The Emerging Value of CCS for Utilities

SHIFTING FROM RETROFITS TO SYSTEM-WIDE DECARBONIZATION

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THE Brattle GROUP

Takeaways

- **TODAY:** Recently passed 45Q tax incentives and sales of captured emissions to enhanced oil recovery operations can offset CCS costs, but retrofitting existing fossil plants are likely not as competitive as new renewables in low-renewable penetration systems
  - Recent case study of Public Service Co. of New Mexico's San Juan Generation Station highlights economic advantage renewables have today
- **FUTURE:** Despite unfavorable economics today with present-day technology, the value of an emission-free dispatchable or baseload resource, such as CCS, will grow as renewable penetration becomes material, and when marginal costs of decarbonization with wind and solar become very high
  - The net-value of CCS increases the closer the grid is to 100% clean, while the net-value of new renewables decrease without long-term storage
  - There are considerable uncertainties regarding the cost, performance, and circumstances for many emerging non-intermittent clean power, all of which appear similarly untested. Utilities will need to evaluate the tradeoffs of competing technologies to ensure cost-effective deep decarbonization as opportunities will vary regionally
- **BARRIERS AND OPPORTUNITIES:** Excluding CCS from the solution set based on present-day economics is likely shortsighted, failing to recognize CCS may have significant value in the future and risks stunting CCS technology advancement
  - CO_2 transmission planning, regulatory uncertainty, and lack of experience barriers needs to be overcome. Utilities and State Commissions have a unique opportunity to overcome barriers by fostering CCS development with their ability to do integrated planning
  - New Allam-cycle technology promises to deliver gas-CCS at the cost and operational flexibility of today's natural gas plants, at little-to-no carbon capture cost and water use, the later often being cited as a negative of present-day CCS technologies

CCS' Role in Electricity Decarbonization is Emerging

The role of CCS in a clean electricity grid is emerging: Today, CCS can already be economically attractive under the right circumstances. In the future, CCS provides significant value in deeply decarbonized systems. Utilities should consider how fostering CCS can help meet long term decarbonization.

- For decades, **Carbon Capture and Sequestration (CCS)** has been heralded as a means to decarbonize fossil power and preserve coal. Despite the advertised potential, however, **development of CCS has been slow** due to unfavorable economics, policy risk, and uncertainty of technology policies for decarbonization
  - Today, only two operational CCS power plants exist in North America, capital costs for retrofitting coal range $1,400-$2,200 per kW and introduces a large parasitic load
- However, recent **federal tax credits ("45Q"),** have created a material incentive for CCS and sparked interest from coal generators
  - With these credits and enhanced oil recovery revenues (where possible), CCS retrofitting may be feasible at little or no net-cost
  - Additional benefits include job preservation and decarbonization in areas with weak solar or wind conditions
- Despite incentives, **present-day CCS technologies may not be as attractive as new renewables and storage when intermittent renewable penetration still low** – as was found by a recent case study of Public Service Co. of New Mexico's San Juan Generation Station
- The value of CCS to **provide clean backup generation in a deeply decarbonized system is likely much higher than for retrofits today,** and is likely to be substantial
  - This is due to the declining marginal value (or avoided costs) per MW of renewables at high renewable penetrations
  - Utilities will need to understand tradeoffs between CCS and other technologies, such as renewable natural gas, to make cost-effective strategies to decarbonize
- Much **work remains to be done to scale up CCS**. Early deployment of CCS and learning-by-doing, ahead of completely favorable economics, will likely make its later use more economical, well-understood, and feasible

CCS Policies, Incentives, and Projects are Growing

- Incentives for CCS and projects under development are growing:
  - **Federal 45Q Tax Credits** provide incentives for capturing CO_2 and sequestering in geologic reservoirs: **$35/ton for enhanced oil recovery** and **$50/ton for storage-only**
  - Additional revenues can be generated by **selling captured CO_2 to enhanced oil recovery (EOR)** operations
- State Legislatures and Commissions are considering CCS in decarbonization plans:
  - Wyoming House Legislature recently passed bill that would allow utilities to rate-base carbon capture projects (up 2% of rate-base)
  - California Public Utilities Commission is currently deliberating the role of CCS in the state's clean energy future
- CCS remains one of the few technologies that bridges **political divides** due to potential to keep existing facilities running, to decarbonize fossil use, and to provide captured CO_2 for enhanced oil recovery (EOR)

U.S. CCS Project Pipeline

COMPANY	STATE	SECTOR	CAPTURE CAPACITY (TONNES/YEAR)	STORAGE	STATUS
Prairie State Generating Company	IL	Power - Coal	6,241,500 to 8,212,500 (design dependent)	Saline Storage	Front End Engineering & Design (FEED) complete
Glenrock petroleum	WY	Power - Coal	1,260,000	Enhanced Oil Recovery	Unavailable
City of Farmington, NM / Enchant Energy	NM	Power - Coal	6,000,000	Saline Storage	FEED
Basin Electric Dry Fork Station	WY	Power - Coal	2,200,000	Saline Storage	FEED
Minnkota Power	ND	Power - Coal	3,265,865	Saline Storage & Enhanced Oil Recovery	FEED
Nebraska Public Power/ Ion Eng	NE	Power - Coal	Unavailable	Unavailable	FEED
Southern Company	MS or AL	Power - Natural Gas	2,250,000	Unavailable	FEED
California Resources Corporation / OGCI	CA	Power - Natural Gas	1,400,000	Enhanced Oil Recovery	FEED
Panda Energy	TX	Power – Natural Gas	Unavailable	Enhanced Oil Recovery	FEED
Golden Spread Electric Coop	TX	Power – Natural Gas	Unavailable	Enhanced Oil Recovery	FEED
Clean Energy Systems	CA	Power - Biomass	300,000	Saline Storage	Pre-FEED
Illinois Clean Fuels	IL	Industrial - Biofuels	8,125,000	Saline Storage	Unavailable
Velocys / Oxy	MS	Industrial - Biofuels	330,000	Saline Storage	Pre-FEED
Blue Flint Ethanol	ND	Industrial - Ethanol	181,437	Saline Storage	FEED
White Energy / Oxy	TX	Industrial - Ethanol	350,000	Enhanced Oil Recovery	FEED
Pacific Ethanol	IL	Industrial - Ethanol	680,389	Saline Storage	Pre-FEED
Lake Charles methanol	LA	Industrial - Petrochemicals	4,000,000	Enhanced Oil Recovery	Final financing
Wabash Valley resource / OGCI	IN	Industrial - Hydrogen	1,500,000-1,750,000	Saline Storage	FEED
Svante / LafargeHolcim / Oxy / Total	CO	Industrial - Cement	725,000	Enhanced Oil Recovery	FEED
Carbon Engineering / Oxy	TX	Direct Air Capture	1,000,000	Enhanced Oil Recovery	FEED

Source: Clean Air Task Force CCS Project Tracker

Capture Retrofits on Existing Plants Today

ANALYSIS OF NET COSTS AND RISKS OF RETROFITTING A BASELOAD COAL PLANT

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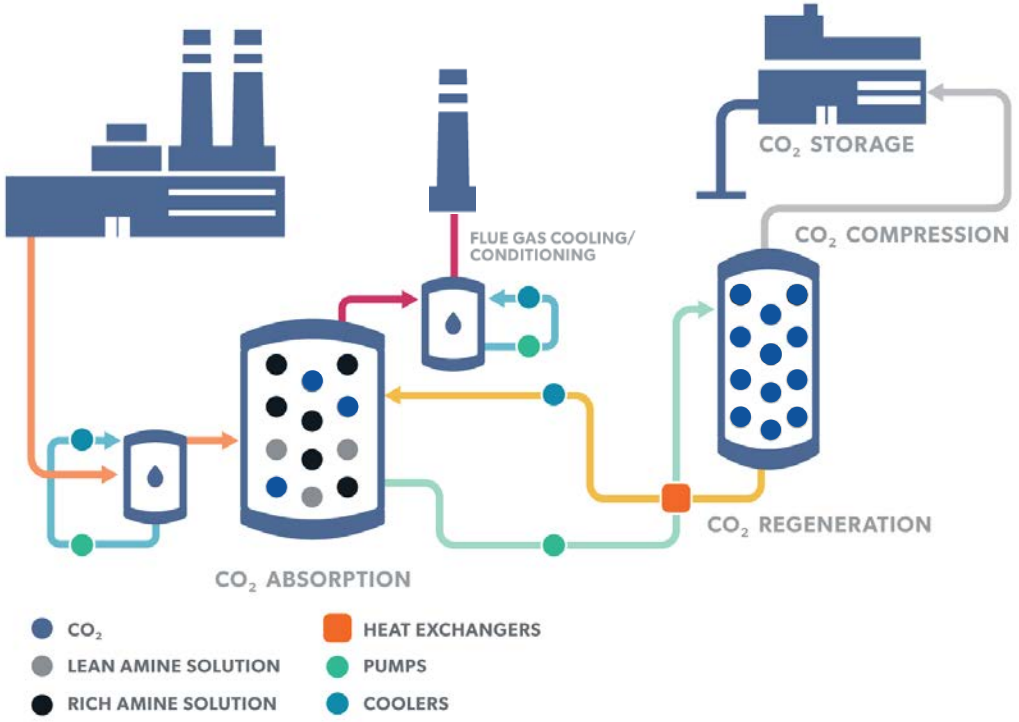
CARBON CAPTURE TODAY

CO_2 Capture at Power Plants

Capturing CO_2 from existing power plants requires adding energy-intensive components that reduce plant efficiency. But new capture technologies hold promise to reduce these costs and increase flexibility.

- Three primary methods of carbon capture for power plants:
  1. pre-combustion capture
  2. post-combustion capture (most suitable for existing plants)
  3. oxy-fuel combustion
  - Drawbacks of capture include **decreasing plant efficiency or requiring the addition of a separate gas unit to supply heat for capture**, and compromised operational flexibility
  - **Innovative oxy-fuel combustion technologies are emerging** that eliminate efficiency losses, provide operational flexibility similar to NGCCs, and are more cost effective than conventional capture methods
- Post-combustion carbon capture units operate by filtering exhaust flue gas to separate carbon dioxide from water vapor, sulfur dioxides, and nitrogen oxides generated during the combustion of fossil fuel
  - **This process requires heat,** which can be met by either **1)** diverting heat from the plant and penalizing efficiency or **2)** building a separate combined cycle unit to produce heat



Post-Combustion Capture

Post-combustion has been most popular, though it imposes significant parasitic or additional power needs. The preferred supply depends on utilization of the plant and whether it is needed for capacity obligations.

- Post-combustion CCS requires heat to separate the carbon dioxide from the solvent, adding VOM costs. Heat can be provided from:
  1. The original plant self-supply
     - Pros: Minimizes upfront capital
     - Cons: Decreases plant efficiency (25-30%), reducing plant capacity and introduces opportunity costs of foregone energy sales
  2. A separate new gas CC
     - Pros: Can maintain plant capacity and increases operational flexibility of plant
     - Cons: Requires additional capital
  3. A combination
- Post-combustion capture currently requires a relatively steady-state capacity factor to operate efficiently
  - Lack of experience operating capture flexibly
  - Reducing capacity factor will increase capture costs

PLANT FEATURES				CCS SETUP			
Plant Owner	Historical Capacity Factor	Electricity Obligation	Capacity Obligation	Energy Replacement Option	Capacity Replacement Option	Impact on Max Capacity	Impact on Net Capacity Factor
Merchant Power Generator	"Low" Capacity Factor (65%)	No	No	Self-Supply and Increase Gross CF	New CT	0%	0%
				New CC Unit	New CC	0%	0%
				Self-Supply and Forego Repl. Power	None	~30% Reduction	~40% Reduction
Merchant Power Generator	"High" Capacity Factor (85%)	No	No	New CC Unit	New CC	0%	0%
				Self-Supply and Forego Repl. Power	None	~30% Reduction	~40% Reduction
Regulated Generator	"Low" Capacity Factor (65%)	Yes	Yes	Self-Supply and Increase Gross CF	New CT	0%	0%
				New CC Unit	New CC	0%	0%
Regulated Generator	"High" Capacity Factor (85%)	Yes	Yes	New CC Unit	New CC	0%	0%

Modeling the NPV of Retrofitting a Depreciated Coal Plant

To estimate the net-costs of retrofit, we model the annual costs and revenue streams from installing a post-combustion capture unit at a depreciated coal plant. We note this is not a value analysis, but rather a cost analysis to compare various CCS arrangements.

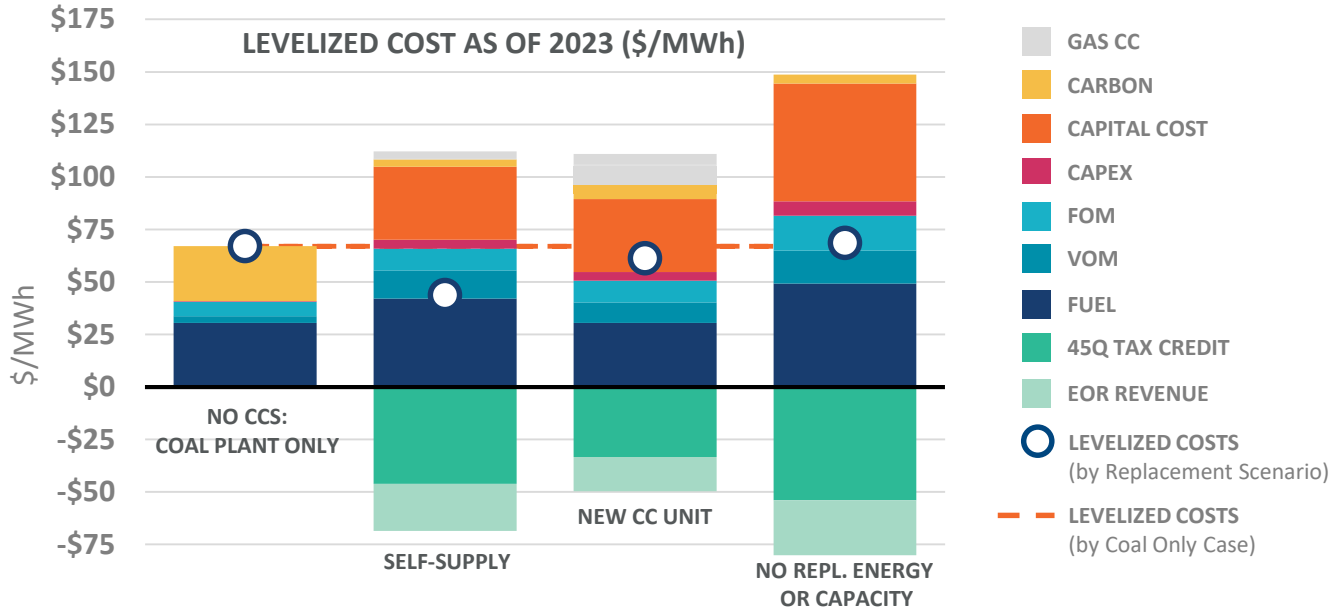
- We evaluate **several plant configurations**:
  1. Plant self-supplies heat by increasing net-capacity factor and replaces capacity with a new NG-CT unit
  2. Plant supplies heat and replacement capacity with a new NG-CC unit
  3. Plant self-supplies heat but decreases net-capacity factor and foregoes replacement capacity
- We assume a **16-year useful life** of the coal plant and CCS unit, and model the 45Q tax credits according to their legislated 12-year schedule
- We assume plant operations and dispatch are not impacted by the addition of the CCS unit in the analysis
- Cost Streams:
  - Capture unit capital ($/kW), applied using a level-nominal fixed charge rate
  - Ongoing capital expenditures at capture unit and coal plant ($/kW)
  - Replacement power NG-CC or -CT capital as applicable ($/kW)
  - Increases in VOM ($/kWh) and FOM ($/kW-yr) from operating capture unit, coal plant, and replacement power unit
  - CO2 Price ($/tonne)
  - CO2 Storage Costs ($/tonne) (if using saline storage)
- Revenue Streams:
  - EOR Revenue ($/tonne)(if selling captured emissions for EOR)
  - 45Q Tax Credits ($/tonne)
- We assume that CCS would only be considered if there is an carbon price, whether explicit or implicit through a clean energy mandate

16-Year Cost Savings for CCS with EOR

Incentives provide *net-savings* over 16 years under a carbon tax, and can offset CCS costs even without a carbon tax

- A meaningful carbon price introduces significant savings, here assumed to start at $20/tonne in 2023 and escalate to $40/tonne in 2038 (nominal $)
- Even in a region with no carbon price but a mandate to have clean electricity, CCS may only impose modest cost increases.

Note: Claiming 45Q credits does not limit claiming the avoided of carbon costs



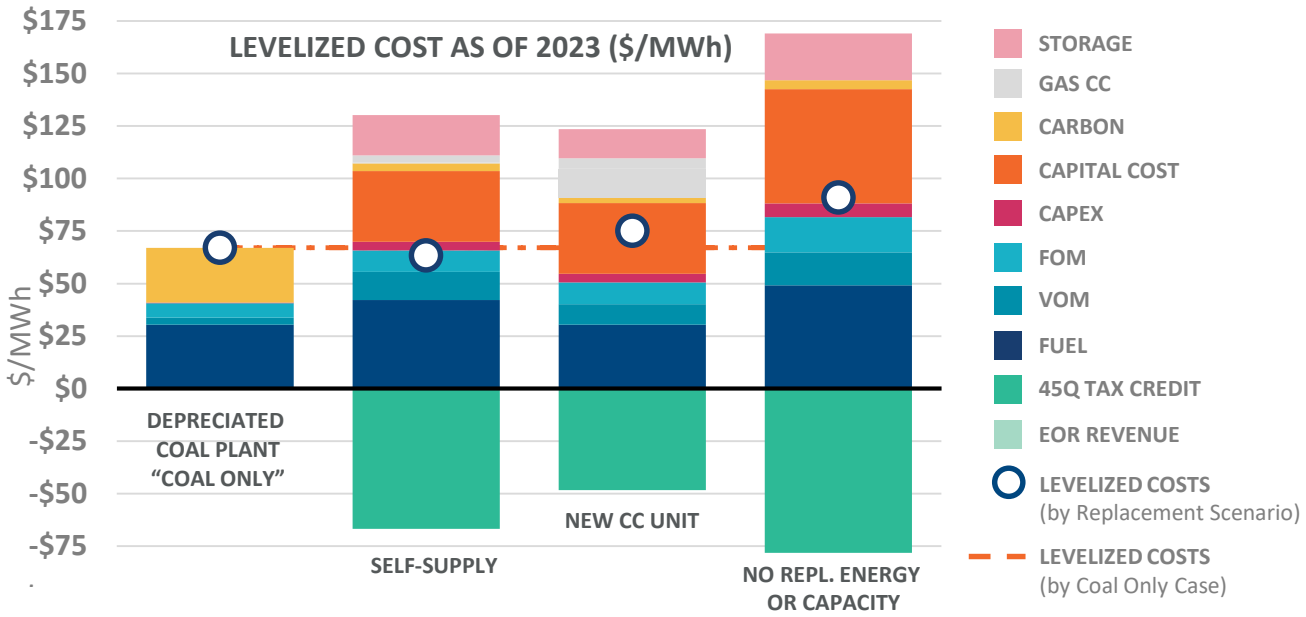
Plant Configuration	NO CCS --Coal Plant Only	Self-Supply	New CC Unit	No Repl. Energy or Capacity
Replacement Energy	N/A	100% Coal Plant	100% from Gas CC	None
Replacement Capacity	N/A	Gas CT	Gas CC	None
Gross Coal Plant Capacity Factor	65%	90%	65%	65%
Net Coal Plant Capacity Factor	**65%**	**65%**	**65%**	**40%**
Lifecycle PV Direct Costs ($ millions)	$4,093	$6,849	$6,770	$5,623
45Q + EOR Revenues ($ millions)	N/A	-$4,185	-$3,031	-$3,031
Net Costs after 45Q and EOR ($ millions)	$4,093	$2,665	$3,738	$2,592
Savings Relative to "Coal Only" ($ millions)	**N/A**	**$1,429**	**$355**	**$1,502**
Savings Relative to "Coal Only" (%)	N/A	35%	9%	37%

Savings under all three replacement scenarios. *Highest cash savings in "no replacement energy" scenario, but lower output and sales.*

Smaller 16-Year Savings with Saline Storage

Even with saline storage instead of EOR, CCS can still be breakeven under certain scenarios

- The increased 45Q credits partially offset the lost EOR revenues
- However, the plant must now **pay to offload the captured carbon for saline storage** (highlighted by the pink storage costs in the figure at right)
- This additional cost ultimately makes saline storage a less economical option compared to EOR



Plant Configuration	Depreciated Coal Plant "Coal Only"	Self-Supply	New CC Unit	No Repl. Energy or Capacity
Replacement Energy	N/A	100% Coal Plant	100% from Gas CC	None
Replacement Capacity	N/A	Gas CT	Gas CC	None
Gross Coal Plant Capacity Factor	65%	90%	65%	65%
Net Coal Plant Capacity Factor	**65%**	**65%**	**65%**	**40%**
Lifecycle PV Direct Costs ($ millions)	$4,093	$7,945	$7,543	$6,397
45Q + EOR Revenues ($ millions)	N/A	-$4,079	-$2,955	-$2,955
Net Costs after 45Q and EOR ($ millions)	$4,093	$3,866	$4,589	$3,442
Savings Relative to "Coal Only" ($ millions)	**N/A**	**$227**	**-$495**	**$651**
Savings Relative to "Coal Only" (%)	N/A	6%	-12%	16%

Two replacement energy scenarios still show (smaller) savings from CCS

Result Sensitivities

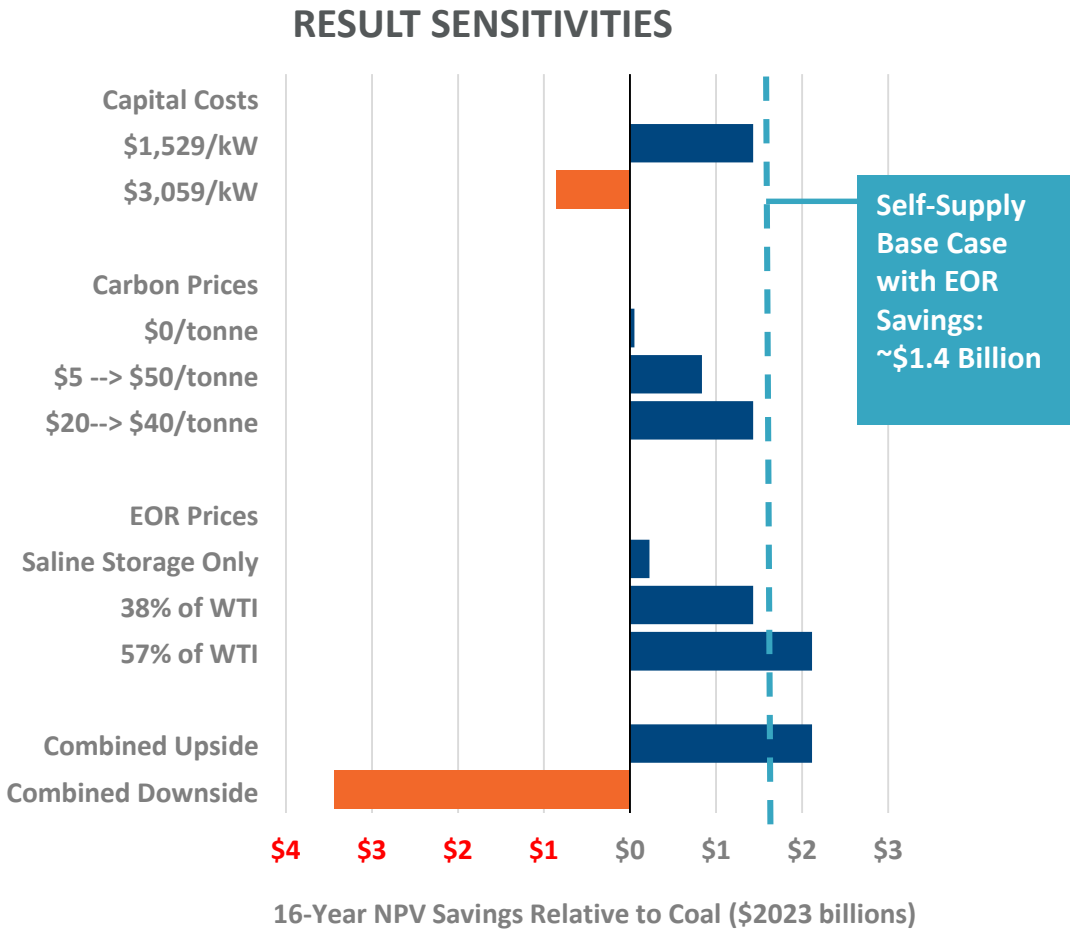
Retrofit savings are sensitive to varying assumptions for capital cost, carbon price, and EOR prices.

Base Case Assumptions

Plant Size, Capacity Factor	1150 MW, 65%
Replacement Power	Self-Supply
Replacement Capacity	Gas CT
Plant Capital Costs	**$1,529/kW**
EOR	**38% WTI**
CO2	**$20/tonne --> $40/tonne**

SENSITIVITIES

- **CAPITAL COST:** $1,529/kW reflects the Sargent and Lundy 2019 estimate for a CCS retrofit at San Juan Generating Station. $3,059/kW (2x the base assumption) is more comparable with capital costs at prior Boundary Dam, Petra Nova projects.
- **CARBON PRICE:** Eliminating carbon price effectively eliminates most cost-saving with other base assumptions.
- **EOR PRICE:** Sensitivities reflect market uncertainty and regional variation (i.e., might not have access to nearby oil fields)
- **DOWNSIDE RISK:** Significant downside risk is also possible with this relatively novel technology. Combining the downside risks of CCS generates losses that are 70% greater than the potential upside (in absolute terms)
- **CAPACITY FACTOR (C.F.):** Retrofitting a plant which historically runs at an 85% c.f. and providing replacement power from a gas CC generates savings of $1.61B because additional of additional revenue generated from the higher volumes of captured carbon



Note: Each sensitivity constructed by holding all other variables constant.

Capture on Natural Gas Plants Also Feasible and Could Breakeven with EOR and 45Q

Post-combustion capture is also feasible for natural gas power plants. Capital costs per kW are lower than for coal, but they capture less CO_2 per MWh and capture costs remain comparable to coal. New gas capture technologies appear promising.

- Currently **no operational natural gas power plants with post-combustion capture**, though same post-combustion capture technology used on coal can be applied to natural gas
- Direct cost for post-combustion capture costs on a NGCC are estimated to be ~$52-$120 ($2019) per tonne CO2 (comparable to coal plants on the lower end), where **lack of experience presents large uncertainty.**
  - Accounting for 45Q incentives and EOR revenues, the net-costs of CCS are $0-$70 per tonne CO2
  - This range suggests costs that are approaching breakeven with $50/tonne benefits (such as 45Q benefits and $15/tonne EOR)
  - Unclear to what degree the capture units can be operated flexibly, possibly compromising the load following benefits of gas
- New **Allam Cycle natural gas power plant design** promises to captures 100% of CO2 while performing similarly to a traditional combined cycle plant at very low incremental costs (capture cost estimated at **$2/tonne**)
- Net Power is a startup utilizing the "Allam cycle," which uses oxy-combustion and supercritical CO2 as the working fluid, resulting in LVT efficiency of 59% with capture and ramping capabilities as strong as NGCC. It is often seen as a crucial technology for wide scale CCS deployment
- Also benefits from little-to-no water consumption, a common critique of present-day CCS technology

Source: Net Power.

CCS vs. New Renewables *Today*

While CCS incentives can offset its costs today, we are simply not at a stage of decarbonization where CCS can compete with solar and wind in its current form in a low-renewable penetration grid. However, the value of CCS in a deeply decarbonized grid is emerging.

- San Juan serves as **an illustrative case study:** In response to New Mexico's 100% decarbonization target, Public Service Company of New Mexico (PNM) decided **to prematurely shut-down the 847 MW San Juan coal plant** to comply with ETA.
  - State regulators asked PNM to explore CCS with EOR and 45Q, incentives would offset costs of CCS. However, shutting down the power plant and replacing with a **suite of renewables and batteries were deemed more cost-effective for PNM**
  - However, San Juan is a fixture of Farmington, where it resides, providing local jobs and taxes, To ensure local jobs remain, Farmington formed an agreement with Enchant Energy, who will take over 95% plant ownership and leave the city with 5**%, to retrofit the plant with CCS and sell the captured emissions to neighboring EOR fields**
- In most electricity grids, where **renewable penetration and curtailment is low,** and grid and integration challenges have not yet surfaced, replacing coal plants with **new renewables is often more economical than retrofitting old power plants**
  - In such grids, a cost-comparison between CCS and other clean alternatives is often sufficient, and often concludes that **CCS is simply more expensive and politically risky compared to renewable on a LCOE basis**
- However, as we transition to **higher penetrations of renewable electricity grids** where clean integration challenges arise and new renewables experience a lot of curtailment, the **net-value (net of costs) of CCS as a clean backup generation** could be significant and reduce system costs of achieving a 100% clean grid. In the next section, we focus on the role of CCS in a deeply decarbonized electricity grid

Role of CCS in the Future

HOW THE VALUE OF CCS CHANGES WITH DEEP DECARBONIZATION

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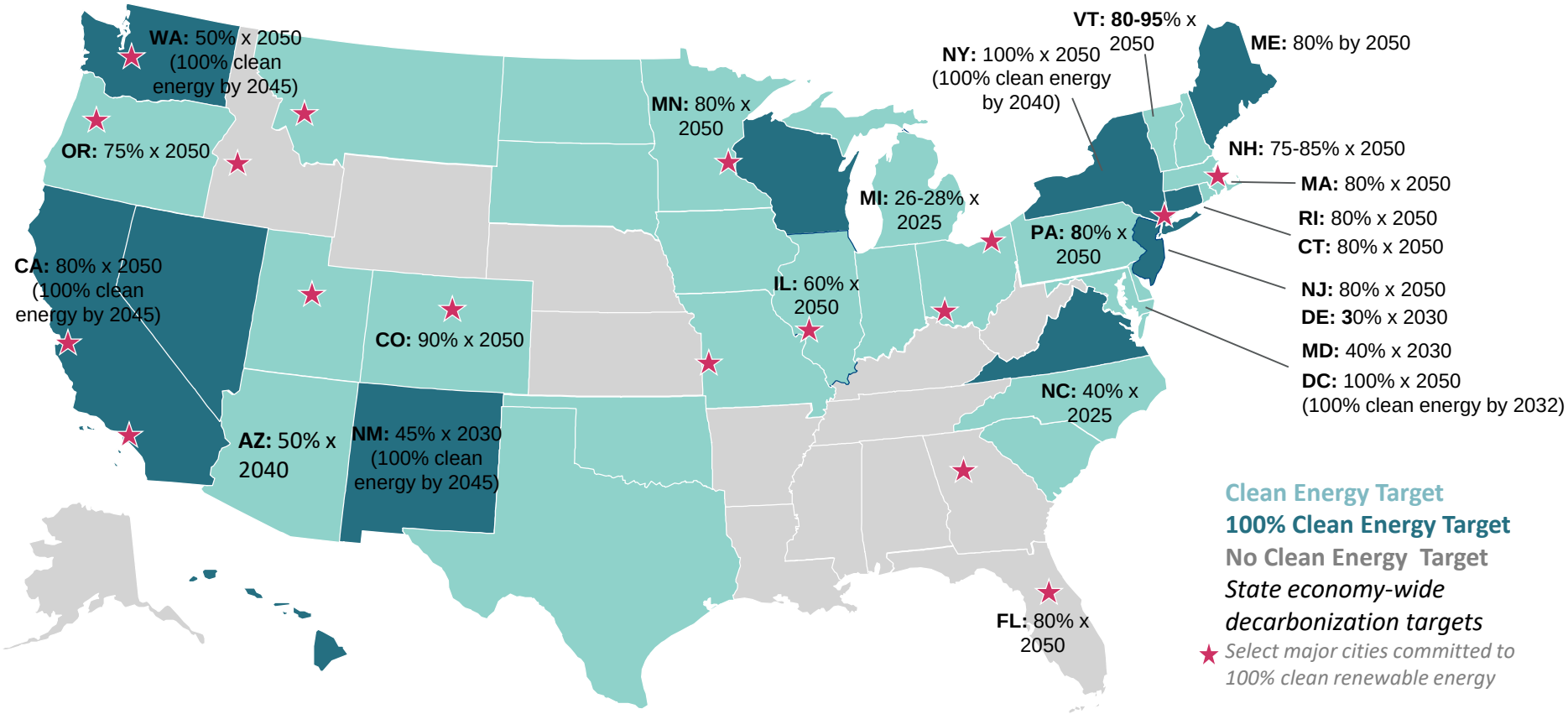
States, Cities, and Utilities are Mandating Clean Electricity

States and cities setting aggressive economy-wide decarbonization goal, all of which will require a clean electricity grid. As of now, many policies and mandates exclude CCS as a technology eligible to contribute to decarbonization.



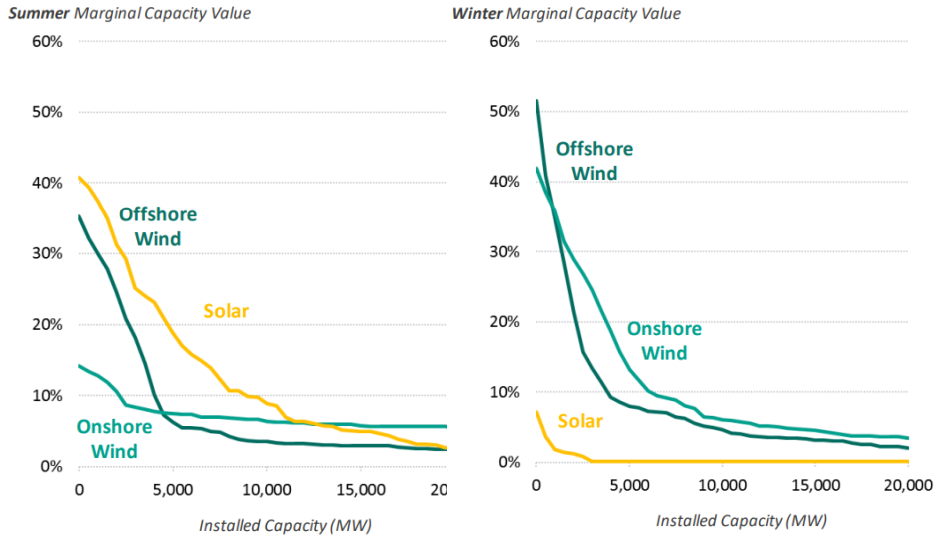
Sources: Center for Climate and Energy Solutions (C2ES), Sierra Club, National Conference for State Legislatures.
Includes states with executive orders for clean energy commitments; various sources.

Challenge: Ensuring Reliable, Resilient, and Affordable 100% Clean Grid

Once wind and solar become the majority of generation, they create strong operational challenges and high-costs for incremental reliability and resilience without significant storage or other clean backup generation.

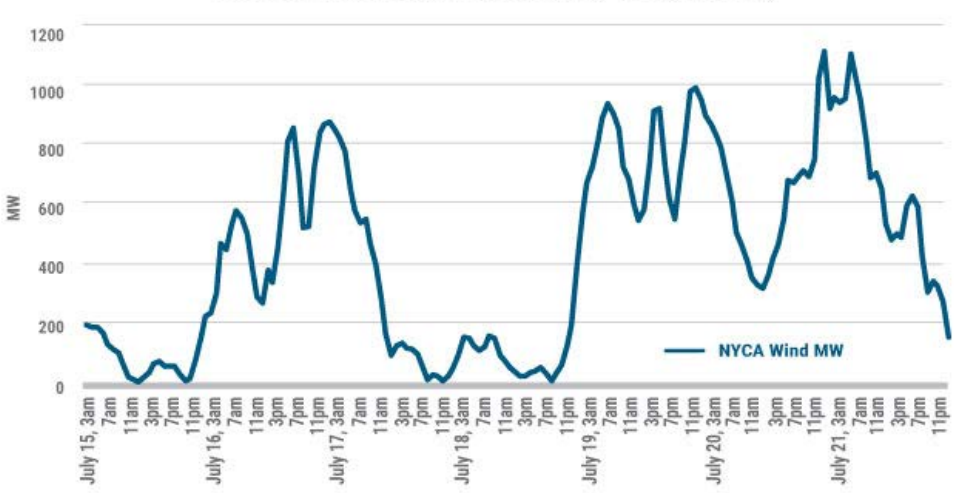
- **Variability and uncertainty** of renewable generation presents significant challenges:
  - Renewable generation droughts and seasonality can result in long periods of time with low renewable output, resulting in need to overbuild
    - NYISO Case Study: 2019 peak demand week, **the average capacity factor of wind was 4% for three days**. For some hours, capacity factor was almost zero.
  - At higher renewable penetrations, the value of new renewables declines as output is often correlated with existing renewables
  - Long-distance transmission to distribute renewables from high-output to low-output regions remains expensive and politically controversial
- Even with ambitious assumptions of lossless transmission across the continent, significant storage, and over-building capacity, a wind and solar-only system struggles to reliably meet electricity demand across the year without over-building

Capacity Value of Renewables without Storage



Source: NYISO Grid in Transition, The Brattle Group, March 2020.

Wind Performance During 2019 Peak Demand Week in NY

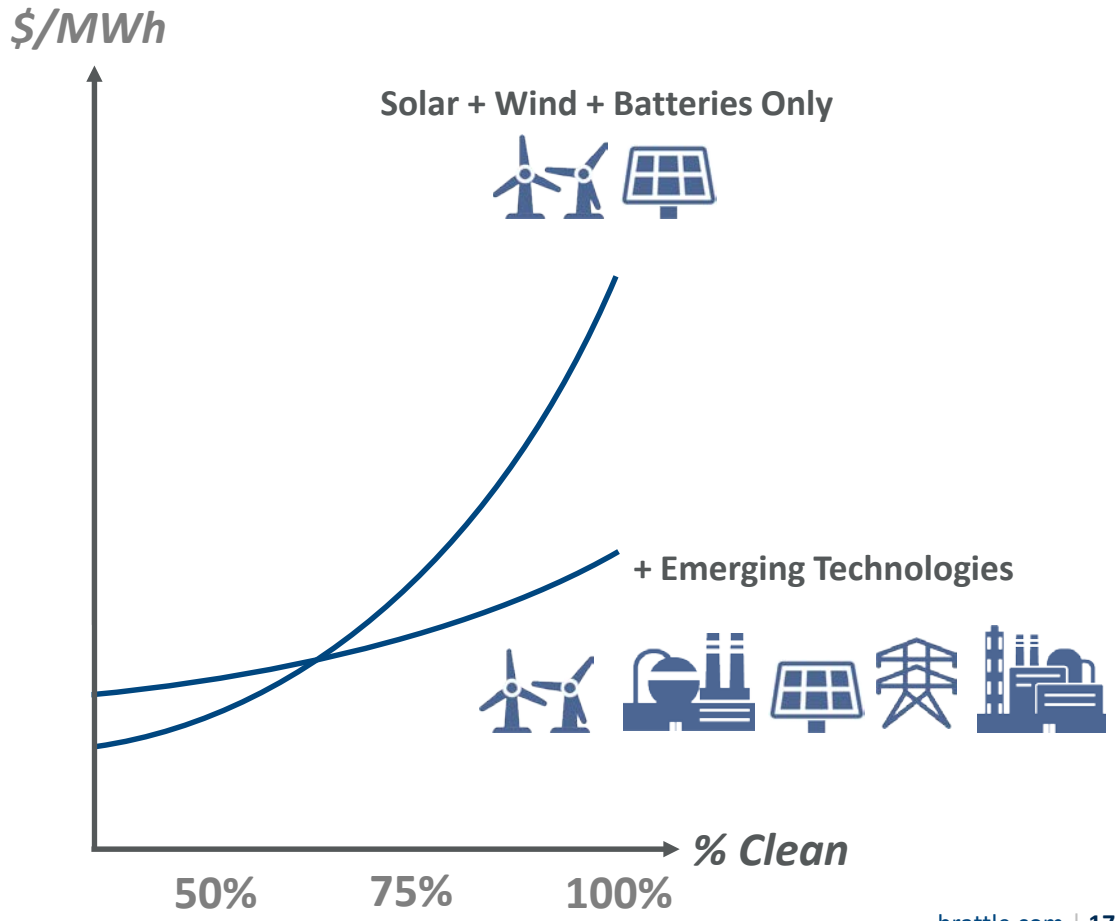


Source: NYISO, August 2019.

High Costs of 100% Wind-Solar-Only and the Value of Clean Backup Generation in Deep Decarbonization

Including emission-free backup generation technologies in the solution set could vastly reduce system costs of deep decarbonization.

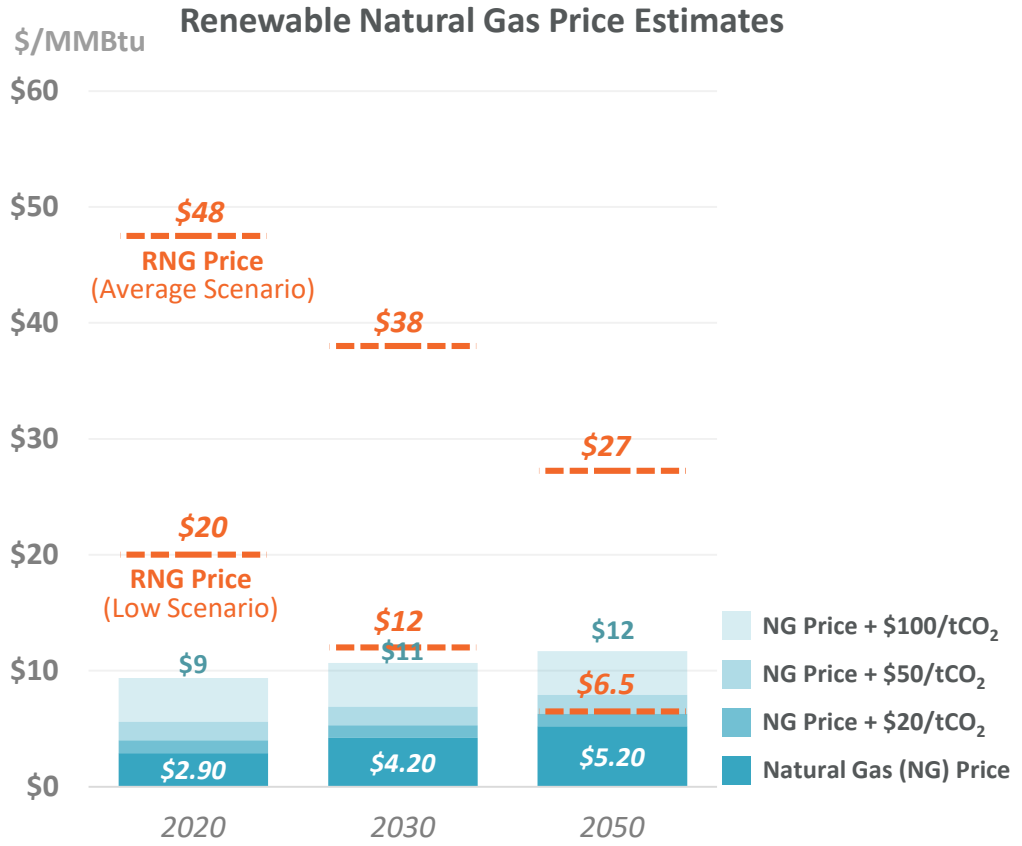
- Having dispatchable emission-free technologies **is estimated to greatly reduce electricity costs by 10% to 60%**
  - In a renewables-only system, **costs exponentially rise** as the emission limit tightens
  - Firm low-carbon technologies included CCS, biomass, renewable gas, and nuclear baseload can greatly reduce costs by avoiding need to overbuild wind, solar, and battery storage
  - How much each technology is deployed is dependent on assumptions about future technology cost reductions, highlighting need for evaluating holistic solution set
- Recent Brattle Study evaluating New York's 100% 2040 target **shows inclusion of renewable natural gas (RNG) is more cost-effective than overbuilding wind and solar,** even with battery storage available



Understanding Tradeoffs Between Emerging Complementary Technologies Will Be Key

CCS is not the only technology that provides clean backup generation. There are considerable uncertainties regarding the cost, performance, and circumstances for emerging non-intermittent clean power, all of which appear similarly untested. Utilities will need to understand tradeoffs to ensure cost-effective decarbonization as opportunities will vary regionally.

- **Batteries:** Batteries provide cost-effective value for short-term storage, though long-term storage technologies suitable for multi-day renewable droughts or seasonal storage remain limited and future costs are uncertain
- **Renewable Natural Gas (RNG):** While RNG variable cost estimates are high (up to 3 times CCS VOM by 2050), RNG may presents capital cost savings at low capacity factors and can operate in areas where CCS is not technically feasible
  - Recent AGF study estimates RNG potential ranges only 6%-15% of total U.S. fossil NG consumption, though future gas demand likely to be considerably lower
  - Recent Brattle study suggests declining RNG prices could become comparable with increases in NG + carbon prices, but not until 2050. RNG may be able to utilize existing gas infrastructure
- **Direct air capture:** Direct air capture aims to capture carbon from a more diluted environment, and therefore faces higher costs ($100-$250 /ton of CO2)
- **New CCS Technologies are Developing:** Net Power promises to deliver performance comparable to NGCC with no additional CO2 capture cost
  - This technology burns natural gas in pure oxygen, instead of air, and actually uses the CO2 byproduct to continue the cycle
- Allam-cycle technology doesn't consume water, making it suitable for water stressed regions



*Gas price forecasts assume demand increases over time. Source: Brattle.

Impediments, Barriers, and Challenges of CCS Remain for Power Generation

1. **Economics remain challenging** for retrofits and new CCS power plants
   - Lack of carbon pricing and CCS mandates makes economic incentives limited and tax credits have long-term policy uncertainty
   - New renewable energy remains most cost-effective clean MWh if integration is not a concern (as shown in San Juan)
2. Widespread CCS deployment will depend on a **CO_2 pipeline network to transport and offload captured emissions and continued fossil extraction.** Developing such a pipeline might present NIMBY and organizational challenges
   - While some convenient storage locations exist, CO_2 transmission planning will be essential to facilitate power-sector CCS
     - Chicken-and-egg problem: Pipeline needs multiple sources to finance, but capture facilities need pipeline to finance
   - Upstream fossil extraction emissions and pollution need to be addressed to provide environmental benefit
3. **Regulatory risk is decreasing, but still remains.** Existing regulatory regime for sequestration and operating projects in the US has significantly evolved over the last decade, including project siting and permitting.
4. **Experience, confidence, and demonstrated successes remain limited** for power CCS projects
   - Previous project cost-overruns (Kemper and Boundary Dam) raise doubts, despite some successes (Petra Nova) and estimates of cost-improvements for future projects

CONCLUSION

Need to Shift from One-off Retrofits to System-Wide Planning for CCS

Utilities need to shift their perspective of CCS as a "retrofit technology" to a technology that should be evaluated as part of a larger solution set that substantially reduces costs of achieving a clean grid.

- CCS can present **system-wide benefits** for deep decarbonization in the right circumstances, utilities need to evaluate CCS along with complementary technologies to understand tradeoffs and plan a cost-effective clean electricity system
- **The amount and timing of when does CCS becomes cost-effective** will depend on the renewable resources in the region, opportunities to sell or sequester CO2, cost of alternative technologies, and degree of decarbonization desired
- Given the potential of CCS, utilities need to consider the value of CCS along with competing technologies with a **long-term policy compliance perspective.** Excluding CCS based on current economics and technologies might prove shortsighted and may stunt development of technology, especially for gas-CCS where little experience exists
- **Regulated-utilities** and State Commissions are uniquely positioned to include and facilitate CCS in long-term integrated planning that considers economy-wide state energy sources, uses, and goals
  - Integrated planning for CO2-pipeline infrastructure (if necessary) can help overcome chicken-and-egg challenges, and facilitate cross-industry collaboration to reduce transport and geologic storage costs (e.g. cement or steel manufacturing)
  - Most promising in states with aggressive decarbonization goals but limited attractive renewable hosting, e.g. no offshore wind. EOR potential in the state provides an additional incentives.

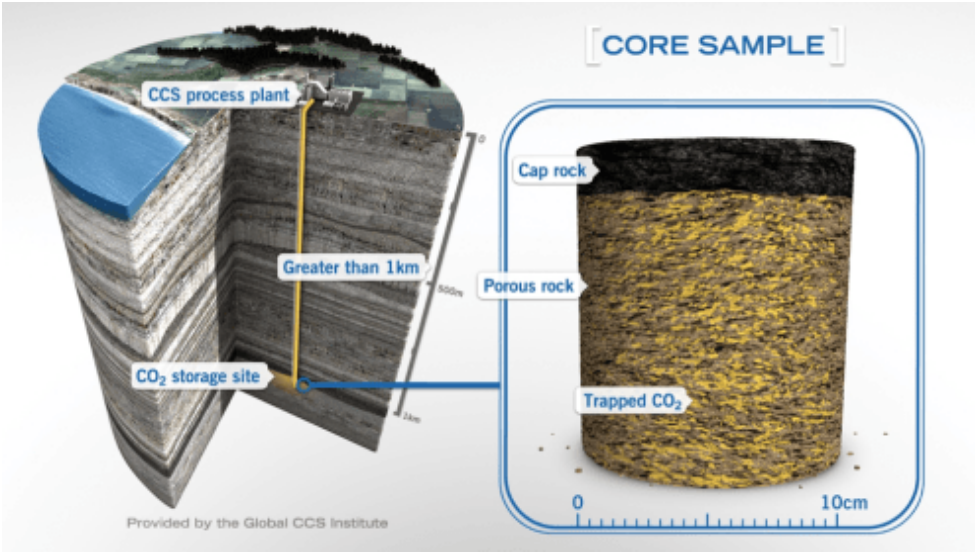
Appendix

Geologic CO_2 Storage

CCS is a demonstrated technology and geologic reservoirs hold enormous capacity to sequester emissions

- Carbon capture and sequestration (CCS) is a technology that **captures emissions at point-sources and disposes of them at a long-term geologic storage sites**
- Geologic storage of CO2 is done in porous rock formations deep in the earth (> 800m) that have overlying caprocks, very impermeable rock formations that "cap" the fluids and prevent upward migration
- Geologic storage is proven, the Sleipner project has injected almost 1 million tonnes of CO2 per year under the North Sea for the past 20 years with no evidence of leakage out of target formation

Schematic of CO_2 Injection into Subsurface



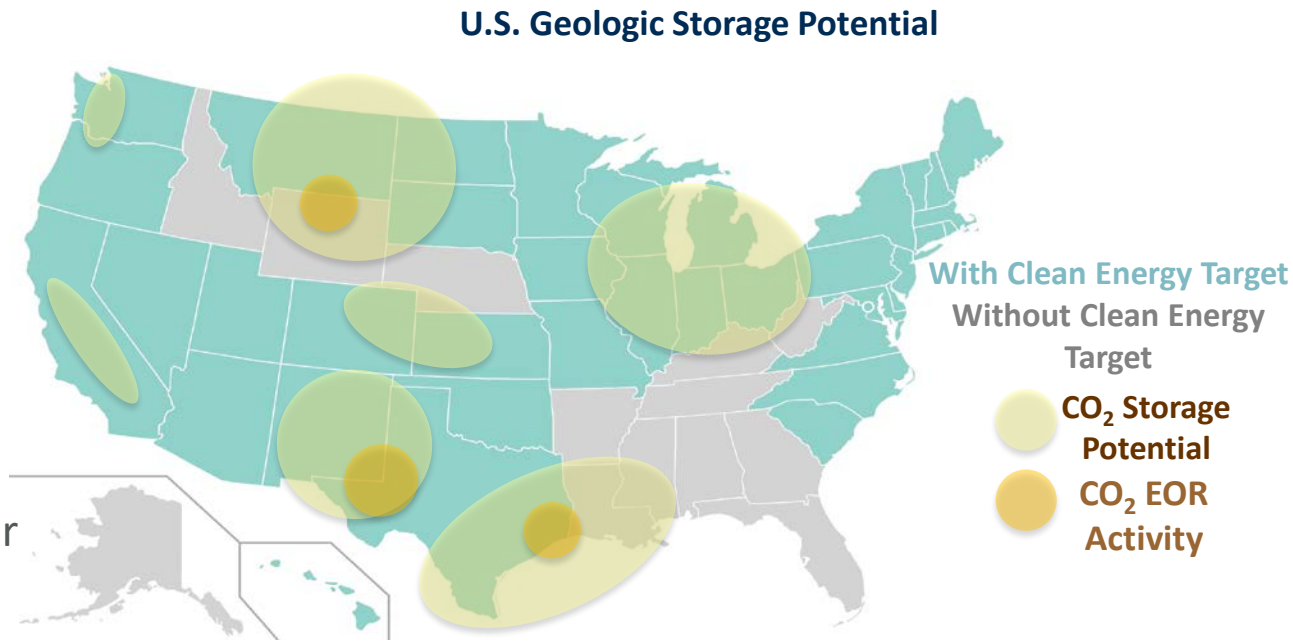
Source: Global CCS Institute

- The oil industry already sequesters approximately 60 million tonnes of CO2 per year into various geological formations in the United States
- The engineering for geologic CO2 storage is well tested, **with 19 operating projects worldwide** and decades worth of experience from successful enhanced oil recovery operations

Geologic Reservoirs in the US

The United States has enormous geologic storage potential (over 2,000 gigatonnes, including both saline and EOR), though much appraisal work remains to be done

- The United States is estimated to have between 2,000 and 21,000 gigatonnes of geologic storage resources available (1,000 gigatonne in depleted O&G reservoirs).
  - For reference, the U.S. power sector emitted 1.6 gigatonnes of CO2 in 2019 (1 gigatonne from coal power plants)
  - Many states with clean energy targets overlie potential geologic storage, making them good candidates
- While some convenient storage locations exist, CO_2 transmission planning will be essential to facilitate power plant sources to tap into an economic transmission network to deliver CO_2



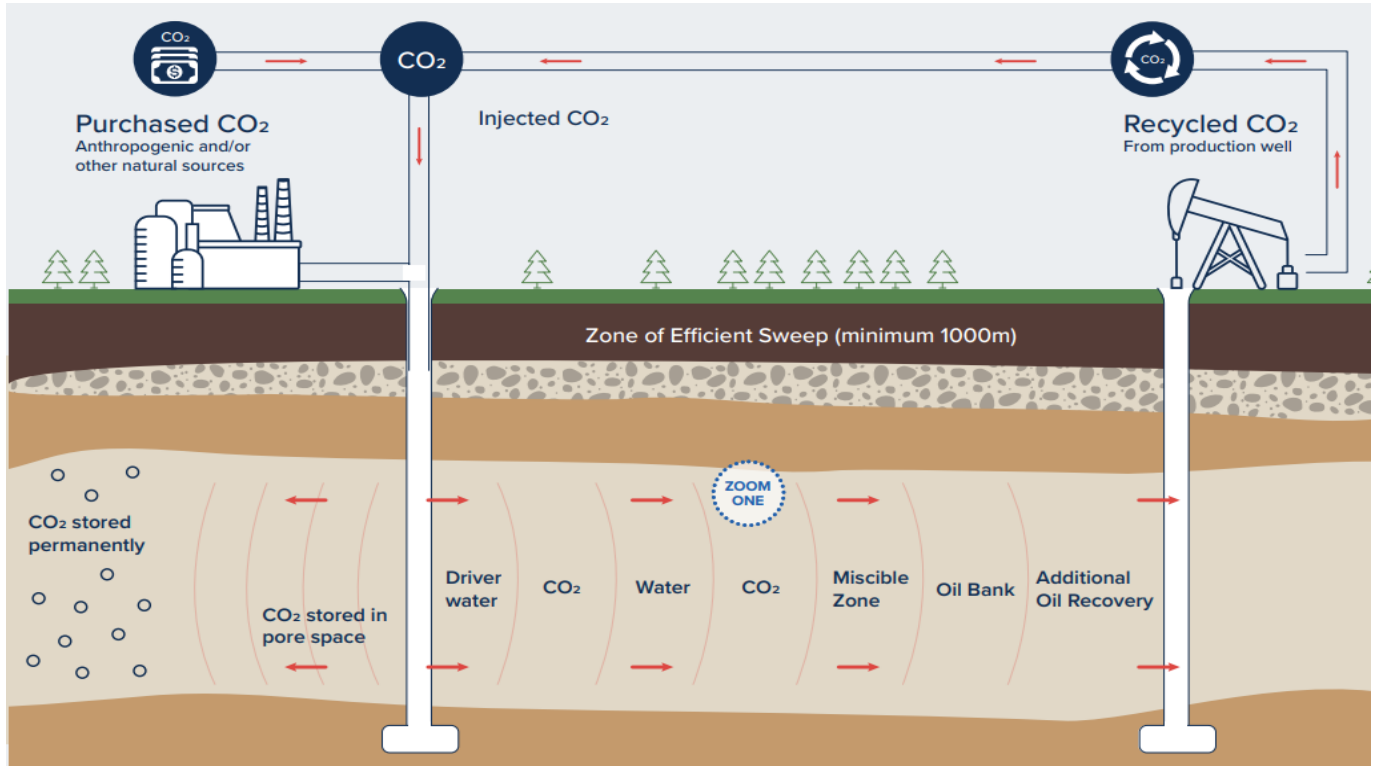
Notes: State targets based on information from the National Council of State Legislatures. Storage potential based on NETL's Carbon Storage Atlas

Enhanced Oil Recovery

Enhanced oil recovery (EOR) injects CO_2 into depleted oil reservoirs to enhance oil recovery. The sale of CO_2 to EOR operators are sources of revenue for CCS projects

- EOR **injects CO_2 and water to extract oil remnants in reservoirs** after the primary and secondary extraction phases, and once productivity has declined. CO_2-EOR can **increase reservoir extraction rate by 10% to 25%**
- During CO_2-EOR, **the majority of injected CO_2 is sequestered in the process.** For conventional EOR, 60% of the average CO_2 emissions of a barrel of oil is sequestered per barrel and be could be much higher, thought this is not to be counted as additional emission reduction
- Oil demand is inelastic and will be primary driver of supply. Increasing EOR and recovery of existing oil fields can **reduce the need for further oil field exploration and development**
- EOR operations present potential buyers of captured CO_2 from power plants, usually paying **~40% of the WTI oil price per tonne of CO_2** (e.g. $20 per tonne of CO_2 when the oil price is $53 per barrel)

Schematic of EOR Operations



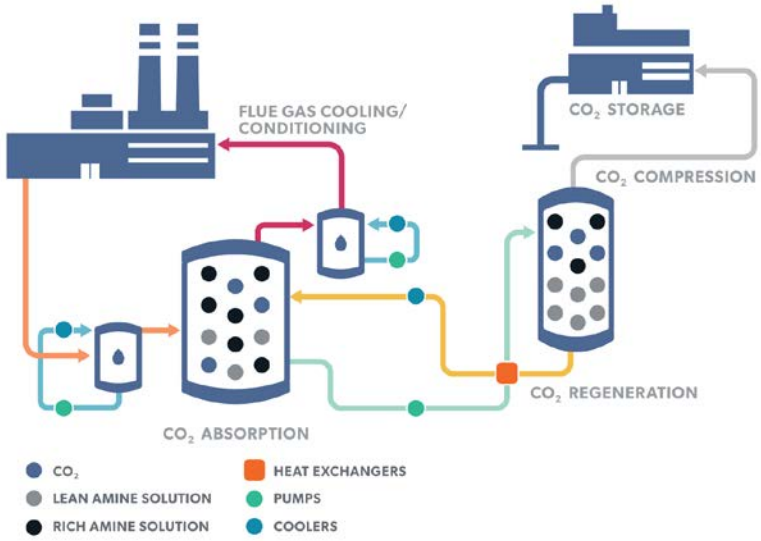
Source: Global CCS Institute

CARBON CAPTURE TODAY

CO_2 Capture at Power Plants

Capturing CO_2 from existing power plants requires adding energy-intensive components that reduce plant efficiency. But new capture technologies hold promise to reduce these costs and increase flexibility.

- Three primary methods of carbon capture for power plants:
  1. pre-combustion capture
  2. post-combustion capture (most suitable for existing plants)
  3. oxy-fuel combustion
  - ▸ Drawbacks of capture include **decreasing plant efficiency or requiring the addition of a separate gas unit to supply heat for capture**, and compromised operational flexibility
  - ▸ **Innovative oxy-fuel combustion technologies are emerging** that eliminate efficiency losses, provide operational flexibility similar to NGCCs, and are more cost effective than conventional capture methods



- Post-combustion carbon capture units operate by filtering exhaust flue gas to separate carbon dioxide from water vapor, sulfur dioxides, and nitrogen oxides generated during the combustion of fossil fuel
  - ▸ As the flue gas travels up a smokestack, solvents absorb the carbon dioxide molecules and release them in a separate chamber where they are **compressed for transport and storage**
  - ▸ The desorption of carbon dioxide from the, solvent **requires heat** which can be met by either 1) diverting heat from the plant and penalizing efficiency or 2) building a separate combined cycle unit to produce heat
  - ▸ Costs of capturing carbon dioxide using post-combustion technology are estimated at $60-$120 per ton CO_2 for natural gas combined cycle (NGCC) plants, and **$40-$60 per ton** CO_2 for **CO_2 for coal plants** (source: Graves, San Juan Testimony for PNM)

Post-Combustion Capture

Post-combustion has been most popular, though it imposes significant parasitic or additional power needs. The preferred supply depends on utilization of the plant and whether it is needed for capacity obligations.

- Post-combustion capture requires the **installation of several components** (capital costs range **from $1,400-$2,200 per kW**)
  - **Quencher:** Cools flue gas down to ambient temperature
  - **Absorber:** Solvent preferentially absorbs CO2
  - **Stripper:** Heat off-gases CO2 from solvent
  - **Compressor:** Compresses CO2 for transport
- Post-combustion **CCS requires heat to separate the carbon dioxide** from the solvent, adding VOM costs. This heat can be provided from:
  1. The original plant self-supply
     - Pros: Minimizes upfront capital
     - Cons: Decreases plant efficiency, reducing plant capacity and introduces opportunity costs of foregone energy sales
  2. A separate new gas CC
     - Pros: Can maintain plant capacity and increases operational flexibility of plant
     - Cons: Requires additional capital
  3. A combination
- For self-supply, heat requirement creates a parasitic load that **reduces efficiency by approximately 25-30%**
- Post-combustion capture currently **requires a relatively steady-state capacity factor to operate efficiently**
  - Lack of experience operating capture flexibly
  - Reducing capacity factor will increase capture costs
  - ARPE-E FLECCS initiative aims to increase capture flexibility to meet evolving demands of the electricity grid

Model Inputs

Key Model Inputs

Market	
EOR Revenues	38% of WTI price, based on WTI forwards as of 4/17/20
45Q Tax Credit	12 year credit, escalating from $27/tonne in 2023 to $35/tonne in 2026
CO2 Price	Escalating from $20/tonne in 2023 to $40/tonne in 2038
Coal Plant	
Coal Plant Size	1,150 MW
Coal Plant Net Capacity Factor	65%
Coal Plant Heat Rate	9,928 Btu/kWh
CCS Unit	
Capital Cost	$1.8B
Life	16 Years
Capacity Loss	29%
Replacement Capacity	335 MW Gas CT or 335 Gas CC
Storage Costs	$15/ton (if EOR not available)
Financing	
Discount Rate (WACC)	7.20%
Tax Credit Montetization Rate	100%, assume tax credits fully utilized

Fuel Prices (nominal)

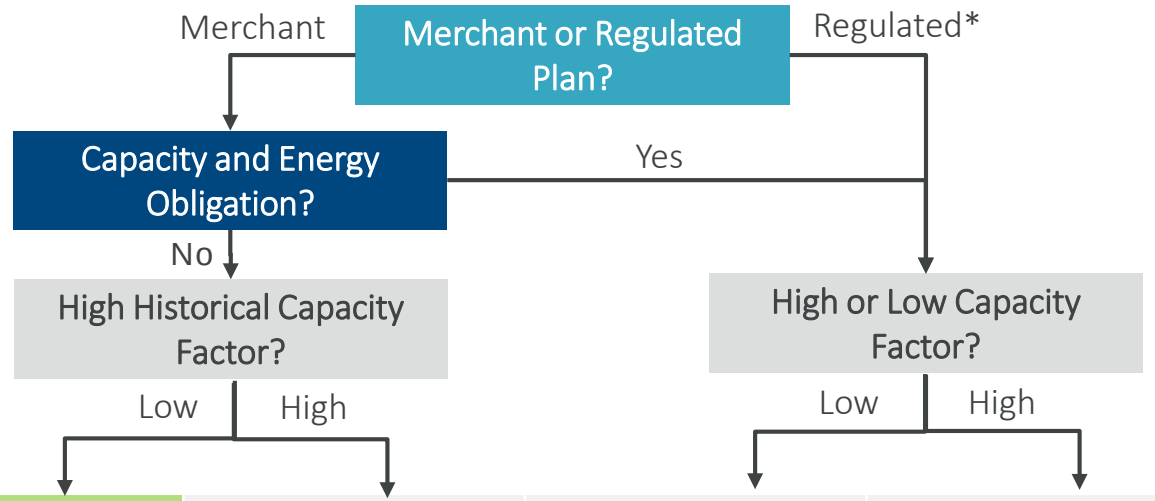
		2023 Value	2038 Value
WTI	WTI forwards as of 4/17/20	$40/bbl	$64/bbl
Delivered Coal	AEO 2019 delivered coal prices for electric power	$2.11/MMBtu	$3.52/MMBtu
Delivered Gas	AEO 2019 gas spot price at Henry Hub	$2.99/MMBtu	$6.53/MMBtu

Selected 65% net capacity factor to allow sufficient headroom to provide replacement energy from coal plant, if desired

- Replacement energy can be provided by the coal plant itself (if it has a low enough initial capacity factor) or by other resources, here approximated as a gas CC constructed to provide exactly the foregone capacity
  - If plant capacity factor is initially quite high, it may only be possible to rely on supplemental sources for the CCS's power
  - If a plant is regulated rather than merchant, it may be essential to replace the parasitic load so that total supply to the utility delivery system is unchanged.

Post-Combustion Capture Power Option Decision Tree

Post-combustion CCS requires heat to separate the carbon dioxide from the solvent, which results in a significant energy and capacity requirement. Several options exists for their supply.

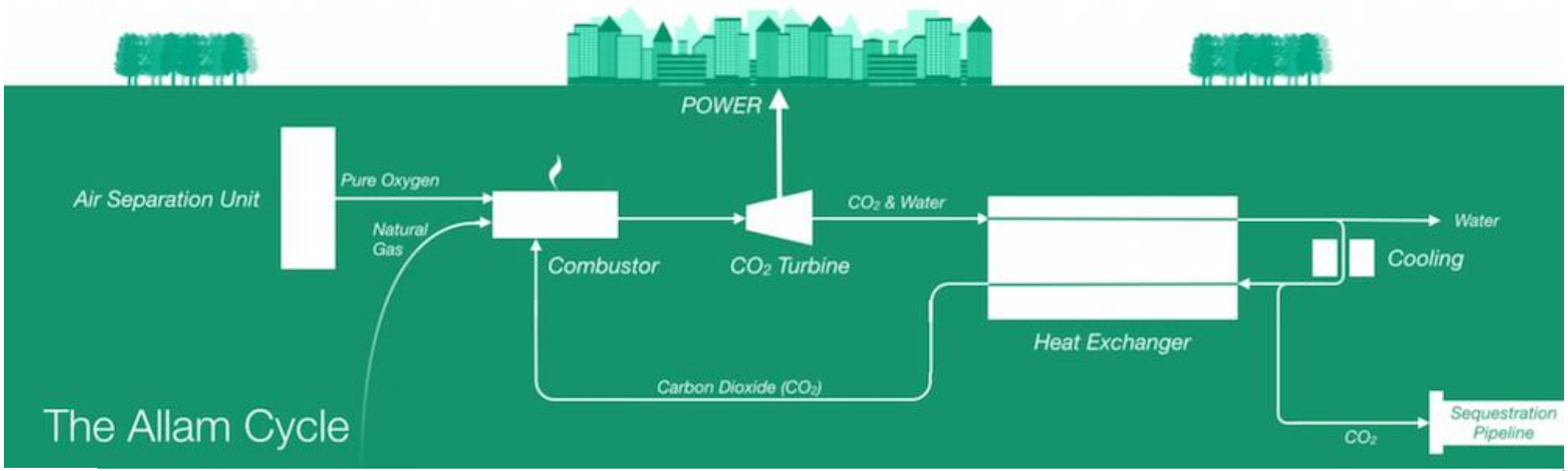


Power Replacement Options Available				
Self-Supply Heat Decrease Net CF Lower Max. Capacity	✓			
Self-Supply Heat Decrease Net CF Replace Capacity w/ New CC	✓	✓		
Self-Supply Heat Maintain Net CF Replace Capacity w/ New CC	✓	✓	✓	
Replace Heat w/ New CC Maintain Net CF Capacity w/ New CC	✓	✓	✓	✓

Allam Cycle Natural Gas Plant

- New Allam Cycle natural gas power plant design promises to captures 100% of CO2 while performing similarly to a traditional combined cycle plant at very low incremental costs (capture cost estimated at $2/tonne)
  - Net Power is a startup utilizing the "Allam cycle," which uses oxy-combustion and supercritical CO2 as the working fluid, resulting in LVT efficiency of 59% with capture and ramping capabilities as strong as NGCC
  - Allam cycle also eliminates the need for water, presenting co-benefits across the water-energy nexus
  - Net Power has built a 25 MW pilot plant near Houston, has successfully demonstrated the combustion cycle, and is continuing testing (though performance metrics remain unpublished)

Allam Cycle Schematic



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