DAC + BAC
A Diversified Approach to Carbon Removal

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February 2022

BAMCORE®

Graphical Summary

	DAC  Chemical Direct Air Capture	BAC  Bamboo Direct Air Capture	WOOD  Wood Forestation
Timing - Deployment	Not production ready	Immediate	Immediate
Timing - Scaling	Through 2050	Ready now, Scalable 5 to 7 years	Ready now, Scalable 15 to 40 years
Technology Risk	High	None	None
Cost/t CO_2	High	Lowest	Low
Land Requirement	Low	Medium	High
Location Constraints	Best in clean air, but other wise global	Tropic & Subtropics	Global
Measurability of Capture	High	High	Low
Circularity - Reuse	Limited	High reuse of building products	Medium to high reuse of building products
Externalities	Neutral to negative	Positive	Neutral to positive

Best OK Undesirable

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Summary

Increasing concern about climate change is driving new government subsidies and private investment in geoengineering technologies that target removing existing CO_2 from the atmosphere. The leading approach, Direct Air Capture (DAC), captures atmospheric CO_2 in a process that is frequently compared to photosynthesis. The captured CO_2 is expected to be stored, most likely underground in depleted oil fields. To reach the needed large and cost-effective scale, DAC could require decades to deploy, investment in excess of $10 trillion and consume as much as one-quarter of all global electricity produced to operate. Trees and especially timber bamboo are the most powerful natural photosynthetic engines on land. When timber bamboo captures CO_2 and the resulting biomass is stored in long term building frames and other durable products, it creates a Bamboo Air Capture (BAC) and CO_2 storage system. BAC complements DAC by offering a ready-to-scale, lower cost solution with many positive externalities. To respond effectively to climate change, we need to employ all available approaches as soon as possible, including nature-based systems like BAC and forestation. Here, we compare DAC and BAC along multiple dimensions to highlight the benefits of diversifying carbon removal approaches to include DAC + BAC.

A. Introduction: DAC + BAC

As 2022 begins, there is broad agreement that to fight climate change humanity must reduce emissions AND **remove carbon already in the atmosphere**. The approaches to removing carbon fall into two groups, geoengineering and nature-based. Removing the amount of atmospheric carbon needed, will require most known removal approaches to be scaled to their feasible limits as soon as practicable.[1] Direct Air Capture ("DAC") is a geoengineering approach that will capture CO_2 that is already in the atmosphere. DAC is only a developing technology that conceptually extends the broader category of Carbon Capture Utilization and/or Storage (CCUS) technologies. CCUS focuses on capturing emissions at the point of initial emission (power plants and industrial facilities) before the CO2 is released to the atmosphere, while DAC captures previously emitted CO2 from the atmosphere. The US Government has been subsidizing CCUS research and development since at least 1997.

Today, recognizing the need to remove CO_2 already in the atmosphere, DAC is quickly garnering venture investment funding and large public research subsidies. The 14 companies directly pursuing DAC, or its dependent technologies have raised just under $600 million in venture funding. From public sources, the *Infrastructure Investment and Jobs Act*, which became US law in November 2021, committed $3.5 billion for four pre-commercial regional DAC hubs along with nearly $5 billion for developing and financing captured CO_2 transport and storage. In Europe, the $1.3 billion EU Innovation Fund will also be financing 2 DAC projects.

Unfortunately, neither DAC nor any of the geotechnical approaches are proven technologies, cost effective, nor ready-to-scale today. Thus, large public subsidies are now being applied to accelerate their development. In 2019, 32 authors in a US National Academy of Sciences report argued that nature-based approaches are already proven technologies, cost effective, and ready to scale.[2] Borrowing from this confidence, the opening sentence of a March 2021 US DOE announcement for a DAC design grant suggests that DAC mimics nature *"replicating the way plants and trees absorb carbon dioxide."*[3] Further, one of the early low carbon ventures backed by the oil industry asserts the parallel to nature as part of the justification for investing in DAC, *"Similar to how trees absorb CO_2 for photosynthesis, DAC pulls air into its systems and, through a series of chemical reactions, extracts CO_2."*[4] Among the nature-based solutions already using actual photosynthesis to remove atmospheric CO_2 is the annual **carbon farming now being done with timber bamboo.** Because of the process parallels with DAC (presented below), we call this **nature-based system "Bamboo Air Capture", or BAC.** BAC is an immediately available solution that complements the longer term hopes of DAC development while avoiding some of the criticisms directed at both DAC and forestation with trees.

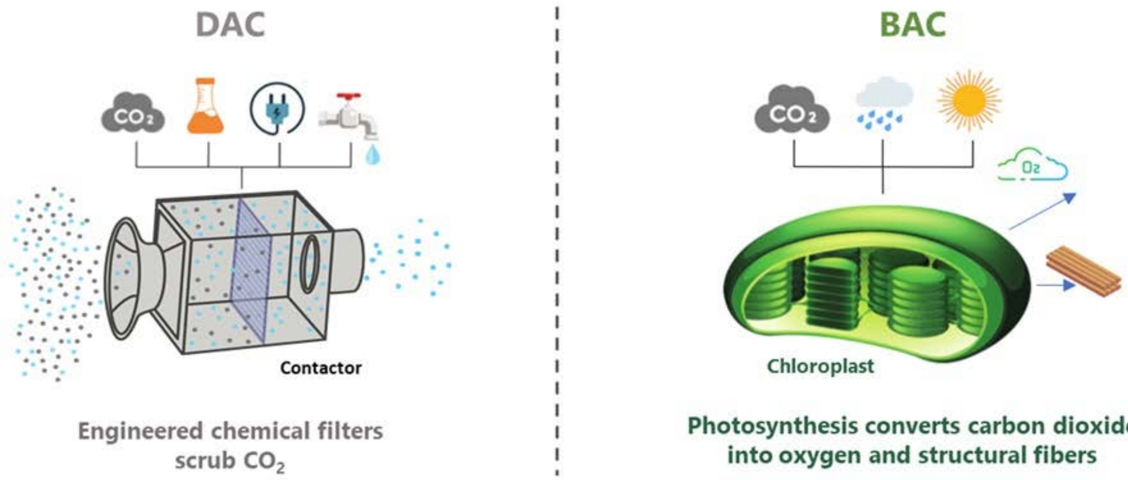
BAC and DAC share four parallel stages: (1) capturing CO_2 already in the atmosphere, (2) converting the CO_2 chemically, (3) transforming it to a new form that (4) can be used in products with long service lives or durably stored out of the atmosphere. Figure 1 illustrates the DAC and BAC parallels across these four stages. In the following, we compare DAC and BAC and find that **bio-based BAC is a lower cost, ready to scale complement**, which when seen with DAC provides an urgently needed diversified approach to atmospheric carbon removal.

A. Operating Stage Parallels

1. Capture. DAC: In absolute terms, atmospheric CO_2 is only a small fraction of the atmospheric gases, ~0.04% (400 ppm). For a DAC facility to capture CO_2 it must move enormous volumes of air through a chemical contactor; thus, large banks of fans are required to funnel air through the contactors.

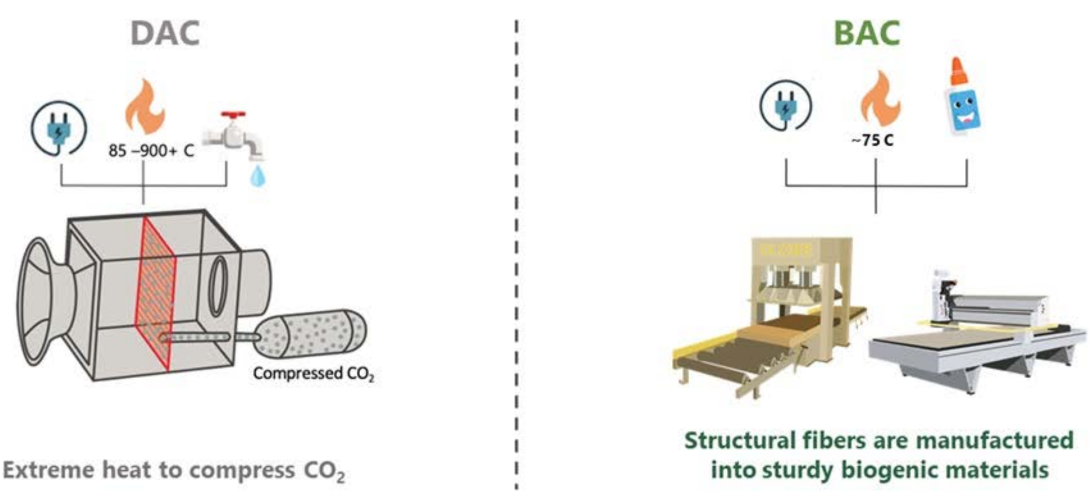
BAC: As a grass, timber bamboo grows from an underground rhizome that has already stored most of the nutrients and energy the stalk (also called culm) needs to grow into its full height in the next growing season of only 6-8 months. Since bamboos evolved in dense forests, they are genetically programmed to **sprint to their full height in a single growing season** to reach the sunshine at the top of the forest canopy. In contrast to slower-growing trees, they do not increase their diameter (only their height) and they spend little energy to add stems and leaves, which appear mostly in the upper portions of the culm as it reaches its full height.

2. Conversion. DAC: Early approaches to DAC favor one of two approaches to CO_2 capture either liquid solvents or solid sorbents (illustrated below). CO_2 is a rather non-reactive molecule that takes considerable energy and proximity to caustic chemicals to be scrubbed out of the air. Emission from the DAC is the same air that the DAC takes in only with a portion of the CO_2 removed. Both technologies are under development, while other technologies are also being explored.



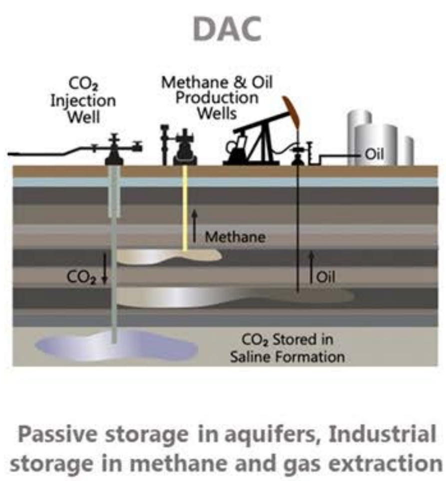
BAC: Timber bamboo absorbs CO_2 passively from the ambient air, combines it with water and uses sunshine to power a metabolic reaction that makes 6-carbon sugar substrates that become the backbone of bamboo's structural fiber. **Photosynthesis is one of nature's most fundamental technologies and has been evolving for nearly 3.5 billion years.** The site of photosynthesis in today's plants is the chloroplast, which itself evolved more than 1 billion years ago. The **main outputs of BAC are oxygen and the plant's super strong structural fibers.**

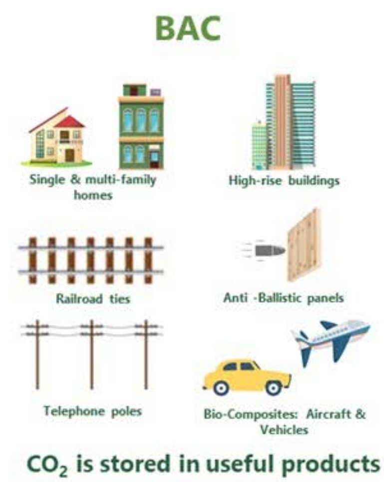
3. Transformation. DAC: Having bound the atmospheric CO_2, the process must be reversed to concentrate the CO_2 for use or storage. The process of unbinding the CO_2 and compressing it is energy intensive and thus expensive. Solid sorbent technology can use waste heat from contiguous industrial or natural sources or use dedicated power generation. Liquid solvents require much more heat, which is best provided by burning natural gas. The released but concentrated CO_2 will be compressed to over 1000 psi so that it can be transported by pipeline or truck to a use or a storage location.



BAC: The bamboo's metabolic processes transform the captured CO_2 into **extremely strong bamboo culms ready for further transformation into durable goods**. There are two general approaches to processing the culms. The first approach sections the culm preserving the longitudinal fiber alignment and glues them into layers that can be pressed into panels, boards, and beams. The second approach flattens or crushes the fibers into a mat and presses the fibers with glue into a large block that can be cut into multiple shapes. Each approach has advantages.

4. Storage. DAC: The compressed CO_2 can be delivered by pipeline or truck to its intended use or storage location. The largest prospective use of CO_2 is to enhance crude oil and methane recovery in depleted oil and gas fields (EOR), where the injection of pressurized CO_2 facilitates the extraction of the remaining hydrocarbons. CO_2 not used in EOR can also be injected in underground saline aquifers for long-term storage or possibly made into synthetic fuels or other products. To minimize the delivered cost of the CO_2, many analysts expect DAC plants to be located directly in depleted oil and gas fields.





BAC: **Bamboo's resulting structural fibers can be fabricated to a wide range of usable products,** including low and high-rise building frames & floors, railroad cross ties, utility poles, anti-ballistic panels, various bio-composites and more. Depending on the use location of the product, the fabrication can occur near harvest origin, but may also require oceanic shipping to reach its final location.

Beyond the above processing parallels, there are valuable diversifying differences between DAC and BAC. These differences can be seen by comparing the projected requirements to establish or build-out, the resulting operating costs, the final use and storage options, the ability to scale and the attendant externalities of DAC and BAC. In the following, to review the diversifying benefits of DAC and BAC for carbon removal, we assume an operating unit (DAC plant or BAC plantation) that removes 1 Megaton (Mt) of CO_2 annually.

B. Establishment Cost

DAC: Three rounds of capital expenditures (Capex) are required to build-out a full Direct Air Capture and Storage system: the DAC facility, the pipeline for transit to storage, and final storage or use infrastructure. However, since the largest use and storage for DAC captured CO_2 is expected to be in depleted oil and gas fields for Enhanced Oil Recovery (EOR), we exclude transport and storage Capex, which already exists in the depleted fields. The estimate for early DAC facilities is $1.13 billion and for a fully scaled steady state plant is ~$780 million, each for 1 Mt CO_2/yr.

DAC		BAC	
$1,130,000,000	Keith[5] (first of a kind)	$54,000,000	BamCore (Latin America)
$780,000,000	Keith[5] (later stage, n^{th} plant)	$180,000,000	BamCore (Southern US)

BAC: The cost to buy and establish a BAC plantation varies primarily based on location. For 1 Mt CO_2 removal, a BAC plantation in Latin America would cost ~$54 million, suggesting that a **comparable size CO_2 removal BAC plantation costs ~1/20th the cost of an early DAC plant** and 1/14th the cost of a late-stage DAC plant, both without transport and storage infrastructure. If the BAC plantation were established in the Southern US, the cost would increase to around $180 million or about 1⁄6th of an early DAC plant and a little more than ¼ of a late-stage DAC plant.

C. Land Area Required

DAC: Land area required for DAC plants includes the area needed for the plant and area for the energy source, especially if dependent on renewable solar or wind. A DAC plant powered by solar will require nearly 2500 Ha, the majority of which is for the photovoltaic arrays. Powering the DAC plant with natural gas can lower the area required to just over 800 Ha. Two drivers will influence specific location. DAC processing is more efficient when the air is pristine, thus the Climeworks DAC first location in Iceland. But storage costs post-capture will lead to locations close to underground storage and especially toward EOR opportunities in depleted oil fields as seen in the CarbonEngineering DAC plant being planned for the Permian Basis in West Texas.

DAC		BAC	
2450 Ha	WRI[6] (solid sorbent w/ solar)	86,200 Ha	WRI[6] (generic wood forestry)
810 Ha	WRI[6] (solid sorbent w/ natural gas)	9,978 Ha	BamCore (harvested bamboo plantation)

BAC: In contrast, land area to capture 1 Mt CO_2 annually from timber bamboo would be nearly 10,000 Ha, indicating a **BAC plantation will require four times the land required for a solar powered DAC.** While this might sound like a lot of land, it is quite small compared to typical forestry projects. For example, Weyerhaeuser Co. owns or controls nearly 4.5 million Ha of timberland in the US and Canada, thus a BAC plantation would be less than 1/450th of Weyerhaeuser's holdings. Moreover, in early 2021, in a single transaction, Weyerhaeuser sold over 58,000 Ha, or nearly 6 times the amount of BAC required land.[7] Latitude and rainfall will be the primary drivers of specific locations for BAC operations. While some timber bamboos grow into the temperate latitudes, the majority of the faster growing species grow best in the low latitudes of the tropics and subtropics.

D. Operating Cost

DAC: Because there are fewer than 20 DAC installations worldwide, most of which are small pilots, projections of operating costs vary widely. The closer to presumed full scale operations, the more the projections depend on the rate of technology "learning." Current cost estimates range between $500 and $700/t of CO_2 removed. For fully scaled costs the estimate varies greatly. For the 2050 horizon, most projections suggest that cost/t of CO_2 will range between $107 to $550. Though at least one optimistic projection foresees costs as low as $32 to $54/t. DAC is an energy expensive process, and the assumed energy source is a critical assumption that impacts cost. Moreover, if the energy source is itself carbon laden, the net carbon removed during capture will decline. The presence of air pollution also increases operating costs materially by accelerating the degradation of the solid sorbent if the pollutants are not pre-filtered from the air flow.[8]

The opinions about the projected DAC operating costs vary even more than the actual estimates themselves. For example, staff members of the International Energy Agency assert, *"In pursuit of net zero, we cannot afford to dismiss CCUS [the legacy technology leading to DAC] as 'too expensive' [no matter the cost]."*[9] Meanwhile, the head of Stanford's Atmosphere/Energy program comments, *"They just make up numbers. They are not atmospheric scientists trying to do this. They're just people trying to make money, and they're giving you nonsense."*[10]

DAC			BAC & General Forests	
$430 - $550	Socolow[11] (optimistic, realistic)		$5 - $100	Sathaye[14] (tropic/temperate wood, current)
$220 - $690	McQueen[1] (levelized costs)		$2 - $51	Sohngen[15] (tropic wood, current)
$94 - $232	Keith[5] (levelized costs)		$20 - $50	Busch[16] (tropic, avoided wood deforestation current)
$107 - $249	Socolow[11] (using Keith assumptions)		$41	Chu[17] (low value wood plantation, global, current)
$700	Sustaera[12] (2023 costs)		$31	Chu[17] (med. value wood plantation global current)
$78	Sustaera[12] (2027 costs)		$19	Chu[17] (high value wood plantation global, current)
$60 - $105	Fasihi[13] (2030 costs)		$5 - $9	BamCore (Latin America bamboo 2023)
$32 - $54	Fasihi[13] (2050 costs)		$0 - $9	BamCore (worldwide, bamboo 2030)

BAC: Cost projections for BAC CO_2 removal are at the lowest end of the nature-based solutions. Based on sub-scale operations already established in Latin American, projected **BAC costs to remove a ton of CO_2 are a small fraction of DAC costs, starting at $5-$9 in 2023** and then falling to $0-$9 by 2030, as scaling increases. Surveys of traditional wood forest sequestration carbon capture generally range from $11 to $50/ton, still below the low end of fully scaled DAC estimates, but require much more land and time than either DAC or BAC.

The operating costs discussed above cover only the removal of atmospheric CO_2. The cost or profit (if any) from the use or storage of the captured CO_2 has to be considered separately based on the specific use or method of storage.

E. Use and Storage

DAC: Today, CO_2, as an industrial gas or as dry ice, has many industrial uses, which are based in part on the purity of the gas. According to the International Energy Agency (IEA), the 2020 global production of CO_2 was about 250 Mt, 91% of which was used in EOR and fertilizer manufacturing, with remaining uses in beverages (3%), food (3%), metal fabrication (2%) and more.[18] The projected need for fully scaled global DAC CO_2 production, starting in 2050, are often stated in the range of 15,000 Mt CO_2. This would produce 60X more CO_2 than is currently consumed worldwide, suggesting a significant supply-demand rebalancing. Today's actual cost of CO_2 extracted from natural sources is a small fraction of the projected costs for DAC extraction. Thus, the development of new high value uses, and storage is critical to make DAC financially viable. In the table below, we show many of the current and prospective uses for captured CO_2 as well as an assessment of the level of the climate benefits deriving from the use or storage.

The question remains if the cost to produce DAC CO_2 can reach break-even or profitability without public subsidies and without radical new volumes of demand for the captured CO_2. There are existing US subsidies under IRS Section 45Q of $50/t and $35/t for permanent underground saline aquifer storage and EOR storage. In the pending US *Build Back Better* legislation, these subsidies increase to $180/t and $130/t. Noting the above estimates for the high operating costs of DAC CO_2/t, these public subsidies could prove vital to the early development of DAC. Beyond the subsidies, EOR is likely the most expandable demand source, assuming it remains desirable to expand the extraction of underground oil and gas at that point in the future. Geological analysis indicates sufficient underground storage capacity, assuming there is no resistance from local populations for underground CO_2 storage in their proximity.[19] The US Dept. of Energy has estimated EOR can extract as much as 67 billion barrels of oil at the cost of $85 or less. If this is so, subsidies and EOR CO_2 use can bring DAC CO_2 extraction toward breakeven. The development of synthetic fuels and concrete replacements is also possible if they are cost effective. Currently, there are no known subsidies for supplying low carbon materials from BAC CO_2 to the building sector. To quantify the projected usage of a 1 Mt DAC plant, we estimate that 1 Mt of CO_2 could drive the release of ~2.5 million barrels of oil, which would be the equivalent of fueling 10,000 average passenger cars for 123,000 miles each and 1000 buses for 190,000 miles each.[20,21]

DAC (IEA[19])		BAC	
Benefits		Benefits	
High	**Build materials** (CO_2-cured concrete, aggregates)	High	**Building materials** (Frames, floors)
Medium - High	**Solvents** (Enhanced oil recovery, dry cleaning, decaffeination)	Medium	**Infrastructure** (Utility poles, railway ties, bridges)
Medium	**Fuels** (Methane, methanol, gasoline, diesel/ aviation fuel)	Medium	**Bio composites** (vehicles, aviation, plastics)
Low	**Polymers**	Low	**Antiballistic materials**
Low	**Ag Yield-boosting** (Greenhouses, algae, urea/fertilizer)	Low	**Furniture**
Low	**Existing direct uses** (Food, beverages, welding, medical)	Low	**Household durables**

BAC: CO_2 captured via bamboo plantations does not have to be buried in the ground to store it out of the atmosphere. Rather, the unusual strength of bamboo fiber lends itself to **a number of societally beneficial durable products, including next-generation engineered structural building materials that can reduce the need for high carbon content steel and concrete while also lowering dependence on wood**. There are also multiple industrial uses of bamboo fiber, such as replacements for hardwoods or chemically treated woods in utility poles and railway ties, as densified composites for anti-ballistic and storm-resistant walls and shelters and as replacements for petrochemicals in new light weight bio-composites for vehicles and planes. In these various uses and more, as timber bamboo substitutes for wood, bamboo's faster growth and denser production helps to limit the harvesting of slow-maturing wood forests which are continuing to remove atmospheric CO_2.

If bamboo captured CO_2 had no societally beneficial uses, it could still be buried in the ground either directly in anaerobic landfills where, like wood, it degrades extremely slowly or as biochar where it remains elemental carbon for centuries.[22,23] Biochar is slowly being adopted in the agricultural sector to improve soil quality and agricultural outputs. Further, as Bioenergy with Carbon Capture and Store (BECCS) is developed, this too can be a use and store opportunity for BAC CO_2.

To quantify the projected usage of a 1Mt BAC plantation, we estimate the converted CO_2 can be transformed into a new generation of hybrid bamboo-wood building panels that can drive the vertical framing of over 31,000, 1500 sq ft, housing units, annually.

G. Ability to Scale

DAC: The main limitations to scaling DAC will likely be achieving low unit-operating costs over time and the disposition of the captured CO_2 if not used in EOR. As mentioned above, several climate analysts project a need for at least 15,000 Mt of DAC CO_2 annually. If one average scale DAC facility in the future is capturing 1 Mt of CO_2 annually, 15,000 such plants would be needed. This is 50% more than the 10,000 coal powered generation plants operating in the world today[24] and about half of the total number of jet aircraft manufactured globally between 1958 to 2007.[25] Even with public subsidies or unexpectedly profitable operations, the impact of this scale is large and construction costs could exceed $10 trillion. Relative to operating energy consumption, ultimately, thermodynamics and the renewability of the energy source will dictate DAC's carbon removal efficiencies. One analysis concludes that at most 57% to as little as 6% of the CO_2 captured is net stored long term.[26] With some analysts suggesting the operating **DAC at this scale could consume as much as one-quarter of global energy production.[16]** However large the need and however economical the technology, decades are still needed to scale to the levels that are called for. And it is undetermined who will pay for this yet-to-be profitable technology to help draw down atmospheric CO_2.

BAC: The main limitations to scaling BAC will likely be initial hesitancies about the amount of land required (even though, due to the efficiency of bamboo's growth, it requires only a fifth of what wood needs) and concerns about preserving biodiversity. Both are important concerns. Relative to land use, estimates of deforested or already disturbed land range from 350 million to 1.75 billion hectares globally.[27]. **In the tropics and subtropics where much timber bamboo is native, there are 500 million hectares of degraded land that could be partially or fully remediated through replanting with timber bamboo**.[28] Relative to biodiversity, it is important to contrast managed wood plantations with managed bamboo plantations. Most building timber comes from stands that are clear-cut or nearly clear-cut during harvest imposing unavoidable ecological damage and loss of biodiversity. Clearing cutting is a commercial necessity because replacement saplings do not re-establish well in the undercover of existing forest canopies. In contrast, timber bamboo is never clear-cut, usually ~20-25% of a clump is harvested annually, leaving the canopy and floor intact. There are no perfect solutions, but relative to wood as an important source of structural fiber, **timber bamboo will use less land, preserve biodiversity better and produce needed carbon-storing structural fiber far faster.** When compared to geoengineering alternatives like DAC, the technologies to use and store BAC CO_2 are far more established and ready to scale.

H. Externalities

DAC: Assuming DAC can be scaled to reduce atmospheric carbon, it will still face two negative externalities. First, the more successfully DAC removes atmospheric CO_2, the more oil, gas, and likely coal will be burned for energy. This generates more air pollution, which is a serious and rising problem today in China, India, and throughout the global south. Reducing air pollution is a separate but considerable expense from the cost of DAC operations reducing just atmospheric CO_2. Second, at the scale contemplated, DAC will generate large amounts of chemical pollutants from the manufacturing, maintenance, and replacement of the contactor and sorbent materials.

BAC: Broadly, **BAC can provide material, positive environmental, and social externalities**. Environmentally, bamboo is known to provide erosion-resisting windbreaks around cultivated fields, stabilize deforested or degraded hillsides, restore degraded riparian banks and corridors and provide phytoremediation soils laden with heavy metals like mine tailings. Socially, the commercialization of timber bamboo through BAC can provide expanded employment for lower-skilled labor both in the country of origin and in the country of use.

I. The DAC Paradox

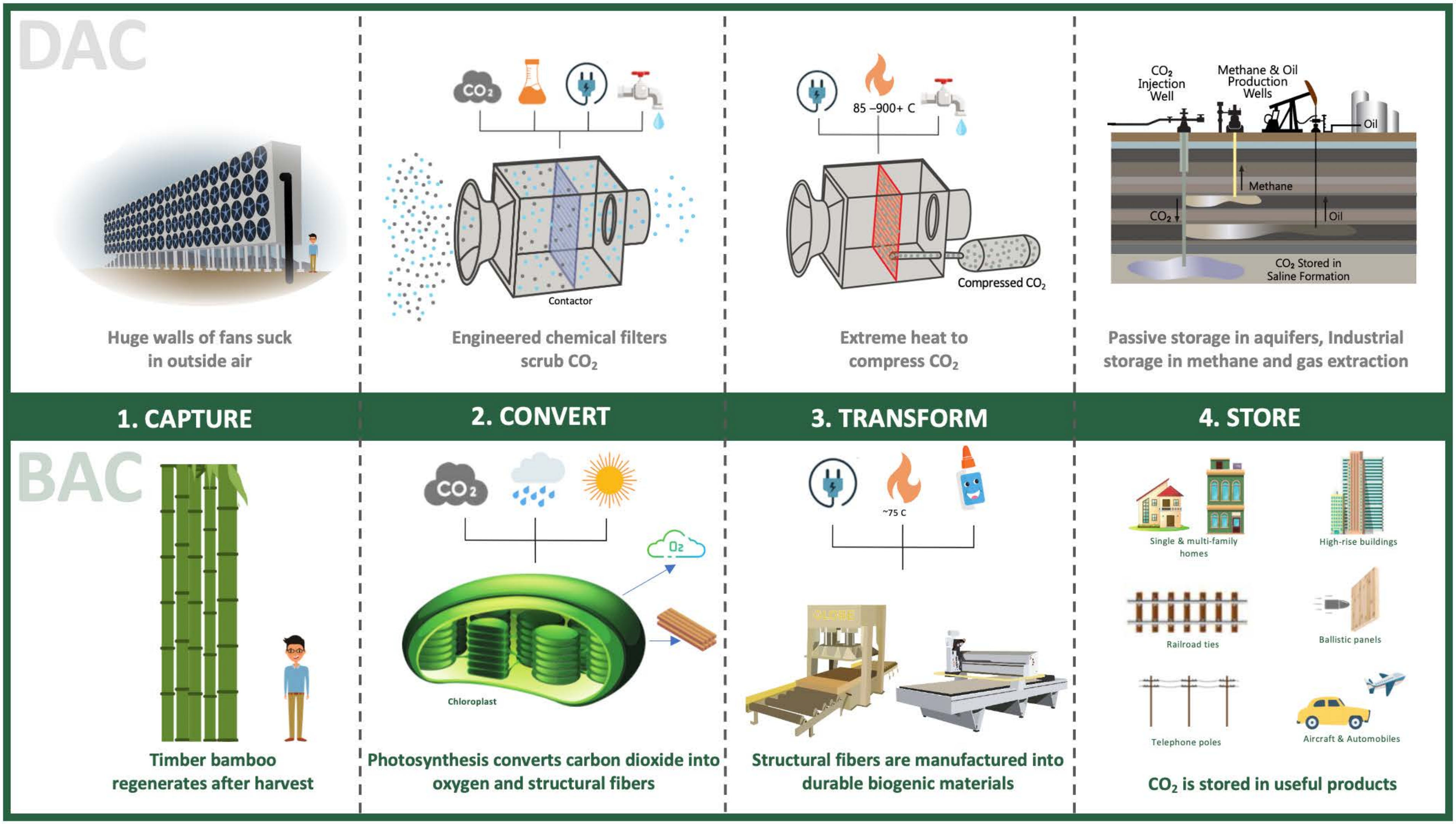
DAC is most economical in conjunction with EOR storage, which presents an environmental paradox. On one hand, DAC CO_2 in EOR allows for crude oil with a lighter carbon footprint than conventional extraction, possibly to the point of being "carbon negative oil." Given that humanity still needs oil for the foreseeable future, this is seen as a desirable outcome by the IEA and others.[29] On the other hand, the more DAC CO_2 is used in EOR, the lower the cost of oil and gas production, encouraging further use of CO_2-heavy petroleum products and the generation of non-CO_2 air pollution. Some analysts see DAC CO_2 in EOR as illusory and argue against it, saying that we are just giving ourselves a "get-out-of-jail-free" card for our continued dependence on oil and gas. This paradox resolves itself when the cost of renewable energy is low enough to drive out the continued use of oil and gas. Is the continued demand for oil and gas, exactly the evidence that shows renewables are not fully cost effective yet thus pushing us back to DAC CO_2 and the other unproven geotechnical carbon removal approaches?

J. Conclusion

Climate change could be an existential threat. A rational response to such a threat follows Pascal's wager and responds to the climate change threat as though it is indeed a reality, without dallying to see if it is. This approach brings all feasible options into consideration. DAC is now being researched and approached as though it is humankind's Hail Mary pass to prevent defeat by climate change. Here, we have argued that the use of timber bamboo in a bio-based BAC framework can complement the opportunity while also diversifying the risk faced with DAC by providing a parallel air capture option. **BAC can begin and scale sooner, has less technology deployment risk, is less expensive to operate, has far smaller relative energy requirements, provides the co-benefits of greener buildings and other needed products, and likely has a better externality profile.**

DIRECT AIR CARBON CAPTURE COMPARISON

Industrial Chemical vs. Timber Bamboo



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