Carbon Management in the Annual Decarbonization Perspective

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Prepared for:

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Agenda

- Model Approach and Key Inputs
- Scenario Results
- Key Findings

Model Approach and Key Inputs

Model Approach – Captured Carbon

- Carbon captured in cement and iron and steel applications determined exogenously on a scenario basis
  - Primary approach in cement is carbon capture
  - Primary approach for iron and steel is hydrogen-based DRI/EAF pathway. Some scenarios have larger amounts of carbon capture in iron and steel.
- Carbon captured in power, biofuels, hydrogen production, and direct air capture processes is determined with optimal capacity expansion technology options

Model Approach - CCUS

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- Underlying geologic sequestration supply curve on a basin/state basis developed with NETL data (x-axis = annual injection potential; y-axis =$/ton). Cost includes local transport.
- Model can sequester the captured carbon to receive the direct emissions benefit or it utilize it in hydrogen-based fuel processes to produce liquids (fischer-tropsch) or gaseous (methanation) fuel substitutes to receive the displacement emissions benefits of avoided fossil
- The model can also deliver the captured carbon for use and storage to other regions by building CO2 pipelines

Key Assumptions

Category	Technology	Source	Notes	Today	2030	2050
Power	Allam Cycle - Gas	IEA	50% efficiency; 100% capture	$2190	$2190	$2190
Power	Allam Cycle - Bio	Princeton NZAP	40% efficiency; 100% capture	$7294	$7294	$7294
Power	Retrofit – Gas	NETL	Assumes incremental cost from comparative new plant applied as retrofit cost; 90% capture	$2552	$2552	$2552
Power	Retrofit – Coal	NETL	Assumes incremental cost from comparative new plant applied as retrofit cost; 90% capture	$1482	$1482	$1482
Hydrogen	BECCS	IEA – CCS in Biofuels Production	50% efficiency; 90% CO2 capture	$4096	$4096	$4096
Hydrogen	Steam Reformation w/CC	IEA Future of Hydrogen	69% efficiency; 90% CO2 capture	$1896	$1638	$1482
Biofuels	Pyrolysis	Princeton NZAP	65% efficiency; 90% CO2 capture	$4154	$4154	$4154
Biofuels	Fischer-Tropsch	IEA – CCS in Biofuels Production	48% efficiency; 90% CO2 capture	$4613	$4514	$4306
Biofuels	Gasification	IEA – CCS in Biofuels Production	65% efficiency; 90% CO2 capture	$2471	$2471	$2471
Biofuels	Corn Ethanol Retrofit	NETL	(assumption $40/ton, 20 yrs, 90% cap factor)	$286	$286	$286

Key Assumptions

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Category	Technology	Source	Notes	Unit	Today	2030	2050
Direct Air Capture	Solid Sorbent	Rhodium Group	Solid Sorbent; 5.9 mmbtu/tonne co2 captured	$/tonne-yr		$650	$534
Utilization	Fischer-Tropsch	Agora Energiewende	65% efficiency	$/kW	$845	$779	$582
Utilization	Methanation	IEA Future of Hydrogen	80% efficiency	$/kW	$739	$673	$516
CO2 Pipeline		NETL		$/ton-mi-hr	$3295	$3295	$3295

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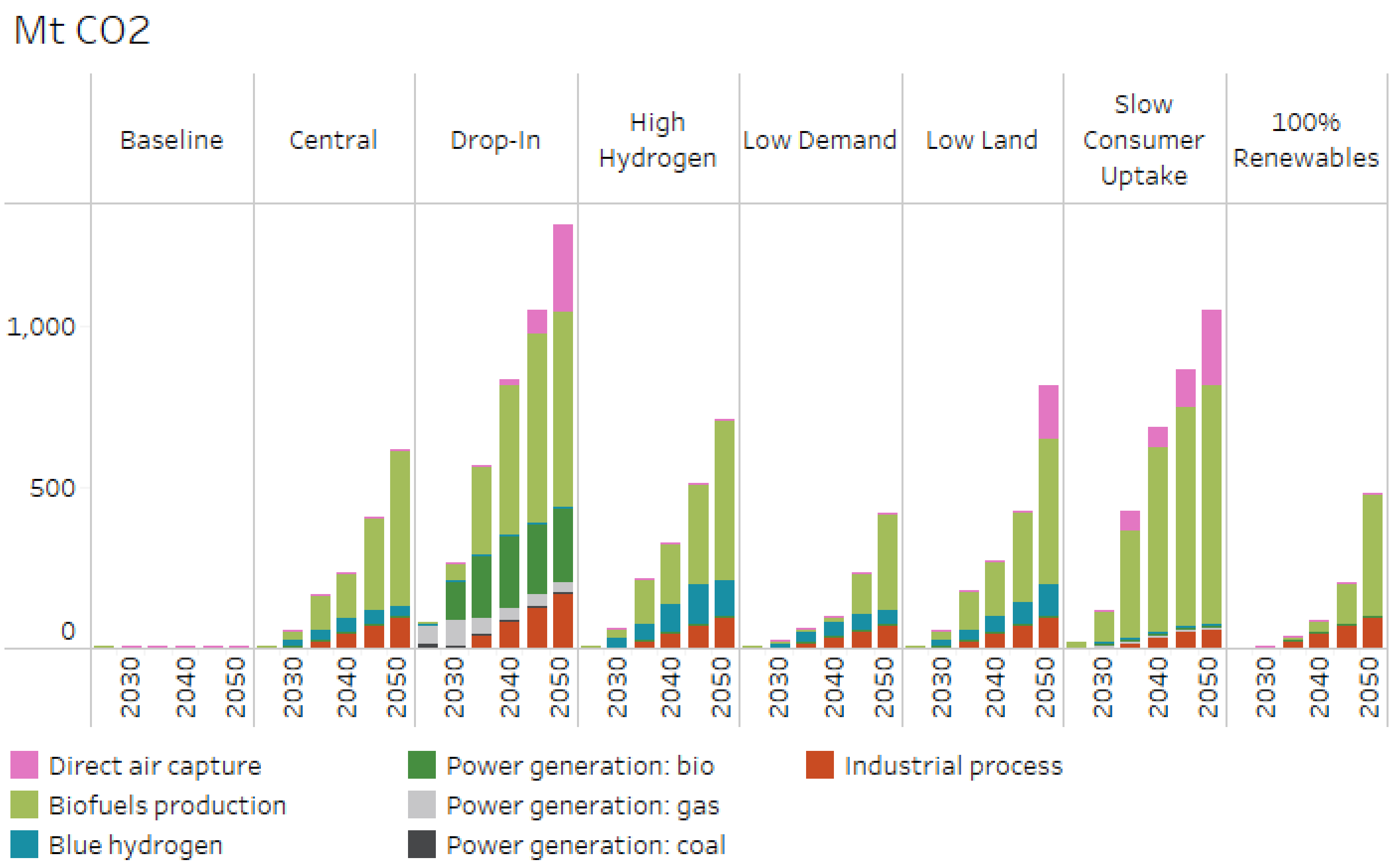
Scenario Results

Scenarios

Scenario	Description
Central	This is the least-cost pathway for achieving net-zero greenhouse gas emissions by 2050 in the U.S. It is economy-wide and includes energy and industrial CO_2, non-CO_2 GHGs, and the land CO_2 sink. It is built using a high electrification demand-side case, and on the supply-side has the fewest constraints on technologies and resources available for decarbonization.
Drop-In	This net-zero scenario prioritizes maintaining the use of existing infrastructure to the greatest extent possible consistent with carbon neutrality, implemented by placing cost penalties on new infrastructure build, delaying the uptake of electrification technologies by twenty years, and avoiding the uptake of other zero-carbon fuel-using technologies (hydrogen and ammonia). It is designed to explore the effects of trying to minimize dislocation on the existing energy industry in the U.S.
High Hydrogen	This net-zero scenario emphasizes the direct use of hydrogen in some applications in which the potential for electrification is uncertain, specifically in industry and heavier vehicles. It is designed to explore the effects of a hydrogen economy that extends all the way to energy end-users.
Low Demand	This net-zero scenario reduces the demand for energy services from that used in the other net-zero scenarios. It is designed to explore how high levels of conservation and energy efficiency, achieved through behavior, planning, policy, and other means, could reduce requirements for low-carbon infrastructure and land.
Low Land	This net-zero scenario limits the use of land-intensive mitigation solutions, including bioenergy crops, wind and solar power generating plants, and transmission lines. It is designed to explore the effect of societal barriers to the siting of low-carbon energy infrastructure for environmental and other reasons.
Slow Consumer Uptake	This net-zero scenario delays by twenty years the uptake of fuel-switching technologies including electric vehicles, heat pumps, fuel-cell vehicles, etc. It is designed to explore the effects of slow consumer adoption on energy system decarbonization, including the impacts on electricity and alternative fuel demand.
100% Renewables	This net-zero scenario allows only wind, solar, biomass, and other forms of renewable energy by 2050. It is designed to explore the effects of eliminating fossil fuels and nuclear power altogether on energy infrastructure, electric power, and the production of alternative fuels and feedstocks.

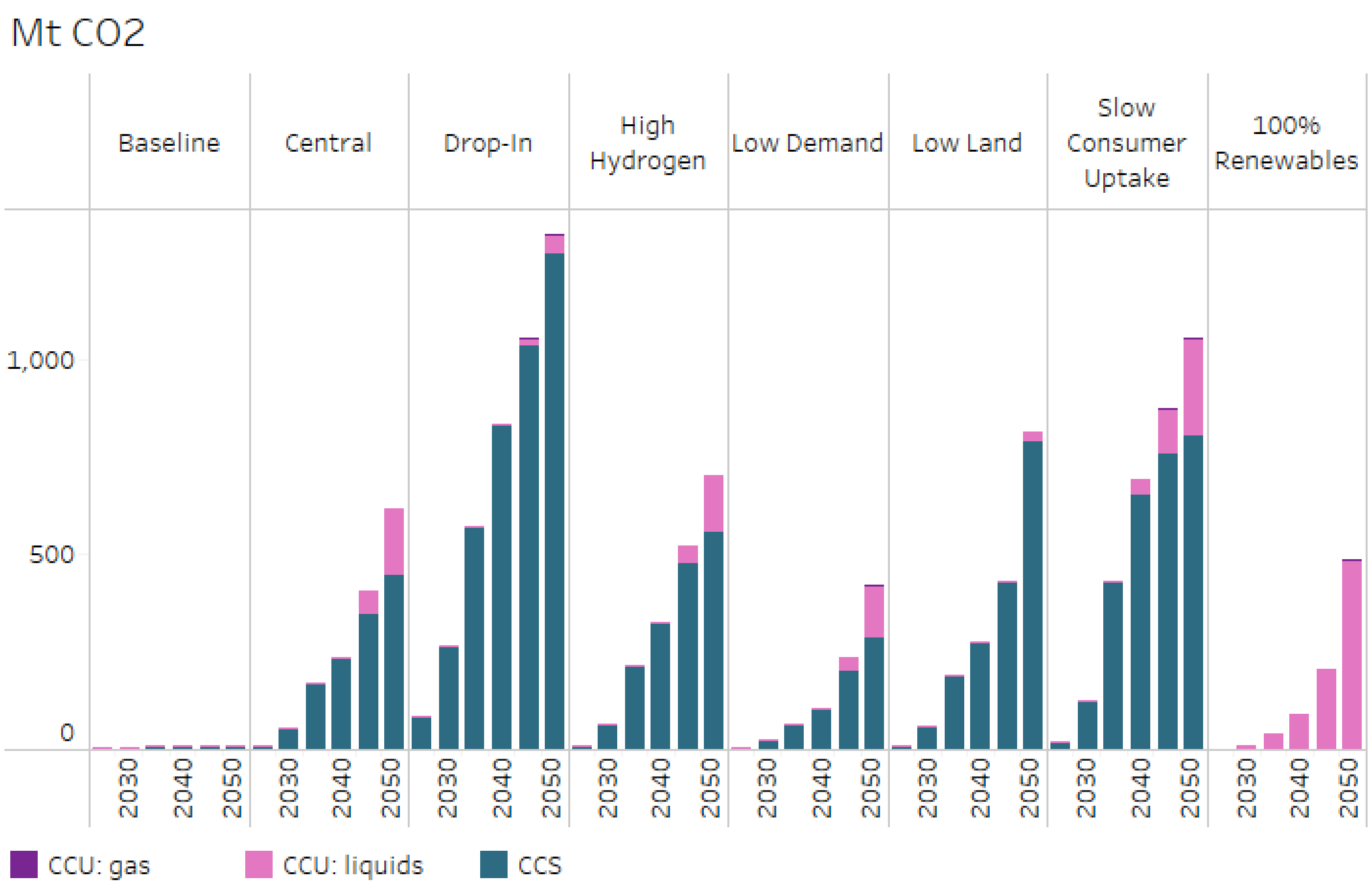
Carbon Sources

- Most consistent source of captured carbon is from biofuels production
  - High capacity factor, concentrated stream of CO_2
- Scenario assumptions dictate CO_2 capture from sources like blue hydrogen, direct air capture, and deployment in the power sector



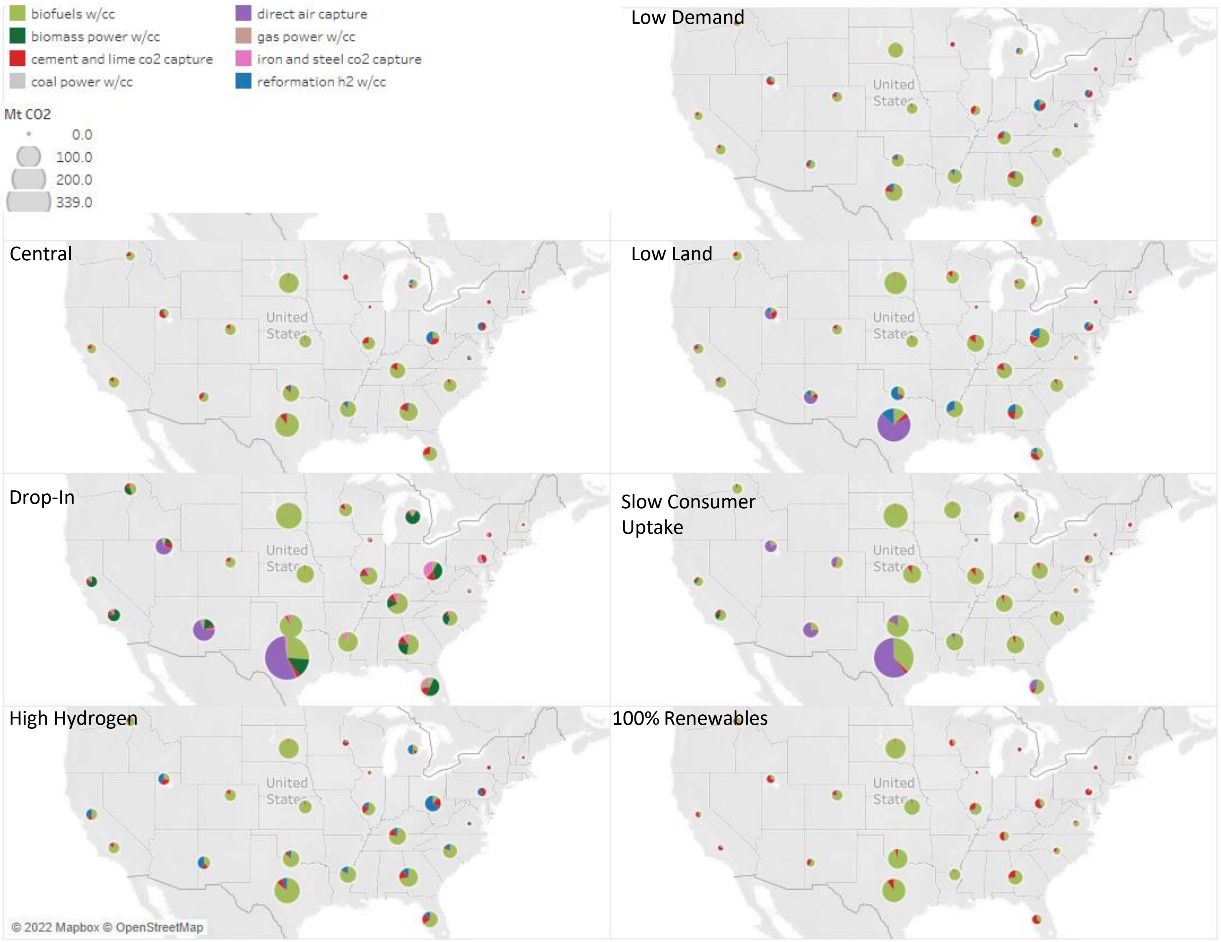
Carbon Uses

- Largest share of carbon captured in scenarios in most scenarios is sequestered
- Relative competitiveness of sequestration vs. zero-carbon fuels is dictated by cost/availability of electrolytic hydrogen and avoided cost of fossil alternative



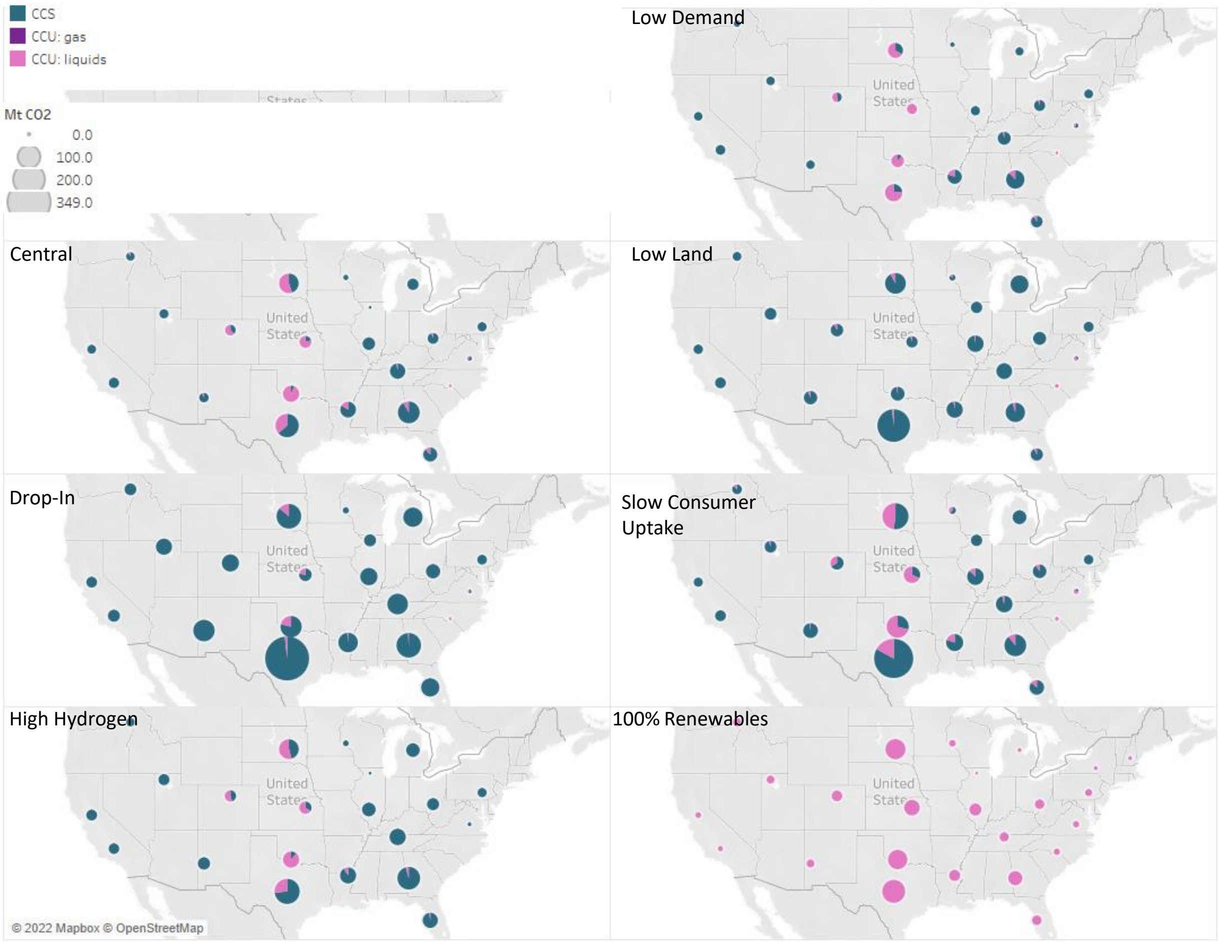
Carbon Sources Map

- Industrial carbon capture (cement and iron and steel) maps to existing facilities
- Biofuels primarily in the Midwest and Southeast
- Blue H2 deployed to areas with low-cost gas and sequestration (Texas, Lower Midwest)
- DAC is co-located with cheap geologic storage or low-cost hydrogen



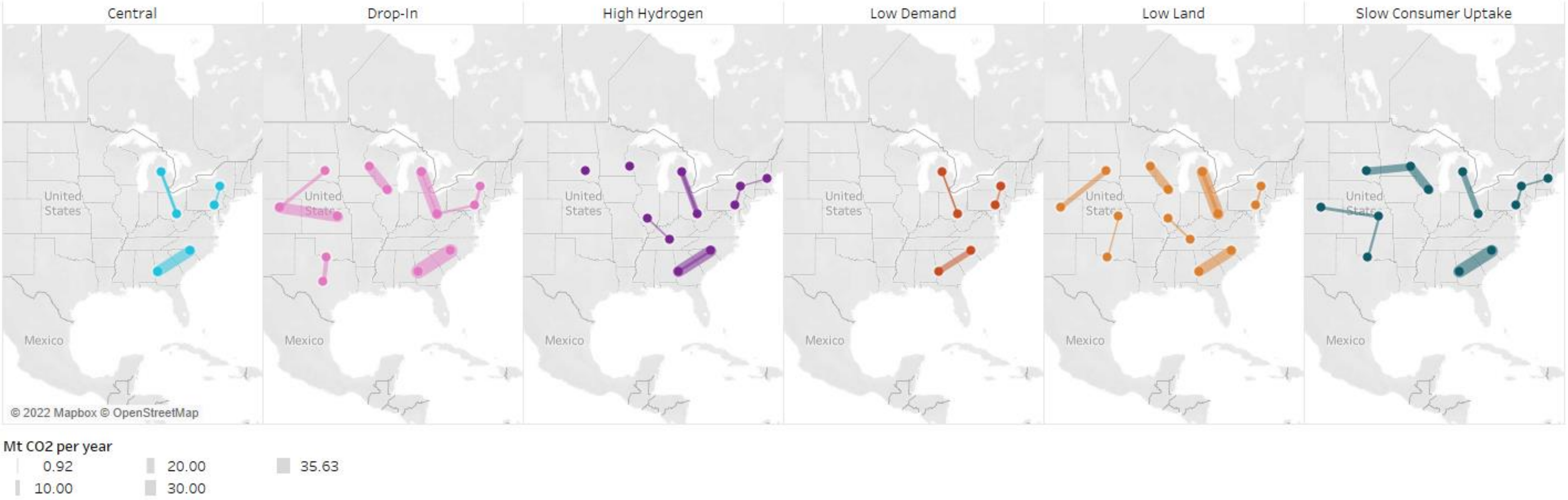
Carbon Uses Map

- Large-scale electro-fuel production concentrated in the windbelt due to low-cost electrolytic H2
- In most other scenarios, other regions primarily sequester
- In the 100% renewables scenario, with no need to sequester (no fossil energy means no gross emissions to offset) all of the captured carbon is utilized in electro-fuel production



Interregional Pipelines

- Large inter-regional CO2 pipelines not a huge factor in the results
- Where they are built, it's to move CO2 captured in areas with limited renewables (so limited ability to produce H2) and limited sequestration



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Key Findings

Key Findings

- There is a large amount of uncertainty on the ultimate volumes of carbon capture that will be necessary, though a significant amount (compared to today) is seen in every scenario
- Continued development of electrified technology may outcompete carbon capture in many applications (cement, iron and steel, etc.)
- The ability to produce synthetic fuels as well as sequester allows for an optimization of use that avoids some need for large pipelines. There is significant uncertainty in sequestration costs and volumes. If there is a larger spread in the cost of injection, then we would see additional pipelines built to access lower cost sequestration.

THANK YOU

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