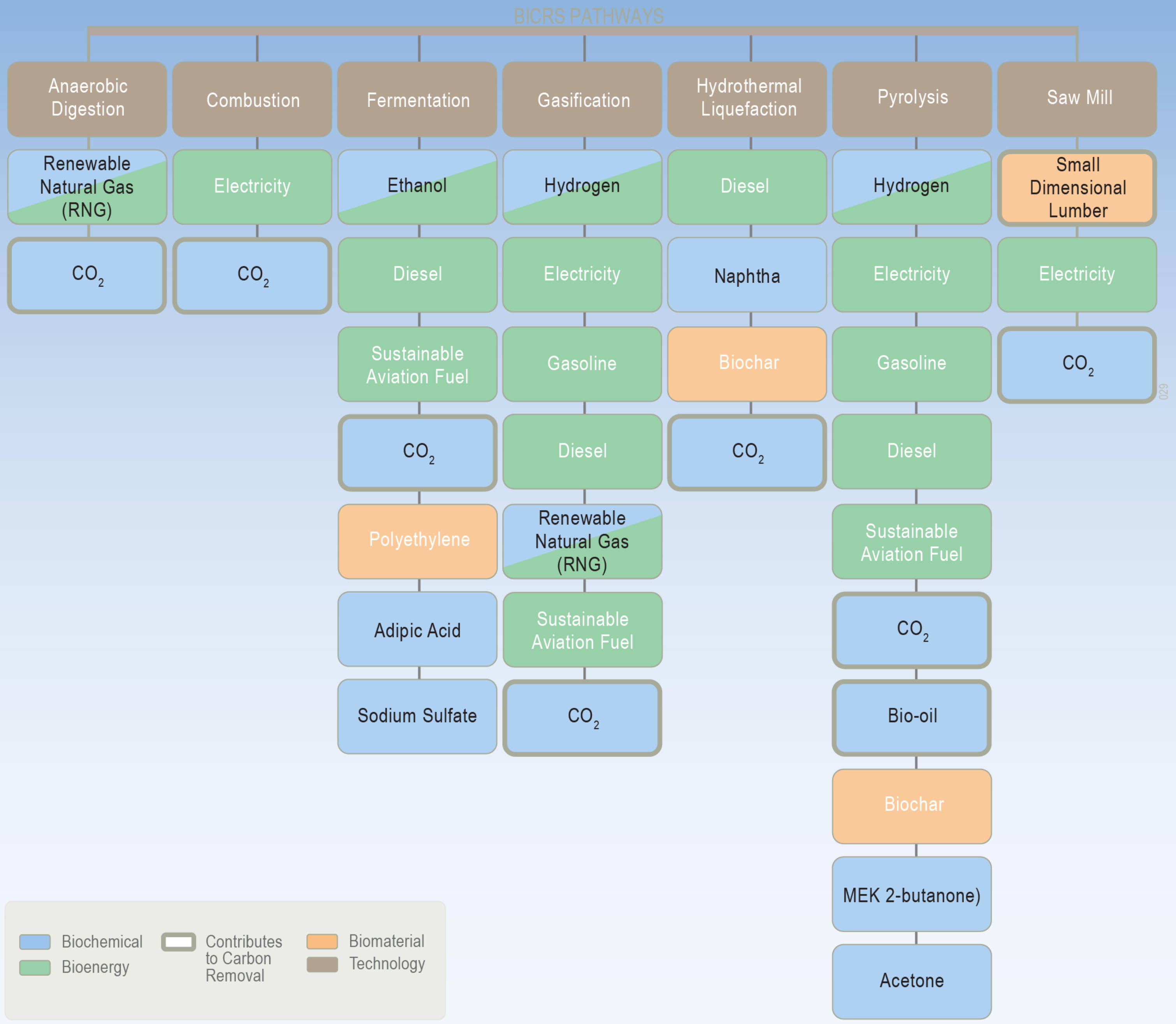


Running Sum of Quantity vs. sum of Price Value. Color shows details about Feedstocks. Size shows sum of Quantity. Details are shown for Price and Feedstocks. The data is filtered on Quantity, which ranges from 1 to 133754698.04.

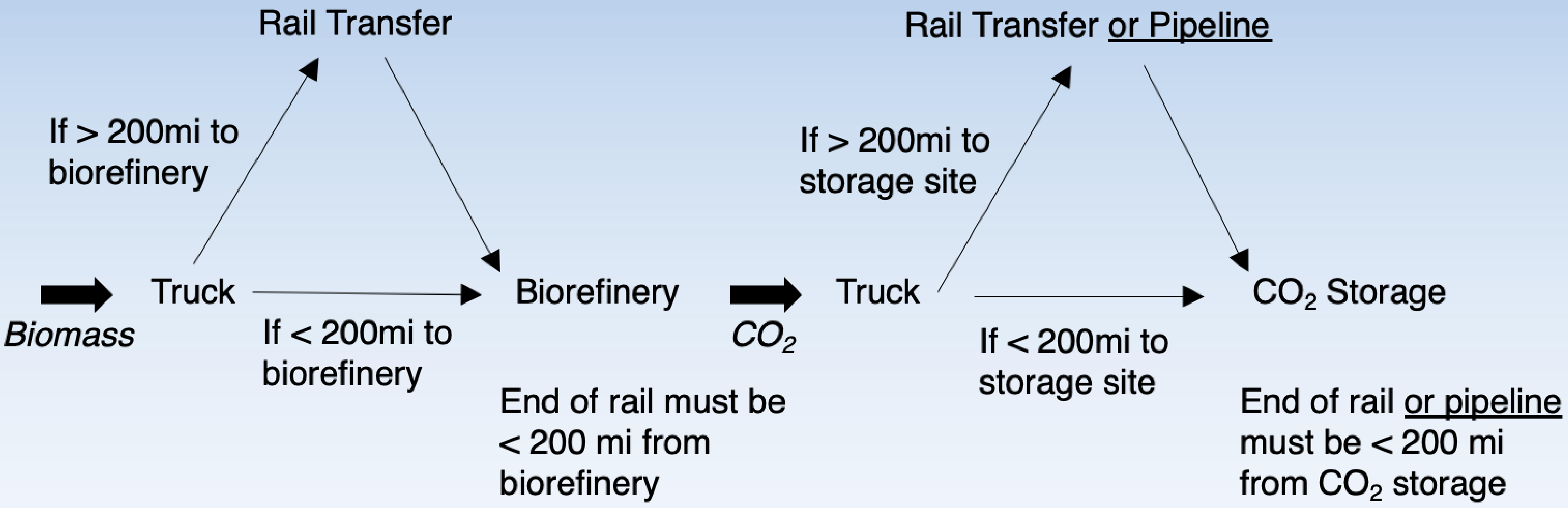
2050 Maximum Potential Biomass Stepwise Curve (up to $100/Metric Ton) for All Feedstocks

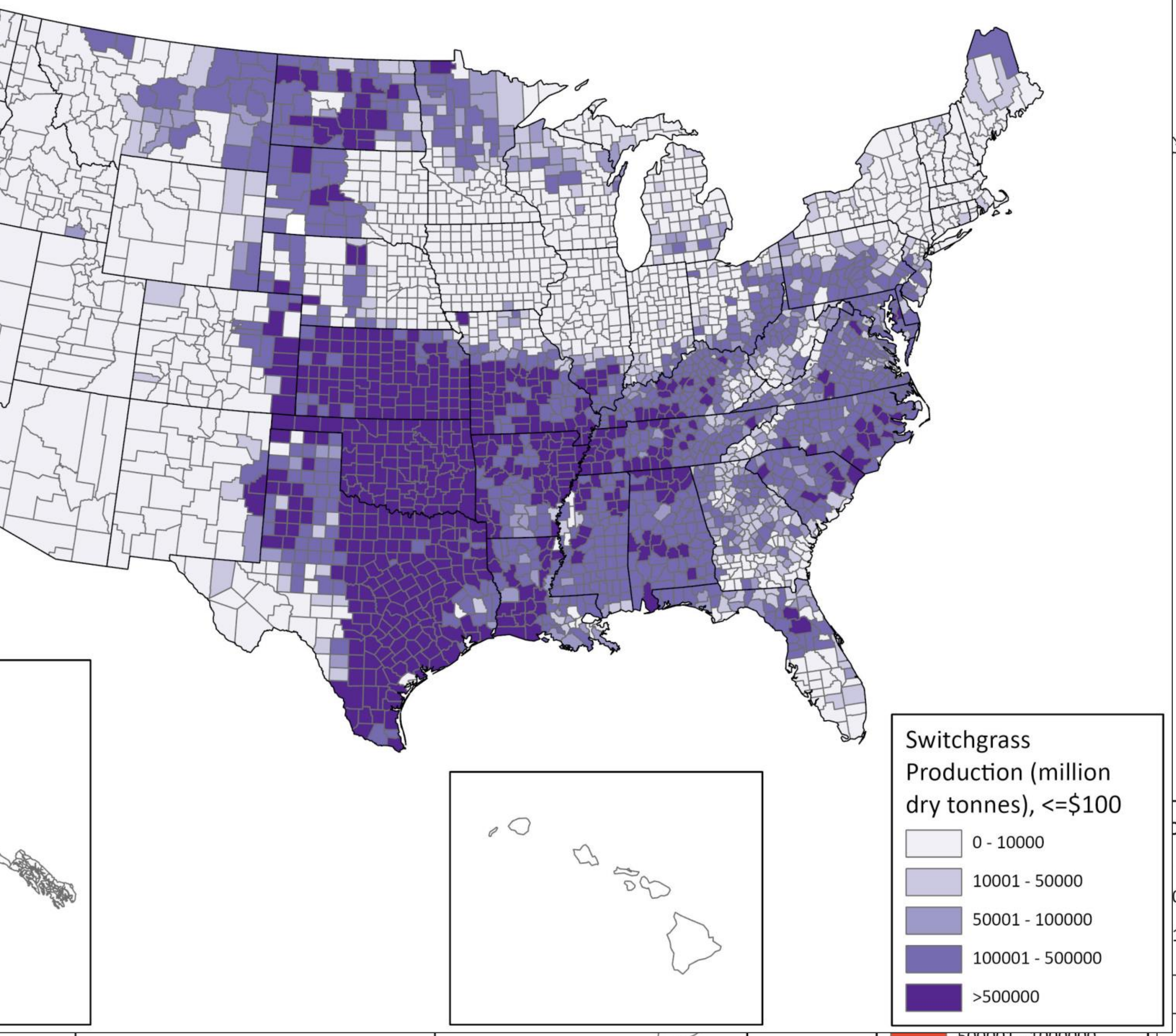


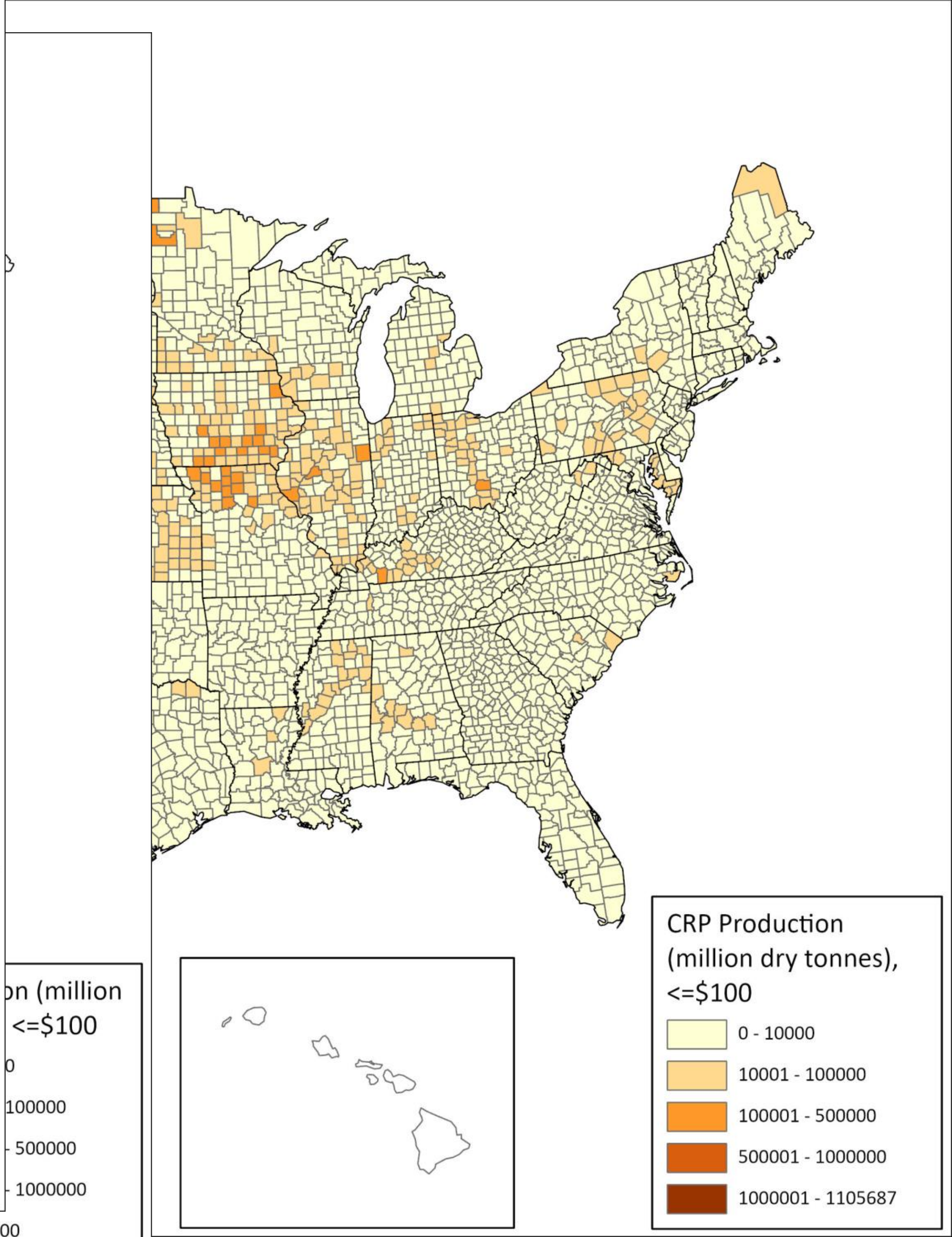
Running Sum of Quantity vs. sum of Price Value. Color shows details about Feedstocks. Size shows sum of Quantity. Details are shown for Feedstocks and Price. The data is filtered on Quantity, which ranges from 1 to 181292245.71.


BICRS PATHWAYS
Anaerobic Digestion
Renewable Natural Gas (RNG)
CO_2
Combustion
Electricity
CO_2
Fermentation
Ethanol
Diesel
Sustainable Aviation Fuel
CO_2
Polyethylene
Adipic Acid
Sodium Sulfate
Gasification
Hydrogen
Electricity
Gasoline
Diesel
Renewable Natural Gas (RNG)
Sustainable Aviation Fuel
CO_2
Hydrothermal Liquefaction
Diesel
Naphtha
Biochar
CO_2
Pyrolysis
Hydrogen
Electricity
Gasoline
Diesel
Sustainable Aviation Fuel
CO_2
Bio-oil
Biochar
MEK 2-butanone)
Acetone
Saw Mill
Small Dimensional Lumber
Electricity
CO_2
Biochemical
Bioenergy
Contributes to Carbon Removal
Biomaterial
Technology

Long-Term Scenario




Switchgrass Production (million dry tonnes), <=$100
0 - 10000
10001 - 50000
50001 - 100000
100001 - 500000
>500000

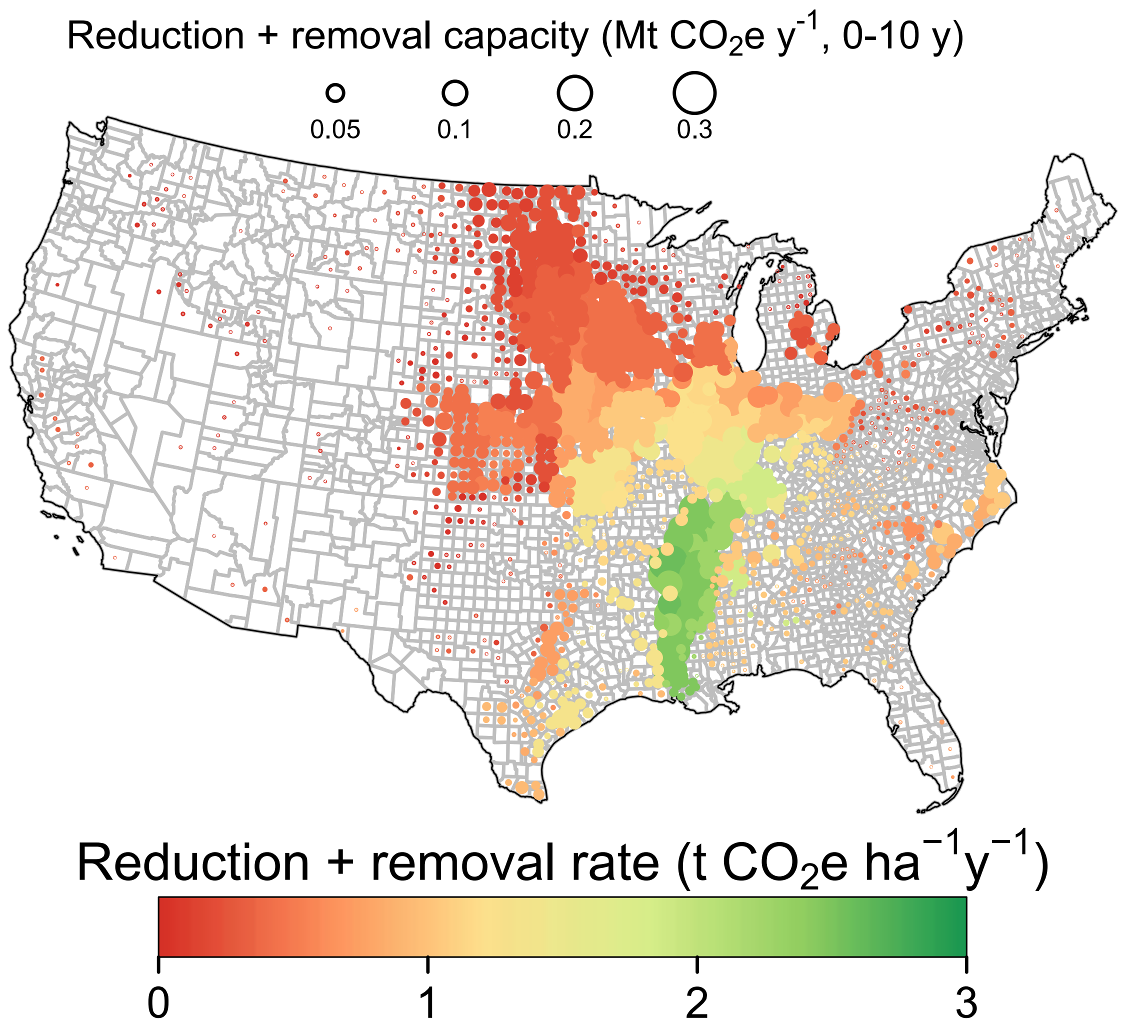

on (million
<=$100
100000
- 500000
- 1000000
500001 - 1000000
CRP Production (million dry tonnes), <=$100
0 - 10000
10001 - 100000
100001 - 500000
500001 - 1000000
1000001 - 1105687

Soil and Agricultural Systems

Assess carbon storage via conservation agriculture (cover cropping) and perennial bioenergy systems

Measure biophysical outputs (using COMET biogeochemical model):

1. Net increase in soil carbon
2. Avoided emissions (e.g., lower N_2O)
3. Yield & biomass supply

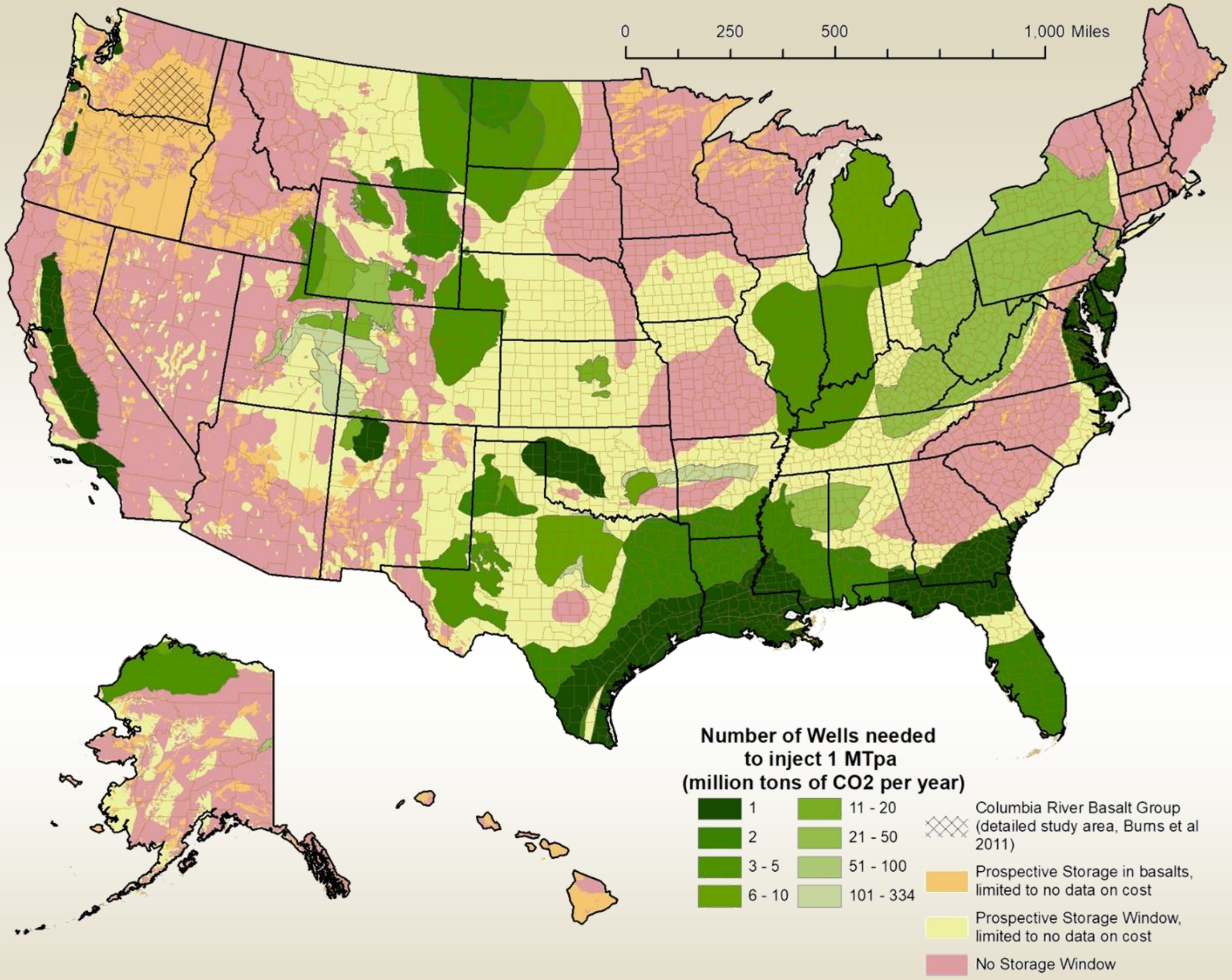


Modelled CO_2 removal & emissions reductions for **cover cropping**

Geologic Storage

- Identify geologic storage options and costs
- Assess storage capacity in saline aquifers – and degree of confidence

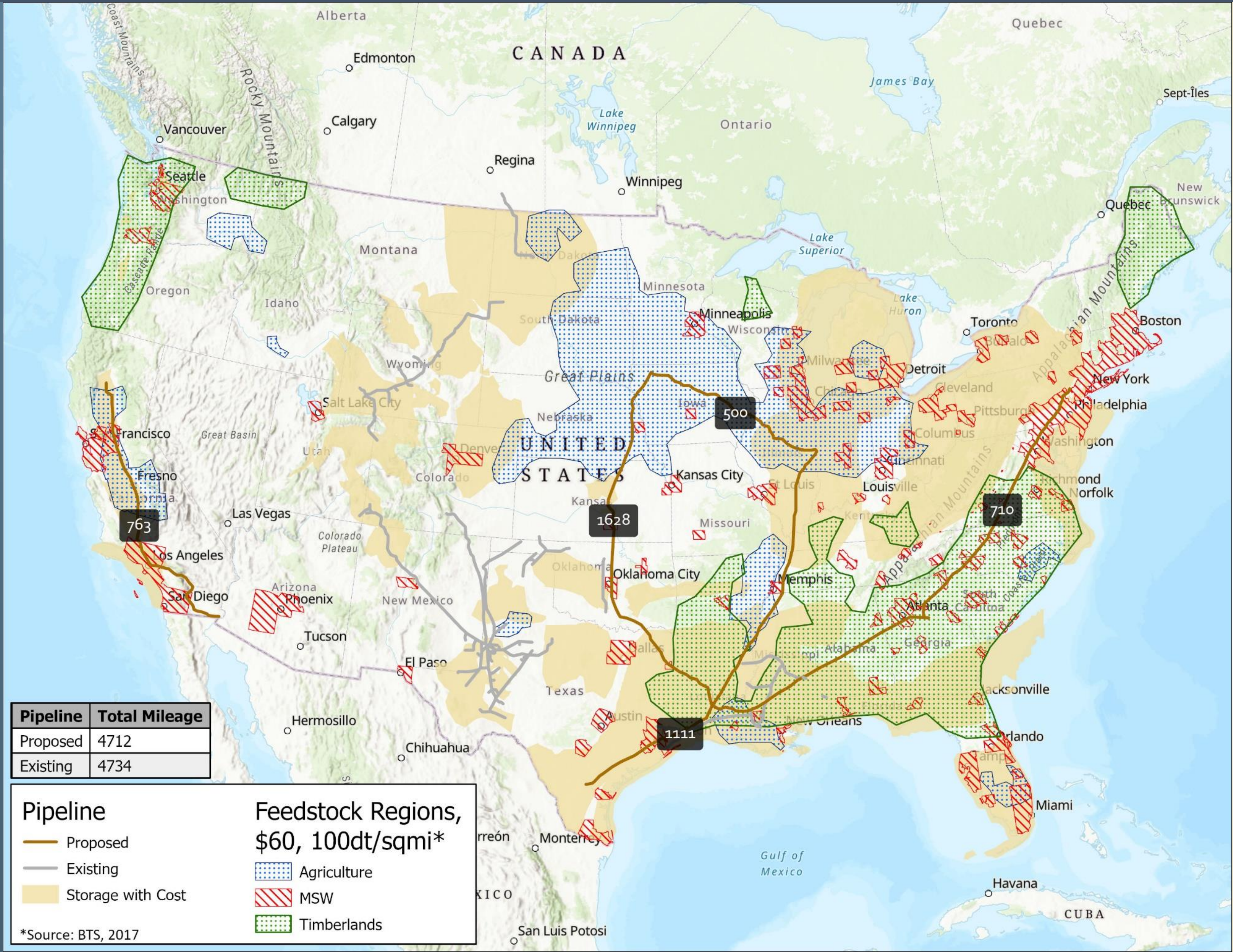
Assignment for ~30 basins.



Bureau of Economic Geology

Lawrence Livermore National Laboratory

Trunk CO_2 pipelines would reduce system cost and use the highest-quality storage sites

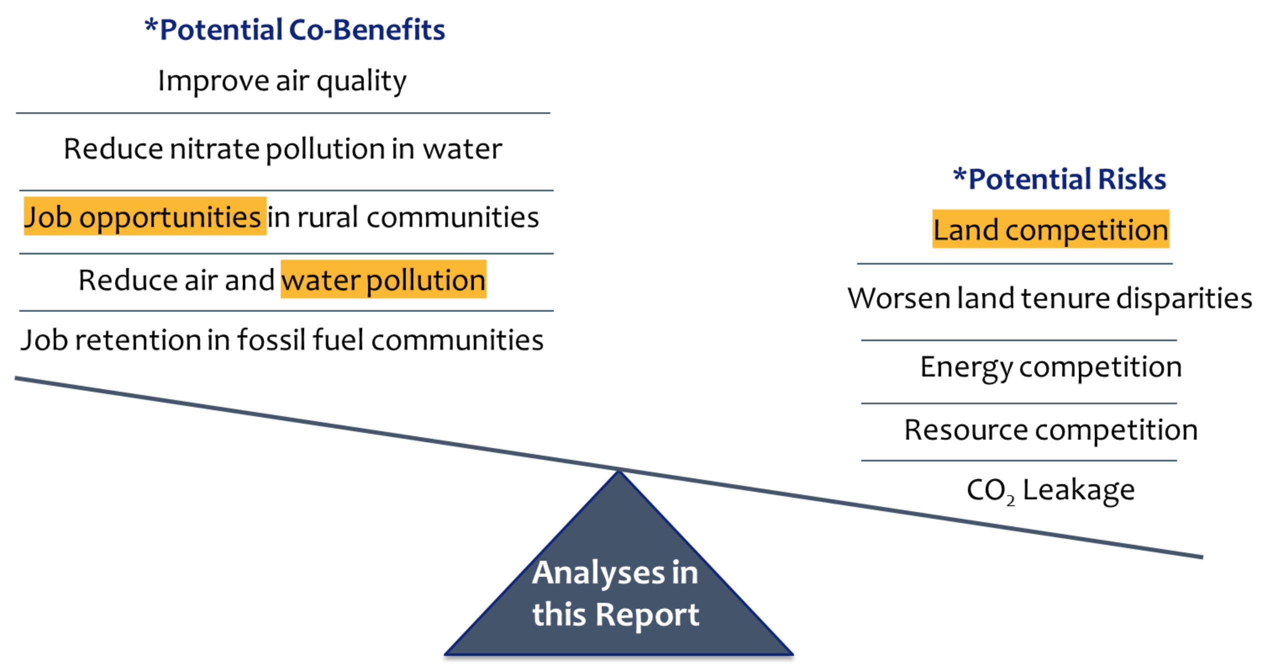


Pipeline	Total Mileage
Proposed	4712
Existing	4734

Cross-Cutting Analyses: prioritizing land/resource use & environmental justice

- Heat sources for DAC
- Water constraints
- Land use
- Transport options and costs
- Effects on pollution, jobs, & land ownership

Quantitative trade-offs



System analysis highlights *who wins & who loses*