What to do with all of this captured CO_2?

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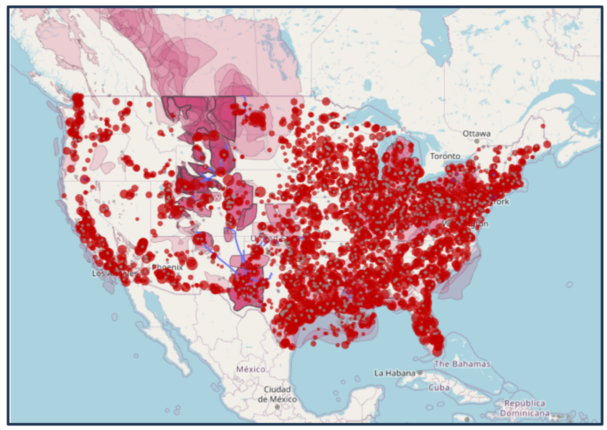
EXECUTIVE SUMMARY: The world will need to capture over 6 billion tonnes of CO_2 a year to meet net-zero goals. An important question is: what to do with all of it? Mantel is tackling emissions in the heavy industrial sector and, based on an analysis of the location of U.S. emissions today, we find there are ample prospects for managing current CO_2 emissions, on top of opportunities to scale carbon management across the economy. We estimate that 95% of U.S. sites, representing 74% of heavy industrial emissions, have clear pathways to manage their current level of emissions with existing infrastructure, through local storage (58%) or transport via truck (7%), rail (26%), ship (17%), or pipeline (8%) for CO_2 storage or utilization. There are many possible markets for CO_2, including synthetic fuels and chemicals, which could soon demand all captured CO_2 globally and would be unlocked through a high willingness to pay and low-cost clean energy. Even without utilization demand, the existing incentives and infrastructure make projects profitable with Mantel's exceedingly low-cost capture technology. In the U.S., assuming top-line revenue for decarbonizing at \$85/tCO_2 (45Q pricing) and transport and storage costs near \$15/tCO_2, the available margin for the capture step is \$70/tCO_2. Mantel cuts capture costs by 50-75% relative to conventional carbon capture technologies, improving returns and making two-thirds of U.S. projects profitable. In the future, additional profitability can be unlocked through demand for CO_2 utilization that provides additional revenue, as well as infrastructure buildout that will drive down the cost of transport and storage.



1. CO_2 Sources and Sinks

To reach net-zero emissions by 2050 carbon capture technologies will need to be deployed and capturing around 6 billion tonnes of CO_2 every year.[1] While a great deal of emphasis is rightly placed on the capture step, the industry's success – and the world's ability to reach net-zero – depends equally on the transport and end use of CO_2, be it utilization or storage. In the U.S., this is already a pressing question for the 2.8 billion tonnes of CO_2 emitted annually from heavy industry (defined as all sources over 50 tonnes CO_2 per day), where Mantel is focused right now.

The source of CO_2 and its final destination matter significantly in determining the impact of carbon capture, as shown in **Figure 1**. CO_2 can be sourced from carbon-containing resources where the carbon has been out of the atmosphere for millions of years (e.g., fossil fuels, limestone, and natural deposits of CO_2) or for much shorter periods of time (e.g., air, oceans, biomass). Over short time horizons, returning long-lived carbon to the atmosphere as CO_2 results in a net-increase in atmospheric CO_2 levels, while returning short-lived carbon has a lesser to no negative impact.

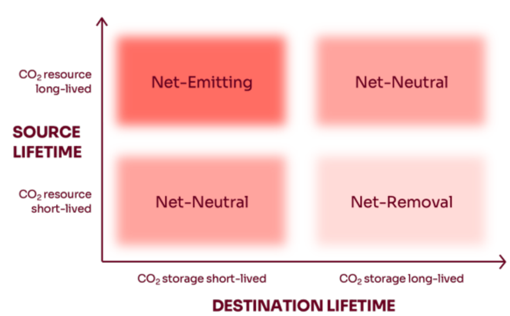


Figure 1. Impact of CO_2 source and destination on atmospheric CO_2 levels

The destination, or the sink, for the CO_2 may also be short-lived (e.g., carbonated beverages, fertilizer, fuels) where CO_2 quickly returns to the atmosphere, or long-lived (e.g., geological reservoirs, building materials, polymers) where CO_2 is permanently removed from the atmosphere.

To reach net-zero emissions, pathways towards net-neutral and net-removal must be pursued. But market needs must also be met, and source and sink dynamics play a role in pricing. While a standardized price on CO_2 emissions remains elusive, a number of mechanisms are creating a deep market for CO_2 abatement. Emission pricing mechanisms now cover 23% of global emissions,[2] and the market is worth nearly a trillion dollars annually.[3] In the U.S. the 45Q tax credit guarantees $85/tonne for CO_2 captured and stored, and $60/tonne when utilized.[4] The European cap-and-trade scheme and other European schemes price emissions reduction at $60-120/tonne.[2] Internal carbon pricing can exceed even these figures and is being widely deployed to inform key financial decisions. Net-removal of CO_2 is inherently harder, commanding a higher price point of $180/tonne from the air under 45Q,[4] and even higher in voluntary markets.[5]

Global demand for physical CO_2 exceeds 100 million tonnes CO_2 per year ($MtCO_2$/yr) today.[6] Unfortunately, the market is generally for short-lived CO_2 (e.g. food and beverage) and is mostly being sourced from long-lived carbon (e.g. underground), resulting in net emissions to the atmosphere. A change in sourcing strategy could improve the situation, but to scale up from 45 $MtCO_2$/yr capture today,[7] to the 6,000 $MtCO_2$/yr required, a larger sink for CO_2 is critical. Fortunately, a multitude of opportunities exist, including new markets for sustainable fuels and sequestration in saline aquifers.

Ultimately, the lowest-cost path to net-zero emissions will dominate the energy transition and the landscape beyond, but the optimal path will depend on available technology and geography. Projects that cost less than the price of emitting will attract investment, and those that cost much less will generate outsized returns. Mantel can cut the cost of capture by up to 75% compared to conventional approaches, but the use case for the captured CO_2 may vary. Hence, understanding the options for CO_2 transport, utilization, and storage is critical to arriving at a comprehensive strategy for 1) what a representative site will do with a million tonnes of CO_2 per year 2) what 5,800 heavy-industrial U.S. sites will do with 2,840 $MtCO_2$/yr of current emissions **Figure 2**,[8] and 3) what the world will do in 2050 with 6,000 $MtCO_2$/y of captured CO_2.

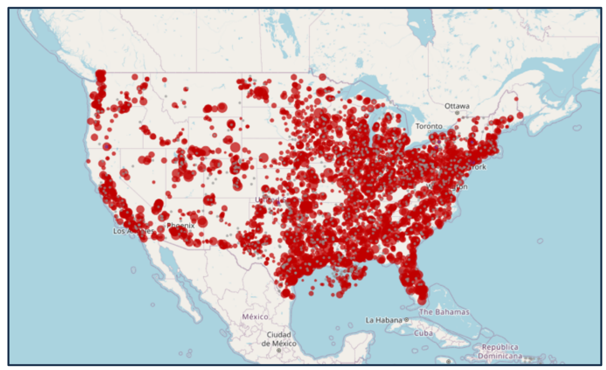


Figure 2. Sources of heavy-industrial emissions in the U.S. today

2. Transport

Moving CO_2 from source to sink can be accomplished by road, rail, ship, pipeline, or a combination thereof. All four modes of CO_2 transport are active today and have built up decades of operational experience. The preferred mode and ultimate cost for a given site being a function of scale, distance, and availability, summarized in **Table 1** and **Figure 3**.

Table 1. Typical features of CO_2 transport modes

CO_2 Transport	**Road**	**Rail**	**Ship**	**Pipeline**
Physical State	Refrigerated Liquid	Refrigerated Liquid	Refrigerated Liquid	Supercritical
Payload	25 tCO_2	100 tCO_2	up to 40,000 tCO_2	N/A
Indirect CO_2 (100 miles)	0.00015% of load	0.00002% of load	0.00002% of load	0.00000% of load
Available Today (US)	99% of sites	58% of sites	12% of sites	7% of sites
Cost (100 miles & 2 Mt/yr)	$18/$tCO_2$	$9/$tCO_2$	$22/$tCO_2$	$4/$tCO_2$

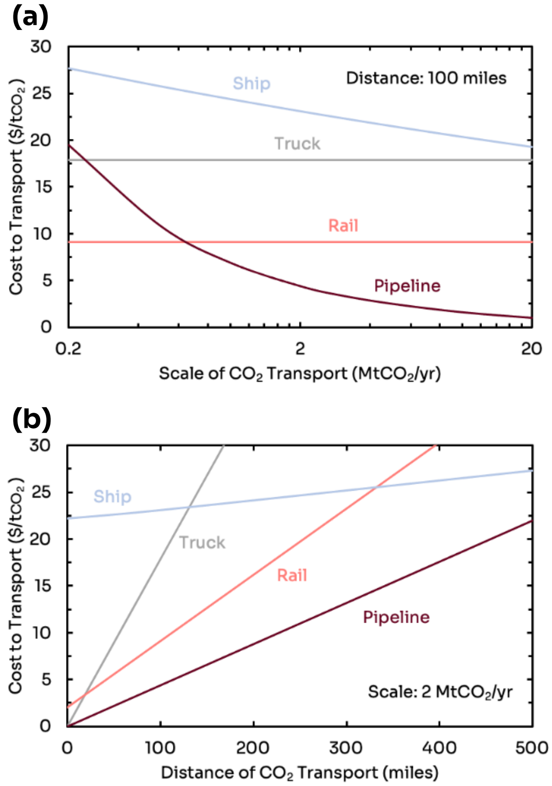


Figure 3. (a) CO_2 transport cost as a function of scale for a fixed distance (100 miles), and **(b)** as a function of distance for a fixed scale (2 $MtCO_2$/yr)

Converting CO_2 from a gas to a liquid reduces its volume by 600x. Therefore, CO_2 is either transported as a refrigerated liquid at modest pressure and low temperatures (e.g. 20 bar, -20°C / 290 psi, -4°F) or as a supercritical fluid at high pressure and ambient temperature (e.g. 150 bar, 15°C / 2,200 psi, 60°F).

Pipelines move CO_2 as a supercritical fluid with compression at the source and minimal infrastructure at the destination. The huge capacity and very low operating costs of CO_2 pipelines make them the ideal option.[9] Pipelines do, however, require upfront investment and the greater their length, the more jurisdictions they pass through, which makes it harder to align all the stakeholders involved in the project.

Fortunately, a network of over 5,000 miles of CO_2 pipelines has already been built, in the U.S.[10] This network, shown in **Figure 4**, passes within 10 miles of 380 sites currently emitting 240 $MtCO_2$/yr (around 8% of heavy industrial emissions in the U.S.). While short 10 mile spur lines connecting local sites to existing trunk lines is straightforward, the required build-out of 65,000 miles of new CO_2 pipelines to connect all sites is more challenging and will take time.[11] Until then other transport modes can unlock ambitious first movers regardless of geography.

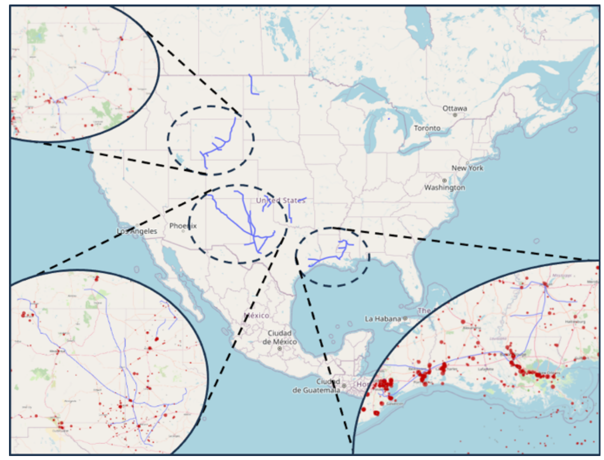


Figure 4. Existing CO_2 pipelines in the U.S. and proximity to emissions sources

Trucks, rail, and ship move CO_2 as a chilled liquid with compression and liquification at the source. The act of transporting CO_2 produces indirect CO_2 emissions and reduces the net amount of CO_2 abated, the mirrored analogy being a fuel truck consuming fuel to transport fuel. But, as with fuel trucks, the impact on a 100-mile journey is exceedingly low, 0.00015% of indirect CO_2 emissions for trucks and nearly 10x less for rail and ship.

CO_2 transport by road is best suited for relatively small amounts where other options are not available.[12, 13] A truck an hour translates to over 0.2 $MtCO_2$/yr, which could be a viable pathway for 75% of U.S. sites emitting 200 $MtCO_2$/yr (7% of U.S. heavy industrial emissions). Minimal upfront investment and the fact that 99% of sites have road access (except for some offshore emitters) means transport via road is particularly attractive for first movers investing in capture technology on the source side, and smaller, often less price sensitive, users on the sink side.

Rail can support larger scales than road transport, with rail servicing up to at least 2 $MtCO_2$/yr at lower operating costs.[14,15] As 58% of U.S. sites are within one mile of the existing rail network, rail could support around 700 $MtCO_2$/yr, accounting for 26% of U.S. heavy industrial emissions. Today, rail moves 28 million carloads of goods a year,[16] but only around 1 $MtCO_2$/yr.[14] The replacement of coal as a freight commodity could unlock 100 $MtCO_2$/yr in rail capacity.[15] A 20% increase in freight capacity – or a return to 2015 freight levels - could handle the remaining 600 $MtCO_2$/yr.

While less common in North America, shipping CO_2 is practiced today in Europe and has rapidly growing interest around the world, particularly Asia. From small 1,000 tonne tankers up to vast 40,000 tonne tankers,[17] international CO_2 transport is not only possible and cost effective but is also an expected pathway for geographies that may be thousands of miles from attractive CO_2 sinks. In the near term, however, offshore pipelines are expected to be lower cost options for shorter distances.[18] In the U.S. 700 sites emitting 470 $MtCO_2$/yr (17% of U.S. heavy industrial emissions) are within 10 miles of an existing port with the option for shipping CO_2 to a site for storage or utilization.

Similar to the transport networks of natural gas and oil that were built in the previous energy transition, the current energy transition will involve a build-out of transport infrastructure across all modes.

Truck and rail will serve to connect isolated sources and sinks to pipelines and ships, all likely coalescing around backbone infrastructure and hubs where billions of tonnes can be moved at exceedingly low cost. Economies of scale support large, coordinated projects with multiple emitters working together; these projects have the co-benefit of reducing barriers to entry for smaller emitters nearby and will be a key feature of the 2050 carbon economy.

However, for many sites a better option is to avoid transport altogether. Sources of CO_2 local to sinks can cut costs and complexity, potentially with CO_2 not even needing to leave the site boundary. To understand this opportunity better requires a deeper dive into the options for CO_2 utilization and storage.

3. Utilization

CO_2 has many uses which can be divided into direct-use and conversion.

Direct-use means using the CO_2 as CO_2, with a wide range of existing markets including Enhanced Oil Recovery (EOR), food and beverage, medical, greenhouses, welding, refrigerants, dry-cleaning, power-cycles, decaffeination, and many more.[6] Other than the more nuanced case of EOR (see aside on EOR), these markets are for short-lived CO_2 where CO_2 shortly returns to the atmosphere.

A note on Enhanced Oil Recovery (EOR)

Today, 70-80% of CO_2 used globally is for Enhanced Oil Recovery (EOR) whereby CO_2, generally from naturally occurring reservoirs of CO_2, is extracted, and transported to an oil field. The injection of CO_2 frees oil inside the pore space and facilitates the extraction of more oil from a depleted reservoir, while permanently storing the CO_2 in the reservoir.

As practiced today, this is a net-emitting activity, although the CO_2 leaving the ground (CO_2 reservoir) then re-enters the ground elsewhere (Oil reservoir) the ultimate combustion of oil results in a net increase in atmospheric CO_2. However, if CO_2 were obtained from a short-lived source (e.g. air, ocean, biomass), a net-neutral outcome with a low-carbon intensity oil product may be possible.

While there are negative attributes to EOR and its future role is uncertain, the practice has resulted in the build-out of thousands of miles of CO_2 pipelines and decades of operational experience handling millions of tonnes of CO_2, all of which will be valuable on the journey towards net-zero.

With 20-30 $MtCO_2$/yr in existing demand (outside of EOR),[6] the current markets for CO_2 utilization, though small individually and relative to the climate challenge, are not so small as to ignore. Bulk CO_2 prices vary from \$10/tCO_2 to over \$400/tCO_2 in small volumes;[19] meeting this demand with more sustainably sourced CO_2 could provide early carbon capture projects with an additional revenue stream that helps the economics of small-scale deployments, particularly those in geographies far from bulk CO_2 markets.

An especially favorable case is one where a site purchases CO_2 but also produces CO_2 (see aside on Mantel's first project).

An alternate use of CO_2 is to convert it into a valuable product; essentially anything that contains the element carbon is an option including but certainly not limited to: fuels, polymers, plastics, foams, resins, diamonds, nanotubes, filler materials, carbonates, solvents, olefins, aromatics, and the rest of organic chemistry to boot. Certainly, a lot of options and not just niche markets. Many of these could in theory consume billions of tonnes of CO_2 every year.

A note on Mantel's first project

Mantel has partnered with a Canadian pulp & paper company, to support ambitious decarbonization goals across multiple sites. Some sites use CO_2 to control pH in the paper making process. The CO_2 reacts to form carbonates which are a stable mineral and constituent in various paper products.

Mantel's first project will capture CO_2 from a steam boiler that powers the site's operations. The system is sized to capture roughly the same amount of CO_2 that the site is currently purchasing, turning a net-emitting process into a net-neutral one, saving the site money on CO_2 purchases and avoiding the cost of CO_2 transport, as well as demonstrating technical performance metrics as a step towards full-scale commercial projects.

Conversion of CO_2 typically requires increasing its energy level, with CO_2 being one of carbon's most stable forms. Increasing CO_2's energy level requires energy input, often coming from the energy carrier hydrogen. The first step is generally to make syngas through the Reverse Water Gas Shift Reaction (RWGS).

$$Syngas: CO_2 + H_2 \rightarrow CO + H_2O$$

Which by further hydrogen addition provides a pathway to a multitude of fuels and chemicals, through Fischer-Tropsch and similar reactions, including methanol, methane, ethylene, gasoline, and other long-chain hydrocarbons. For example:

$$Methanol: CO + 2H_2 \rightarrow CH_3OH$$

$$Methane: CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$Ethylene: 2CO + 4H_2 \rightarrow C_2H_4 + 2H_2O$$

$$Gasoline: 8CO + 17H_2 \rightarrow C_8H_{18} + 8H_2O$$

There is a case for using synthetic fuels as a drop-in replacement for hard-to-decarbonize modes of transport. These fuels represent a potential 1,670 $MtCO_2$/yr use case for captured CO_2 today,[20] enabling both sustainable aviation (780 $MtCO_2$/yr) and shipping (890 $MtCO_2$/yr) to fully decarbonize. Synthetic chemicals including the production of fertilizers, solvents, and plastics add 1,540 $MtCO_2$/yr,[21] through the sustainable production of urea (120 $MtCO_2$/yr), methanol (90 $MtCO_2$/yr), ethylene (420 $MtCO_2$/yr), propylene (270 $MtCO_2$/yr), butylene (250 $MtCO_2$/yr), aromatics (360 $MtCO_2$/yr), and carbon black (40 $MtCO_2$/yr).

With expected growth in aviation, shipping, and primary chemicals through 2050, these use cases will grow by 175%,[22] 112%,[22] and 22%,[23] respectively, providing a potential use for 5,900 $MtCO_2$/yr - a close match to the 6,000 $MtCO_2$/yr of capture needed for net-zero.

As a high-energy molecule hydrogen acts as the energy carrier, while the CO_2 makes it easier to transport and store this energy as a synthetic fuel or chemical. But since 96% of global hydrogen production is derived from hydrocarbons today,[24] (i.e. the reverse of the above reactions), a substantial expansion of clean low-cost energy in the form of hydrogen is necessary.

As an approximation, today's fuel prices provide a guideline for how to eliminate the green premium on synthetic fuels. Assuming conventional fuel production costs of $2.0/gallon ($80/barrel) a pathway from CO_2 and hydrogen requires hydrogen at $0.6/kg, or an electricity price close to zero (i.e. no costs beyond the levelized Capex of a $700/kW electrolyzer at 100% capacity factor).[6]

The price of hydrogen, or electricity for electrolysis, to produce synthetic fuels at large scales, for a certain cost is estimated in

Figure 5 as a function of CO_2 price.[25,26] Negative numbers implying the CO_2 capturer will pay the utilizer to take the CO_2, perhaps to avoid the cost of transport and storage. However, in the U.S. with 45Q tax credits worth \$25/tCO_2 less when the CO_2 is utilized vs. stored, the utilizer is more likely to pay the capturer. Also, transport costs may remain as the ease of handling CO_2 will result in it being moved to sources of clean energy, instead of the other way around.

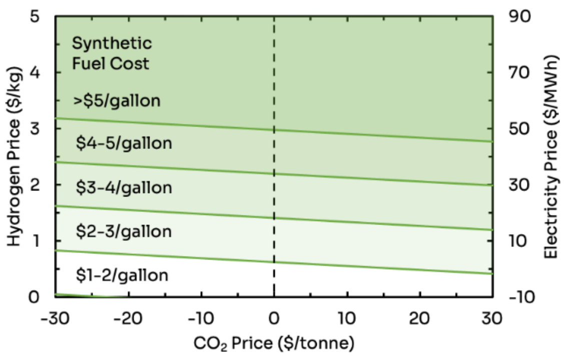


Figure 5. Cost of synthetic fuels with hydrogen, electricity, and CO_2 prices

A premium for sustainably produced fuels and chemicals dramatically improves the economics of CO_2 conversion, and the low sensitivity on CO_2 price makes it possible for utilizers to pay, rather than be paid, for the CO_2 they need. Consumers of synthetic fuels have few attractive decarbonization pathways and are under significant pressure to find a solution. High premiums are therefore not unrealistic, creating an opportunity to drive up top-line revenue on CO_2 capture projects by selling to utilizers rather than paying for storage.

Alternatively, to avoid large energy requirements, one option for conversion is to find pathways that lower CO_2's energy level (i.e. do not require energy input) rather. Making and selling carbonates is a good example to consider. Since carbonates are a very stable form of CO_2; over millions of years CO_2 in the atmosphere has produced an abundance of carbonates at Earth's surface. Therefore, many natural resources are extracted as carbonates and processed to make more valuable materials, such as the extraction of limestone (calcium carbonate) to make lime (calcium oxide), the key ingredient in cement.

$$Lime: CaCO_3 \rightarrow CaO + CO_2$$

Cement is then mixed with other materials to make concrete. However, before the concrete sets, there is an opportunity to 'cure' the concrete with CO_2 by injecting CO_2 such that some CO_2 reforms carbonates, reversing the above reaction. When used in this way CO_2 acts as a filler material, adding bulk to the concrete, and potentially improving the concrete's properties,[6] while also permanently trapping the CO_2.

CO_2-Curing today's global cement production could provide a sink for 1,000 MtCO_2/yr,[27] growing to 1,200 MtCO_2/yr in the future. The need to transport CO_2 to many disparate sites and conservative building regulations present challenges the low energy requirements and potential value-add of using CO_2 in this way is likely to result in a higher willingness to pay for CO_2.

Although most carbonates near the Earth's surface have already formed through the reaction with CO_2 in the air, below the Earth's surface is a different story, and there is enormous potential to store CO_2 deep underground.

4. Storage

CO_2 can be stored underground in the same geological formations that have kept the CO_2 out of the atmosphere for millions of years. Additionally, an even larger storage resource is Deep Saline Aquifers - large expanses of porous rock and salty water that can soak up CO_2.[18]

Using techniques and equipment from the oil and gas industry, supercritical CO_2 is injected into a well until the reservoir is full and the well is capped. At first the CO_2 is physically trapped below an impermeable layer of rock but over a period of years the CO_2 dissolves into the salty water, causing the dense liquid to sink into the base of the formation. Over hundreds of years the dissolved CO_2 slowly reacts with the rock to form carbonates. This mineralization process locks away CO_2 for millions of years.

Poorly capped wells, weakly characterized reservoirs, and other errors can lead to CO_2 leaks which require near-term monitoring, but the mechanisms involved provide high assurances around permanence. Multiple projects globally have been sequestering CO_2 in geological formations at a rate of 8 $MtCO_2$/yr for many years.[28]

Global sequestration resources have a total capacity to store between 8,000 and 55,000 $GtCO_2$,[29] over 1,000 and up to almost 10,000 years of storage capacity for the expected volumes of captured CO_2 needed to reach, and sustain, net-zero emissions.

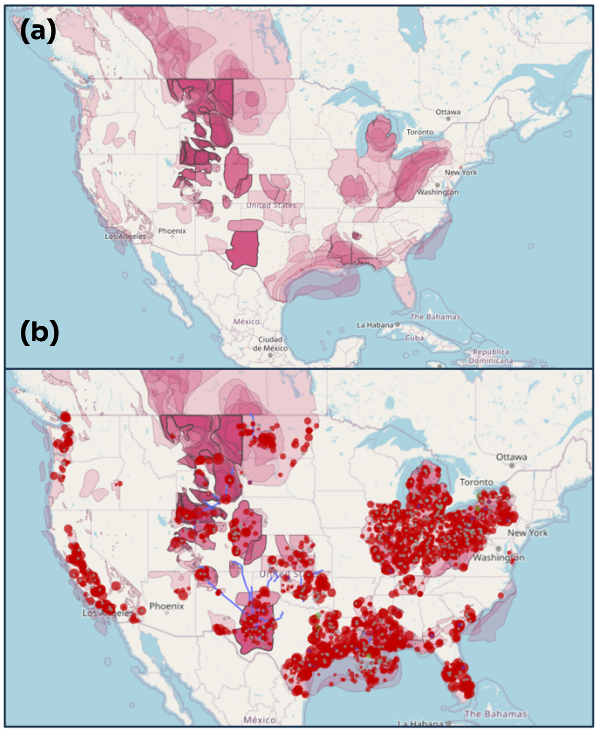


Figure 6. (a) Favorable sequestration geology in U.S. (darker shade indicates deeper reservoir) **(b)** with local site overlay

Not only are storage resources vast, but they are also geographically distributed around the world and in North America, **Figure 6**. In the U.S. 54% of sites are located directly above favorable CO_2 geology with the capacity to store 500 to 4,000 $GtCO_2$.[29] Depending on the availability of other options, U.S. emitters representing over 1,650 $MtCO_2$/yr, or 58% of emissions, may have the option drill locally and avoid the cost of CO_2 transport.

In the U.S. the federal government has been slow to approve permits for sequestering CO_2 into geological formations (Class VI wells), with a backlog over 160 projects and a 6 year timeline.[30, 31] Although the EPA is now equipped to approve permits in under 2 years,[32] some projects are making use of the much faster process of approving CO_2 injection into oil and gas reservoirs (Class II wells) while waiting for permit approvals.[33]

Many states are expediting the process by taking over permitting control. Notably, North Dakota and Wyoming have cut the process to less than 10 months,[34] and Louisiana, where one third of pending permits reside, recently received primacy.[35] Many other states, including Texas, West Virginia, and Arizona are in the process of obtaining primacy.[35] While permitting has proven to be a bottleneck in the near term, the longer term outlook is promising.

Industrial clusters and CO_2 hubs sharing infrastructure to achieve economies of scale makes local storage practical. At several million dollars to drill an injection well and minimal operating expenses, the cost of CO_2 storage can be exceedingly low on a $/$tCO_2$ basis. While there is a technical opportunity to re-use existing infrastructure from well-characterized depleted oil and gas reservoirs, the added cost of using aged equipment may only modestly impact cost.[9]

The main factors that drive cost are geological (depth, permeability, thickness) and the scale of the operation, **Figure 7**. The volume-weighted average cost across a range of U.S. regions is $8/$tCO_2$,[9] sufficiently low that storage local to the source of capture is expected to become widespread.

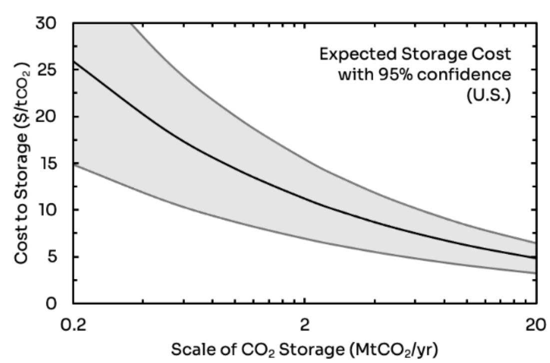


Figure 7. CO_2 storage cost as a function of scale and uncertainty due to geological considerations

5. Putting it all together

Accounting for all the various pathways, 95% of sites and 74% of heavy-industrial emissions in the U.S. have a clear, practical, and cost-effective pathway to handle their current level of CO_2 emissions with existing infrastructure. 100% of sites have a long-term pathway through the build-out of CO_2 pipeline networks, which will be the lowest cost path for all but the smallest emission sources. While utilization opportunities could technically meet every site's needs, the economics support moving the CO_2 to where clean energy is cheapest.

Transport costs are a function of scale and distance but for most emissions a range of \$0-20/tCO_2 is expected. With storage costing \$5-20/tCO_2, the total for transport and storage is \$5-40/tCO_2 with a weighted average around \$15/tCO_2. Shared pipelines and wells hold the potential to bring these costs down further to the range \$5-15/tCO_2.

Both near-term and long-term utilization opportunities could offset these costs, or justify the cost of transport, and add to top-line revenue beyond the financial benefit of decarbonizing. With a revenue of \$85/tCO_2 in the US, the available margin for the capture step is \$40-80/tCO_2 in the near-term and \$70-80/tCO_2 in the long-term. Since most conventional carbon capture technologies cannot hit this cost point, it is no surprise that few projects have been commercially successful without further support. By slashing the cost of capture 50-75%, Mantel makes it profitable to abate over 60% of these emissions with existing incentives, not only for the best positioned sites but for a majority of U.S. sites.

Of the expected 6,000 MtCO_2/yr captured in 2050, it's anticipated that the majority will be either stored in saline aquifers, permanently trapping CO_2 deep underground, or, with abundant clean energy, demanded by producers of synthetic fuels and chemicals. In the nearer term, utilization opportunities are small but can provide pathways for initial projects and first movers to scale-up, de-risk, and rise to the challenge of net-zero by 2050. But ultimately carbon capture projects must be profitable to attract investment, and here Mantel's technology will play a pivotal enabling role.

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