Nature based solutions and their success in Climate Tech

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Abstract

Since the start of the industrial revolution, anthropogenic activities have increased the atmospheric concentration of carbon dioxide, leading to catastrophic changes to Earth's ecosystem and human lives. In order to stop further climatic damage, humans need to drastically stop emitting CO2 into the atmosphere by decarbonizing all industries. Decarbonization however is not enough to keep the Earth's temperature below 1.5°C and we additionally also need negative emissions technologies to store carbon for millennials. The scale of changing conventional, heavy emitting technologies across all sectors is massive and needs rapid and cost-effective deployment. To ensure that the next generation of technological innovations are going to be truly carbon free and don't have overlooked negative effects to our climate, we need better models to draw inspiration from. In this report, I propose that nature as a model for new technologies is an effective tool for negative emissions technologies. Next to that, we explore the impact venture capital has on the deployment of new technologies within the climate deep-tech space. Ultimately, this report is a setting ground for how we need to perceive the next wave of technologies aimed at decarbonizing all industrial sectors.

Layman's summary

Human livelihood has been dependent on the exploitation of Earth's resources and caused release of greenhouse gasses (eg. CO_2, CH_4, N_2O) into the atmosphere. These gasses trap heat in Earth's atmosphere and cause a warming effect which results in climatic changes that present itself in the form of intense droughts, storms and heat-waves, rising sea levels, melting glaciers and warming of oceans. Currently, Earth's temperature is at 1.04°C warmer than pre-industrial times and we can already see some of these effects in the record summers that we have experienced. We thereby need to drastically decrease our emissions before the effects of climate change become irreversible. To do this, new technologies that will replace current emitting industries need to be developed and scaled. Next to decarbonizing all industries, we also need to capture and store some of the carbon that has been emitted back and create artificial carbon sinks. The infrastructure, scale and human investments needed for this challenge is massive and requires incentive of all scientists, engineers or self-thought experts. More importantly, we need to make sure that emerging technologies do not have overlooked effects to our climate. In this report, I critically analyze the concept of using nature as our model for climate solutions, especially in removing and storing carbon. Next to that, I reflect on the impact venture capital has accelerating climate technologies. Lastly, this report is a proposed method of looking at how to build meaningful technologies that are in line with a circular economy.

Keywords

Circular economy, Negative emissions technologies, Climate Change, Decarbonization

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Introduction

Since the starts of the industrial age (~1750), anthropogenic activities have increased the atmospheric concentration of carbon dioxide (CO_2), leading to catastrophic effects on all Earth's ecosystems and human lives. CO_2 is an important heat-trapping gas that warms the planet and is released through human activities such as deforestation and burning fossil fuels as well as natural process such as respiration and volcanic eruptions. To meet the 2 °C climate target set in the Paris Agreement, atmospheric CO_2 concentrations should not exceed 450ppm (or 430 ppm for the 1.5 °C) (Spier, 2020). Current atmospheric CO_2 concentrations however is at ~417 ppm (NASA, 2022). This means that in the next decade humans need to stop emitting GHGs to near zero emissions (Gordijn & ten Have, 2012). As seen in figure 1 however, reaching net zero by 2050 will not be sufficient to reach the global climate targets of below 2 °C and we thereby additionally need to start removing CO_2 directly from the atmosphere and storing it. Removing CO_2 from the atmosphere is called Carbon dioxide removal (CDR) and technologies that focus on this area are called Negative emissions technologies (NETs). The current estimates for the amount of CO_2 that needs to be removed through NETs annually by 2050 is set at ~ 10Gt CO_2, and 20 Gt CO_2 yr at 2100(Figure 1, IPCC, 2014, Fuss). However, at this point NETs only exists in pilot projects and have thus far removed 6000 tons of CO_2 as of 2021. This is only 0.0000006% of the total cumulative tons of CO_2 that needs to be removed by 2050 (Peter Reinhardt, 2021). The mass deployment, new materials and infrastructure that is needed to scale these technologies have been attributed to be similar to running the whole fossil fuel industry in reverse and the costs for all the infrastructure needed to achieve net zero by 2050 would be about $275 trillion (McKinsey Global Institute, 2022). Currently NETs are being bought on a voluntary basis, without regulation of the actual amount and permanence of CO_2 stored.

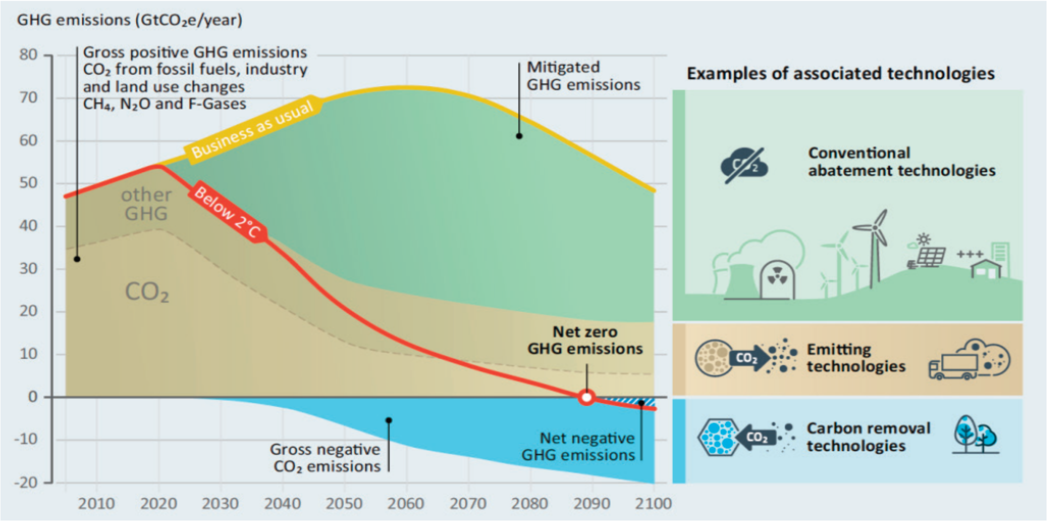

Figure 1. Expected scenario of the role of negative emission technologies in reaching net zero emissions(National Academy of Science, 2018; National

According to the latest Intergovernmental Panel on Climate Change (IPCC) report, three special aspects have been highlighted with extreme prominence (IPCC,2022). This includes, the use of fossil fuels that desperately needs to be abandoned, the dietary habits of humans which includes a high use of livestock and lastly, the traditional urban organization which resulted in unlivable cities. Additionally, another heat-trapping gas, namely methane (CH_4), has for the first time ever been reported to have reached unprecedented levels in the atmosphere. CH_4 has a global warming potential 84 times higher over a 20-year period compared to CO_2 (IEA, 2021a). Mitigation strategies for this extremely potent, but short-lived GHG desperately needs to be taken into account as an effort to climate change mitigation.

In short, to achieve net zero GHG emissions, we desperately need to change the way all emitting industries work by bringing new net zero emissions technologies to the market. However, bringing a new technology to a market is not straightforward and is accompanied by many barriers with the most prompting being high start-up costs (e.g. oil and gas, airplanes or shipping industries entry costs are millions), monopolies (e.g. firms that control a significant part of the market) and technical knowledge (Nahata & Olson, 1989). We are however at a pivotal time where climate tech investments at all funding rounds have been at an all-time high. In 2021 alone, $37B funds have been raised in climate tech, a 2100% increase compared to the previous decade (Holon IQ, 2022). This means that turning an innovative idea into a climate tech startup at this point in time offers the highest amount of market permeability than any other time in history due to the large incentive we see from investors that fund new ideas.

Across life cycle assessments (LCAs) however, how will we ensure that the next generation of technologies that are brought to market will be impactful and not cause catastrophic effects to our climate? In addition, how will we make sure that these technologies are the very best of their kind and thereby acquire funding from investors? For the first concern, we need a model to acquire inspiration from. One proposed model that has been around for billions of years and has been able to create the most efficient and adaptive systems that are circular and regenerative, is nature. For the second concern, we need experts that have intricate knowledge on how start-up ecosystems work in order to create admirable roadmaps to persuade investors that the technology they propose works and is the best of its kind. I propose that a synergy between these two components allows for the creation of the most impactful technologies that will shorten the loop towards a net zero world.

Emissions by Sector

When dividing anthropogenic GHGs emissions per sector we see that the primary source of emissions comes from energy production (73.2%) (Roser & Ritchie, 2020). Energy supply comes mainly from fossil fuels for industrial processes including iron and steel manufacturing or chemical production such as ammonia for synthetic fertilizer or other pharmaceuticals. Next to that, energy is heavily needed in transportation for road transport, shipping and aviation. Lastly, energy use in buildings for both residential and commercial buildings is a significant asset of fossil demand. All these industries thereby rely on renewable energy from solar, wind or geothermal energy to turn their products net-zero. Additionally, low carbon energy from nuclear power, although controversial, is also a key contributor to our net zero future. The second biggest GHGs emitting sector is attributed to agriculture, forestry and land use (18.4%). This includes livestock and manure, agricultural soils, crop burning and deforestation. Hereafter comes GHGs emissions from direct industrial processes (5.2%). This means, that additional to the energy needed for these industrial processes, they also emit CO_2 as a by-product. Perhaps the most shocking of industrial processes is the fact that cement production equated to 3% of all global CO_2 emissions and most of the emissions comes from the calcification of limestone (CaCO3) to lime (CaO) which occurs at a 900 degrees and releases CO_2. Lastly, waste covers the remaining 3.2% and is divided in wastewater and landfills.

In order to achieve the Paris Agreement all above mentioned carbon emissions need to become close to net zero by 2050. In some industries however, reaching net zero is not straightforward due to lack of technology or transition costs that remain prohibitive. These industries are termed “hard-to-abate” sectors and aviation is an example of such. Hard-to-abate sectors and other industries that are unable to reach net zero by 2050 will have to buy carbon credits from those that offer NETs, which makes rise to a new market called the carbon market. This market currently already exists in a voluntary basis. Delta airlines has been on the forefront of this battle and have a carbon offset program where they have already invested $137million in capital towards carbon removal (Delta, 2021). Furthermore, some leading tech companies in the Silicon Valley such as Google, Shopify and Stripe announced that they will be buying roughly $900million of carbon removals through frontier (Frontier Climate).

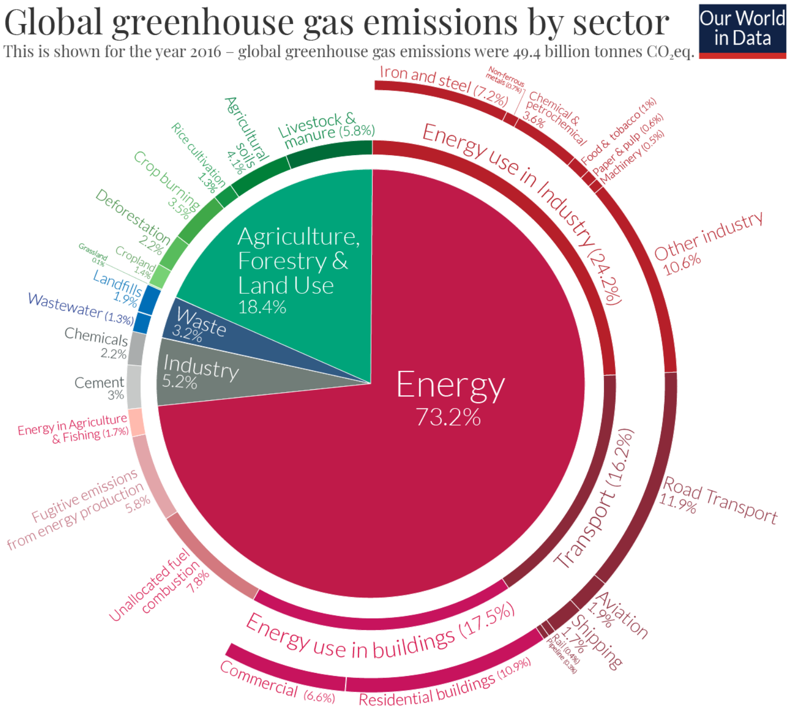

Figure 2 Visual global greenhouse gas emissions by sector (Roser & Ritchie, 2020)

Nature based solutions: Biomimicry

For billions of years, nature has been solving complex challenges to adapt to Earth's atmosphere. The results of this continuous reinvention of how natural systems can effectively adapt and survive in an environment can be seen through both structure of living organisms and metabolic processes that allows for the maintenance of these structures (Pathak, 2019). That is why it is becoming more evident that environmental challenges we face today, have previously been dealt with by living organisms over geological time and that we thereby need to look for answers of our complex (climate) problems to nature (Bar-Cohen, 2006). The idea of using biology as model has been given the term Nature-based solutions (NBS) or Biomimicry in the late 20th century and offers enormous potential for inspiring new possibilities to develop future technologies.

Perhaps one of the most well-known attributed results of biomimicry are aircrafts that were inspired by birds. The exact history of how airplanes became what they are now is a strenuous timeline where at times scientists even argued that copying birds was a reason for decade-long flight constraints (Aaron Randle, 2021). The reason for this is that the technology behind birds flying was not well understood and was far more complex then adding wings to the arms of a man (Bart, 1955). However, some key design aspects in birds have been successfully emulated in airplanes due to the fact that these structures were well coupled with their function. One of which is the streamlined shape, together with the smooth surface area of birds. This design allows for minimal air resistance in birds when in motion and is thereby the main design seen in planes (Figure 2)(Lakhtakia & Martín-Palma, 2013).


Figure 3 The streamlined shape of birds and planes

More recent studies have proposed a new airplane model that mimics the adaptability of wings. The idea is that adaptive wings can increase airplane performance, including fuel saving, longer range and reduced noise (Aage et al., 2017).

An interesting more recent discovery showed that the architectural design of the mounds of southern Africa termites (*Macrotermes michaelseni*) is structured in a form that it is a self-cooling system, through its efficient induced air flow and thermal capacity. Termite mounds thereby have a stable temperature of 30°C all throughout the year even though the outside temperature can vary from 2°C to 45°C (Singh et al., 2019). Emulation of the principles of these termites' mounds have resulted in buildings that can cool itself and thereby reduce household energy consumption by 90% compared to conventional air-conditioning or heating systems.

Figure 4 Tubercles shape in whale is used in wind turbine blades

The force of waves has long been seen as a potential for generation of renewable energy and researchers have successfully been able to make a triboelectric nanogenerator to be deployed in oceans and generate energy(Wang et al., 2019). The structure of this generator was inspired by giant kelps (*Macrocystis Pyrifera*) that accumulate and form dense kelp forests that remain intact even though they are faced with diverse surface waves and currents daily (Rosman et al., 2013). Another fascinating application is the development of bio-inspired wind turbine blades that were 35% better at capturing wind, more stable, quiet and durable than conventional wind turbines due to the addition of tuberclus (bumps) at the end of the blades (Figure 4). The inspiration of this innovation came when two biologists were researching the morphology of the humpback whale (*Megaptera novaeangliae)* and saw that the tubercles (bumps) on the leading edge of humpback whale flippers act as a passive-flow that improves performance and maneuvering of the flipper (Fish & Battle, 1995).

Whilst the application of biomimicry for climate tech solutions have proven to be effective in the examples mentioned above, not many nature-inspired designs have emerged in recent years in the climate deep-tech space. However, given the fact that Earth's atmosphere 4.6 billion years ago was 95% CO_2, and natural systems such as photosynthetic organism efficiently sequestered and stored CO_2 in sediments, rocks and oceans, using nature as model for creating NETs should be seen as an integral part of new technologies that remove carbon from the atmosphere. In addition, living organisms have found spectacular ways to co-exist without burdening their environment and thereby learning and emulating their metabolic processes offers a chance to replace heavy emitting technologies with net zero ones. "Life's principles" is the concept coined when evaluating products that are in line with NBS and circularity. It is embedded with the idea that life integrated and optimizes strategies to create conditions conducive to life (Biomimicry 3.8, 2015). Using these principles is the key to model innovative strategies, measure designs and ultimately allow to be mentored by nature. There are a total of 6 life principles

Figure 3. The Biomimicry design lens (Biomimicry 3.8, 2015)

1. Adapt to changing conditions
2. Be locally attuned and responsive
3. Use life-friendly chemistry
4. Be resource efficient
5. Integrate development with growth
6. Evolve to survive

The venture studio model

Venture capital (VC) is a form of private equity that funds young, high-risk companies / startups. In return for investments in these early-stage companies, VC firms acquire significant equity positions in these companies which can give them returns when the company starts to trade shares on a public market(D. P. Lee & Dibner, 2005). In many ways, the emergence of VC firms was revolutionary in the area of invention & innovation since new companies with limited operating history were 300% more likely to reach the initial public offering (IPO) stage. Some experts have estimated that on average, “a dollar in VC appears to be three to four times more potent in stimulating innovation than a dollar in a traditional corporate R&D” (Dessí & Yin, 2012).

The next decade is considered as the “critical decade” since the impacts of climate change become visible and even more alarming. Revolutionary technologies for climate mitigation and adaptation need to be deployed in all sectors of the economy worldwide. There is thereby a desperate need to merge scientists and experts with entrepreneurship to create start-ups that will fight for net zero emissions. In the past, there has already been a merging between industry and academia, namely the university-industry collaborations (UIC) which showed to significantly enhance innovation by facilitating technology transfer(Perkmann et al., 2013). UIC often has risks due to mismatch in priorities between academia and industry (Eg. Education vs commercial interest) and in some cases also disagreements in the rights of the Intellectual property (IP)(Pronk et al., 2015). In addition to UIC, there is a space needed to promote scientists and engineers to get the knowledge they have acquired into climate solutions.

Marble is a first of its kind climate tech venture studio based in Paris that aims at building deep-tech startups that decarbonize industrial processes, remove carbon from the atmosphere and create climate resilience. In contrast to other VC firms, marble aims at offering a more personalized mentorship to its Founders in Residence (FIR), by having a maximum of 8 FIRs every 9 months.
An FIR begins with a 3 month "explore" process, where we scope opportunity areas together with the founder so their skills can unlock radical solutions to hard climate problems. The scoped ideas will be evaluated using multiple venture hypothesis including structured ideation, technical landscaping, market research, expert interviews, and techno-economic analysis. This process is continuously evolving and at the end of the 3 months period there is a "GO NOGO" evaluation on how the project has progressed and how it will move forward. If the founder is successful at this stage, a 6 month "create" phase follows that is completely focused on turning the idea that was scoped into an investable startup. The main goals at this stage will be to validate the technical strategy, find a go-to market, demonstrate customer traction and find Co-founders and Advisors. At the end of this phase the FIR and its Co-founder will pitch in front of the investment team and if successful, get a $250K pre-seed funding in order to turn their high impact idea into a prototype.

As a Climate tech analyst at Marble, I was in charge of scoping opportunity areas in biotechnology, specifically looking at NBS for climate deep-tech. When an idea was well scoped, we tried to find the most potent candidate to become an FIR. Next to that, I worked with FIRs on their technical due diligence (TDD) in order to critically evaluate their technological advancements and de-risk many parts of their technological stack. Sometimes this included creating an early-stage proof-of-concept.

Research Conducted

In this research, I aimed at answering the question: What influence can **design lessons** from nature (life's principles) have in determining the **success** of a climate tech venture.
To answer this question, I researched the metabolic processes of some critical organisms in nature as well as key organisms that influenced the massive drawdown of carbon that we have had over the past 4.6 billion years. Additionally, I aimed at identifying realistic, high impact solutions, meaning that these solutions had roadmaps that clearly showed their potential to become cost competitive and reach rapid industrial scale within a certain time period. Next to that, I also critically analyzed opportunity areas that have already been scoped at Marble, in order to see whether these products have components of using nature as model. Ultimately this would help me to get a strong conviction if using life's principles is a reliable and concrete method of evaluating climate tech ventures.

Definition of a successful venture

Traditionally, the definition of a successful technological ventures has been synonymous with high initial and long-term market profits, clear business plans and working prototypes (Blank, Steve Gary; Dorf, 2013). Within the climate deep tech venture space there are additional parameters that heavily influence the definition of a successful venture, including reliable LCAs and infrastructure for scaling a technology. The parameters of evaluating the success for a venture are shown in table 1. From a table perspective it is clear that there is a well-established protocol of evaluating the business, economics, founder potential and technology of a venture in the form of total addressable market (TAM), the Go-To market strategy, product unit economics and Techno-economic assessments (TEA) (Table 1). In contrast, there is a highly superficial overview on characterizing the success of a climate venture in terms of short- and long-term environmental impact and its societal effects. My research question will be aimed at rephrasing the traditional method of defining the success of a venture studio by looking at the possibility of incorporating life's principles as a parameter to evaluate their success.

Market + Customer	**Economics + Finance**	**Founder potential + Co-founder dynamics**	**Product and Technology**	**Sustainability and Long term environmental impact**
Target audience and Market size: Total addressable market (TAM)	Unit economics and Profit margin	Compatibility + Complementation effect with given founder	Risk matrix and reliable advisory	Life cycle assessment (LCA)
Initial Go-To market strategy	Techno-economic assessments (TEAs)	Soft skills: Networking, teamwork, creativity, time management, Conflict resolution,	Product roadmap and long-term vision	
Customer acquisition cost (CAC)	Lifetime produce value + CAC recovery time	Hard skills: Language skills, Salesmanship	Intellectual property (IP) and novelty factor	
Customer retention rate	Company Monthly burn + runway	Mentality switch from academic to businessman	Scalability and timeline	

Opportunity areas scoping process

Given the large pool of biodiversity within natural systems, a fast and efficient way was needed to filter through as many organisms and their functional structures, metabolic pathways and overall performance in a given ecosystem. During my first month at marble, the research team and I realized that the most effective way of going through biological structures is by spending a short amount of time on each domain of life, specifically identifying the most interesting species that have complex and interesting processes to balance themselves in an ecosystem. This process involved looking at how they gather energy, nutrients and carbon feedstock for their growth, how they compete and adapt within an ecosystem and to which extend they have been researched in laboratory conditions. If a species was relevant enough within our problem statement, we will contact experts who are knowledgeable in this field to find out the reason these organisms have not been deployed already and what needs to be optimized in order for them to become relevant in an industrial setup. Ultimately, we aim at getting an FIR for a maturely scoped opportunity area. In this process, we also need to have clearly defined what the ideal skills for this candidate are.

Results

During my six months internship at Marble, I have been involved in two projects that are currently in formation to become a start-up and five opportunity areas that were scoped and assigned to their rightful FIRs. I have however worked on scoping roughly 20 opportunity areas. In this section, I aimed at:

- Identifying solutions to climate problems by looking at how nature deals with them
- Analyzing opportunity areas that have already been scoped and try to find and enhance their climate impact
- Analyzing feasibility of turning scoped nature inspired processes into a start-up in terms of cost competitiveness, novelty edge and scalability

Atmocooling

AtmoCooling is a project to combat desertification by misting seawater in coastal arid regions to create stable microclimates. When stable microclimates are created, the soil will be stimulated through fertilization and cover crops until it is in a healthy state that allows for agriculture. Next to that, this technology also is focused on creating cool urban areas.

Heat extremes have accelerated on a global scale over recent decades and will continue to become more prevalent under future global warming (Russo et al., 2014) . This imposes great threats to human livelihood and natural ecosystems that can collapse due to extreme weather events. As a first principle, this project was seen as a climate adaptation strategy that is aimed at enhancing resilience of an ecosystem as well as adapt to predicted changes in the near future. This technology strongly incorporated two of life's principles in its product, namely, a product that allows for an ecosystem to adapt to changing conditions as well as using resources (seawater) efficiently. Given the maturity of the core technology in this project, I leaned towards identifying additional value propositions that can be incorporated in order for the project to have a more visible climate impact. For this effort I looked at the differential ways nature sequestered and stores carbon.

Biological carbon sequestration

The most common form of biological carbon sequestration is attributed to photosynthesis, the two-reaction process in which CO_2 is converted into carbohydrates in a plants chloroplast (Johnson, 2016). Annually, photosynthesis removes around 120Gt of Carbon from the atmosphere. However, plants also release carbon back to the atmosphere through respiration. Respiration represents approximately half (60Gt) of the carbon that is returned to the environment annually. Through the process of decomposition organic matter is released back into the atmosphere in the form of CO_2 or gets accumulated in soil in the form of soil organic matter (SOM)(Janzen, 2004).

Biological Carbon storage

Approximately 2,500 Gt of carbon is stored as SOM, making it the largest pool of terrestrial organic carbon (Janzen, 2004; Jobbágy & Jackson, 2000). The impact of SOM in the global carbon cycle is significant and could also influence positive feedback to climate change (Schlesinger & Andrews, 2000).

Decomposition of SOM ranges from a few minutes (i.e. root exudates, simple sugars, leaves) to 1000s of years (i.e., resistant organic matter such as charcoal). This decomposition rate is influenced by three major factors, namely, soil organisms, the physical environment and the quality of the organic matter (Brussaard, 1994). In order to turn soil carbon into a NET, we need accurate measurement, reporting and verification (MRV) of the amount and quality of carbon stored in a given area. Given that soil organisms are extremely dynamic, and their activity is influenced by multiple factors, MRV is a major bottleneck in deploying SOM as a NET. Some researchers have even highlighted that this approach might never be marketed since we cannot control or accurately predict behavior of (soil) organisms, the major driver of SOM decomposition(Jim Giles, 2021).

Desert soils have the lowest amount of SOM amongst soils because of the scarcity of plant remains and the rapid rate of organic matter decomposition due to the heat (Thomas et al., 2012). Terraforming desert soils might be seen as a more straightforward NET play given that we can account the amount of carbon stored through the amount of vegetative land created. Additionally, cooling of arable regions has also been proven to slow decomposition of SOM.

When looking at biological carbon storage, it is clear that the challenge lies in accurate MRV that can give relevant measures of the actual amount of carbon stored. The climate potential of Atmocooling should be purely focused on its adaptive properties and also future abilities to allow for food security in areas that have long relied on importation as their primary source of food.

Alternative low carbon fuels

The transition from fossil fuels as our primary energy source to low carbon alternatives belongs to the major changes that needs to be accelerated in this decade (O. Pörtner & Cambridge University Press. In Press., 2022, Figure 2). Fossil fuels are originally made from dead organisms (mostly plants) that resisted decay since they were entrapped under water or mud with no oxygen (O_2). When fossil fuels are burned, the solar energy once captured through photosynthesis millions of years ago is released in the atmosphere as CO_2. What makes fossil fuels the preferred energy source lies in the structure of its chemical bonds, namely the structure of hydrocarbon molecules (C_nH_{2n+2}). The moment hydrocarbons are in contact with heat and O_2, a chain reaction occurs and causes its breakdown which leads to release of energy, CO_2 and H_2O. Given that we can control the breakdown of hydrocarbons and they can be efficiently stored up until their energy is needed, they are the best energy sources for transportation, most notably for aviation, long-haul shipping and rocketry.

Some proposed alternative fuels that have been looked into over the past decades include, biodiesel from microalgae, clean hydrogen, clean ammonia and new synthetic hydrocarbons produced by bacteria (Chisti, 2007; Cruz-Morales et al., 2022; Wan et al., 2021). When looking at how nature acquires energy, we see that this is either light (photosynthesis) or chemically (chemosynthesis) mediated. Plants absorb sunlight to generate Adenosine triphosphate (ATP), a coenzyme that is the source and use of energy at the cellular level. Given the excellent energy efficiency of ATP, some researchers have attempted to synthesis this enzyme on an electrode (Gutiérrez-Sanz et al., 2016). This would mean that energy intense cellular processes such as bio-catalysis, would have an efficient way of retrieving energy. When looking at solutions as such, there are major considerations needed given the high demand of energy in the world. Applying NBS for alternative fuels thereby is extremely difficult as the default that would come in mind is renewable energies from the sun or wind. However, the inefficiencies in these systems lies in their inability to store the energy, given that they do not have the abilities of cellular level, ATP. Additionally, we cannot look into solutions that abandon the current infrastructure (transportation, residential or commercial heating) of the machines that require energy. We thereby need to look for alternative, low carbon fuels that may still be compatible with current engines, are able to scale to the production rates humans need and are infinite in resources.

Z-fuels

Z-fuels is a project working on a breakthrough pathway for producing low carbon alternative fuels at scale. These fuels are produced on-site and thereby support a decentralized energy system. This would allow for less costs and CO_2 emissions from logistics of distributing the fuels to their designated location. Their approach to produce these low-carbon fuels are by harnessing the power of some unexplored mechanisms in biology. This project is completely focused on decarbonization of multiple different energy intense industries. This project is currently under formation and I am thereby unable to mention more information of their progression.

Clean ammonia

Perhaps one of the most influential inventions of the 20th century is the Haber-Bosch (HB), an artificial atmospheric nitrogen fixing process. This process allowed high yield and low-cost production of fertilizers which caused an admirable boost in food production. This technology unintendedly sparked a global population boom and is the reason humans have gotten to numbers surpassing 7.7 billion people (Smil, 1999). Due to high reaction temperatures (450°C) and pressure (200 atmospheres), as well as the feedstock being natural gas, HB is amongst the most polluting chemical reactions causing roughly 1.2% of global CO2 emissions annually. The potential of ammonia as a future fuel lies in its high energy density, easy storage and abundance in the atmosphere. There is an increased effort to produce "clean" ammonia by either using renewable electricity or changing the production process through alternative catalysis methods(Brown et al., 2016; Capdevila-Cortada, 2019; Milton et al., 2016). Particularly the shipping sector is becoming interested in ammonia in their decarbonization effort (IRENA, 2021)s. However, there are some noticeable challenges in scaling-up such high ammonia production. Additionally, some reports have estimated that ammonia as shipping fuel could disrupt the entire nitrogen cycle and thereby cause even more unprecedented harm to our environment (Wolfram et al., 2022). Clean ammonia is evidently an interesting molecule that requires more nature inspired methods for its production. Having said that, I explored how organisms currently fix nitrogen and what this could mean as an industrial process.

Biological nitrogen fixation

Biological nitrogen fixation (BNF) is a unique microbial mediated reaction whereby atmospheric N_2 is reduced using the nitrogenase enzyme (Dixon & Kahn, 2004). This reaction is extremely energy intense for diazotrophic bacteria, using 16 ATP per mole of NH_3 produced. Next to that, this enzyme is oxygen sensitive and will thereby become irreversibly inactive when exposed to oxygen. Some bacteria (e.g., Cyanobacteria) who live in aerobic conditions have differentiated compartments, called heterocysts that are anaerobic and allow for nitrogen fixation even under aerobic conditions (Kumar et al., 2010).

In an ideal world, we would rely solely on (BNF) as our primary source of nitrogen (N). This would mean that the total amount of N now produced using HB (roughly 235 million metric tons of N), is translocated to production by microbial life. This would allow for a low emission production of NH3 that is in line with life's principles. The scale of such production however, is immense and given that BNF is extremely energy intense for a bacteria, it is unlikely that we can get to such high levels before 2050. We thereby systemically need to decrease our dependency of N by looking for alternative pathways that is not just external production of N. One proposed method is to genetically modify cereal crops to have the nitrogenase enzyme, thereby making them self-sufficient. This method offers major genetic engineering challenges given that mitochondrial DNA transformations are difficult and the enzyme is only active when all 16 of its associated genes are transformed (Curatti et al., 2005). Nonetheless, many research attempts have focused on this, unfortunately with minimal industrial applicable results (Allen et al., 2017; Ivleva et al., 2016).

Another alternative approach that has been explored and tested in a laboratory, harnesses the power of diazotrophic bacteria to reduce N_2 using hydrogen generated from renewable electricity (Liu et al., 2017). This approach showed the highest ammonia production ever reported in a biocatalytic system and was also done through a modular design. Although promising, it is still unclear whether this system will be able to achieve relevant production yields. On a pure biochemical motive however, we see that nature exceeds the theoretical turnover frequency of a Fe-catalyst HB process by an order of 4 (Buscagan & Rees, 2019). This implies that nature to date has been more efficient in reducing atmospheric N_2 and is a setting ground to further develop a system in which we can deploy its power.

Clean hydrogen

Hydrogen molecules (H_2) store a significant amount of energy that can be released when burned, with the only by-product being water. Annually around 70 million tonnes of H_2 is produced by using natural gas to energize a wide range of applications including fertilizer production. H_2 has long been seen as a potent energy source to replace fossil fuels if the production process is derived from low-carbon sources such as renewables, geothermal or nuclear energy. Storage of H_2 however, remains a bottleneck as it has a low volumetric energy density and thereby needs large volumes for its storage. Current prospects for commercialization of H_2 deal with three major optimization criteria, namely the cost, performance and durability of a fuel-cell component (Debe, 2012). A report by the international energy agency has calculated that the amounts of hydrogen needed by 2050 is around 17,000 TWh, a five time increase of current production rates (IEA, 2021b).The energy requirements to produce these amounts of hydrogen is attributed to be twice the amount of the current worldwide production of electricity from renewable energies. This would need an unprecedented scaling of renewable energies as well as electrolysis for the water splitting. In short, we need to find out what other alternative, nature inspired pathways there are to implement hydrogen-based fuels into our bioeconomy that do not rely heavily on just renewables as their decarbonization strategy.

Photobiological Water Splitting

Biological hydrogen production is the process of using microorganisms and sunlight to turn water into H_2. Common challenges in this area include the inefficiencies of enzymes that produce hydrogen, namely hydrogenases. Hydrogenases are hyperefficient metalloenzymes that operate at rates up to $\sim 10^4$ per second (Lubitz et al., 2014). The primary functions of hydrogenases are to be able to provide energy to an organism by oxidizing molecular H_2 which in turn leases energy and produces electrons. Depending on the location of the hydrogenases, they can either be turned for hydrogen evolution or hydrogen uptake (Lubitz et al., 2014). Common organisms that express hydrogenase include green algae, purple photosynthetic bacteria, and even some heterotrophic bacteria. Next to that, there is increased incentive to do cell-free catalysis, that is, using an enzyme without the microorganisms in an industrial process.

Harnessing the power of these enzymes alone however is incredibly challenging as they become irreversibly inactive when exposed to oxygen, making research with these enzymes time consuming and costly (Lubitz et al., 2014). However, multiple research groups have unlocked mechanisms to by-pass this oxygen sensitivity by using thin films or redox-wired polymers that trap these enzymes into an anoxic state (Li et al., 2019; Oughli et al., 2020). The roadmap to turn lab-scale research innovations into industrial scale production starts with improving the activity and thermostability of these enzymes. To improve thermostability, we can look into identifying more hydrogenase variants by specifically looking into natures diversity of extremophilic bacteria or archaea. Next to that, engineering enzymes with directed evolution or site-specific mutagenesis have shown to improved thermostability as well as enzyme turnover rates in bio-catalysis (Eijsink et al., 2005). Cell-free catalysis is interesting when looking at life’s principles as it uses electrochemistry, a highly resource efficient process, for the synthesis of hydrogen. Amongst many requirements in this process, cofactors such as NADH and ATP are the most expensive parts of getting this reaction to work (Bergquist et al., 2020). Attempts at getting cell-free catalysis to be cheap and circular have looked at regenerating these cofactors in the same matter that microorganisms do so through their intricate metabolic network. Until this cofactor regeneration process has been well elucidated, whole-cell catalysis using hydrogen-expressing microorganisms combined with anaerobic fermentation will be the only viable option to rapidly and cheaply scale. This fermentation process occurs in the dark and thereby requires additional substrates such as an electron donor to be added to the reactor, making it a reaction process that does not completely compile with life's principles (Torzillo et al., 2015). Ideally, one would use photosynthetic hydrogen-expressing organisms when wanting to completely compile with life's principles, however, there are many engineering, production and harvesting challenges for these organisms. Over the past two decades, many companies have attempted and failed to decrease the costs of producing biofuels using photosynthetic organisms (namely micro-and macroalgae) and to date biofuels still remains orders of magnitude higher than fossil fuels. Some experts have even gone so far to state that the only possible way algae-based biofuels may become marketable is through green premiums of extremely hard-to-abate industries (Mckinsey, 2021).

Geochemical hydrogen production

Natural or native hydrogen is a form of hydrogen that is abundant in Earth's subsurface that has been generated by geological processes. An example of a hydrogen reduction is when ferrous iron (Fe^{2+}) gets in contact with water, causing its oxidation and as a by-product, release of hydrogen (Kelley et al., 2005). This oxidation process occurs naturally under the ocean floor where conditions are favorable in terms of temperatures and metal availability. The same reaction can also take place with other metals such as magnesium (Mg^{2+}).

Although the opportunity of generating hydrogen natively is promising, it is understandable that there will be large skepticism to this technique due to its similarities to the exploitative industrial fossil fuels mining process. From a first perspective however, this process is significantly less invasive compared to traditional fossil fuel mining and does not release GHG when the energy is utilized. As explained, the infrastructure needed for green hydrogen production by 2050 is too large, making geochemical hydrogen production an alternative to reach these production levels (IEA, 2021b).

Bioproduction

Production of chemicals and petrochemicals account for roughly 3.6% of annual GHG emissions (Figure 2). In order for the chemical industry to be able to decarbonize their production, they cannot completely rely on transitioning towards renewable energy sources since their main feedstock input needs to be a carbon-based molecule (R. P. Lee, 2019). Currently 90% of our chemicals and fuels are produced using wither crude oil (C8H18) or other fossil feedstocks for biomanufacturing (Corma et al., 2017; Ennaert et al., 2016). The rise of industrial biotechnology has long been seen as a promising route to sustainable chemical production, however, to date it has only been economically viable to produce high-value products such as aromatics, fragrances and enzymes using microbial systems (Scown & Keasling, 2022). Microbes require sugar feedstocks (C6/C5 sugars) that become extremely expensive when aiming for high production titers, and is thereby not economical to do so with low-value products such as biodiesel or bioplastics (Hermann et al., 2007; Scown & Keasling, 2022). The use of these sugar feedstocks often requires long biosynthetic pathways that results into carbon loss and thereby higher GHG emissions. Additionally, the extraction of fermentable sugars from crops requires massive land-use, nutrients, water and energy resources which results in overlooked GHG emissions (Hermann et al., 2007).

The ability to rewire organisms in order for them to produce a desired compound is a setting stone for industrial biotechnology, but the process of completely decarbonizing this sector with this method remains a challenge. Nonetheless, industrial biotechnology remains a relevant approach for chemical industry decarbonization since the outcome of it may result in a domino effect, whereby fossil fuel dependency in other industries can also be decreased. There are multiple approaches to this challenge and for this research I mainly looked into using alternative feedstocks in bioproduction and rewiring the metabolisms of industrial workhorses like *Escherichia coli* and even incorporating more efficient biocatalytic production.

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Synthetic autotrophs

The definition of alternative feedstocks in the concept of chemical industry decarbonization, is the use of feedstocks that are not derived from petroleum or require large lands for their production. Examples of alternative feedstocks include C1 (CO_2, CH_4 or methanol) and C_2 (Ethanol, Acetate), that are produced either through carbon capture and conversion and waste (lignocellulosic or plastics (Ma et al., 2022). These alternative feedstocks should be cheap at scale and won't compromise the production titers of a bacteria. Furthermore, they should be energy dense molecules that are highly available (Clomburg et al., 2017; Wendisch et al., 2016). One proposed method is to metabolically engineer model organisms to be able to use alternative carbon sources in their biomanufacturing (Wendisch et al., 2016). On the other hand, one can also explore the use of bacteria that already grow on a C_1 or C_2 carbon source and engineer them to have high production titers.

Rewiring the metabolisms of common model organisms such as *E. coli*, *Saccharomyces cerevisiae, Pseudomonas* and *Bacillus* is a very straightforward process since their complete genomes are sequenced, they have many genetic tools to perform recombinant DNA technologies and their doubling time are extremely fast, ranging anywhere from 20-90 minutes. Laboratory scale attempts in changing the carbon source of *E. coli* have been successful in making it partially photosynthetic and also growing on CO_2 as its carbon source (Antonovsky et al., 2016; Satanowski et al., 2020). More recently, some researchers have been able to turn an *E. coli* strain methylotrophic, and thereby making it able to grow on methanol (CH3OH) as carbon source (Keller et al., 2022). A constant in all these researches is that the doubling time of *E. coli* significantly increased, resulting into engineered strains that grow with a doubling time ranging from 6 to 8 hours, compared to a wildtype that doubles within 20 minutes. Possible superficial approaches to decrease the double time, lay in improving the media and nutrient conditions as well as defining the optimal growth temperature with these new engineered strains. Moreover, exploring bioelectrochemistry might be a relevant solution for these relatively slow growing strains, since unlike with traditional fermentation, a bio-electrochemical system does not rely on bacteria growth as a parameter for high production outputs. This would require further engineering however, since E. coli is not an electron active bacteria and thereby needs to rely on electron mediators for them to be able to grow (Feng et al., 2020).

Improving native autotrophs

Autotrophic bacteria are bacteria that live on the thermodynamic edge of life and have been able to maintain homeostasis within extreme environments on Earth. They have been able to adapt and evolve through many different atmospheres and carry a testimony of these adaptations within their genetic make-up (Scown & Keasling, 2022).

One example of such bacteria, are acetogenic that are able to convert two molecules of CO_2 into acetate using the anciently preserved Wood–Ljungdahl pathway. Interestingly, this pathway is the only known biochemical pathway that converts inorganic carbon to energy conservation using two membrane-bound enzyme complexes(Schuchmann & Müller, 2014; Scown & Keasling, 2022). A known acetogenic bacteria, called *Clostridium autoethanogenum*, is able to grow on CO and synthesize ethanol as well as 2,3-butanediol autotrophically. Since both these products are commercially relevant, some researches have metabolically engineered this organism to produce high titer (9.7 g/L) of ethanol (Liew et al., 2017). Given that this organism is autotrophic, there are many areas where they could optimally grow in including still gas waste, agricultural residues and generally all gas streams that contain CO, H_2 and CO_2. They become particularly interesting to decarbonize the chemical industry, if we are able to engineer novel biosynthetic pathways of industrial compounds inside their metabolism. Previous research that attempted to metabolically engineering Clostridia, have failed to get high production titers, rates and yields and have gotten to production rates in the order of milligrams per liter (Jullesson et al., 2015). In order for them to be competitive enough to current industrial production, they should have production rates that are thousands of magnitudes than current benchtops. Moreover, there is currently no established metabolic process for acetogens that is commercially competitive. Another pool of interesting organisms are methylotrophic bacteria, that is, bacteria that are able to grow using CH_4 or CH_3OH as their carbon source. Particularly, *Pichia pastoris* has been a successful organism in industrial biotechnology by producing many enzymes such as lipase and xylanase as well as biopharmaceuticals such as insulin. The use of *P. pastoris* in industrial chemical production however has been largely underestimated, mainly because episomal vectors for this species are unstable, leading to challenges to insert high copy numbers, expression cassettes within this organism, a bottleneck for high-level protein secretion (Scown & Keasling, 2022). To date, there is only one other interesting methylotrophic bacteria that have been identified to be potent for use in industrial processes (Balk et al., 2003). Perhaps next efforts should explore nature's diversity in methylotrophs to find more industry viable strains.

Overall, innovations in synthetic biology have shown major improvements in the past decades, especially those focused on engineering novel biosynthetic pathways in a non-native host. Current optimization technologies within synthetic biology include more efficient metabolic flux analysis, kinetic models of metabolism, proteomics as well as a novel in vitro prototyping and rapid optimization of biosynthetic enzymes (iPROBE) program (Karim et al., 2020; Scown & Keasling, 2022). Future successes in decarbonizing the chemical industry lies in innovations in synthetic biology and with that, particularly incorporating more complex organisms that have been able to sustain themselves on Earth, be resource efficient and thrive using the very life's principles we want to adapt in our society.

Nature based CDR

As mentioned in the introduction, in addition to decarbonization we need to remove around 10 GT of CO_2 in the form of NETs (IPCC, 2022). Given that Earth's atmosphere removed significant amounts of carbon in previous events, nature-based CDR solutions are considered a very realistic approach to finding inspiration and ultimate NETs. Earths systems have removed carbon from the atmosphere on geological timescales, ranging in the millions of years. Given that we have less than 30 years to remove gigatons of Carbon, looking at nature-based solutions should especially be focused on the process towards accelerating the natural rates of carbon sequestration and storage. Additionally, NETs require MRV that can assure the actual amounts of carbon that is stored as well as the permanence of the stored carbon. In this section, I researched multiple carbon withdrawal events that occurred and see how we can emulate these in our current society.

Carbonic anhydrase

Carbonic anhydrase (CA) are enzymes that catalyze the reversible hydration reaction of CO_2 to carbonic acid (H_2CO_3) and bicarbonate ions (HCO_3-). They are considered the fastest enzymes on earth, with a turnover frequency up to 10^6 s^{-1} (Alvizo et al., 2014; Talekar et al., 2022). Many living organisms, including humans use CA as a key enzyme for metabolic pathways that require dissolved CO_2 or hydrated CO_2 in the form of HCO3-. Given CA's high turnover rates, they could be explored as potential enzymes that are used for atmospheric CO_2 capture, since they could greatly improve the absorption and desorption rates of CO2, that currently are not seen using chemical solvents. Next to that, CA can also promote accumulation of HCO3-, which can improve *in vitro* conversion of bio- or thermos-catalytic processes (Talekar et al., 2022). Implementing CA for CO_2 capture however remains a challenge, since the enzyme is not extremely robust and thereby cannot withstand reaction conditions with high temperatures. Current work on improving thermostability of CA, have looked into identifying extremophilic organisms that express CA as well as engineering the enzyme for better stability (Alvizo et al., 2014; Capasso & Barboiu, 2019). Another proposed method to make CA thermostable is by immobilizing the enzyme on a carrier surface, since other enzymes have turned remarkably stable with this approach (e.g., a-amylase stability) (Talebi et al., 2016). The future of CO_2 capture using CA thereby lies in engineering of the enzyme for higher robustness. The applications for this robust enzyme can range anywhere from technologies that capture CO_2 from high temperature flue gasses to using vesicles that capture CO_2 in the ocean.

Azolla event

Azolla is a fern that is most commonly distributed in aquatic habitats, mostly stagnant waterflows such as ponds, canals and water patches. *Azolla* have been in a symbiotic relationship with *Anabaena azollae*, a cyanobacteria capable of fixing atmospheric nitrogen (Hemalatha et al., 2019; Padmesh et al., 2006). Due to this symbiotic relationship, Azolla is self-sufficient and is amongst the fastest growing plants on earth, able to grow in hostile environments such as anoxic waters. This symbiotic relationship, that appeared roughly 100 million years ago, is unique in biology and some research evidences have strongly suggested that Azolla is one superorganisms rather than a symbiont (Carrapiço, 2010).

There are multiple applications for *Azolla* in a sustainable economy, one of the more straightforward one being its use as a biofertilizer, since it can fix its own nitrogen. Moreover, *Azolla* biomass has a unique composition of proteins and vitamins and thereby also has potential as an alternative feed for animals or humans. Interestingly, when looking at paleoclimatic simulations of *Azolla*, there are multiple use cases of it in CDR. Some strong indications have shown that during the Eocene (~50 Myr ago), *Azolla* grew abundantly in the then anoxic, arctic ocean and led to major drawdown of CO_2 (roughly 3.5 10^6 Gt) (Brinkhuis et al., 2006; Speelman et al., 2009). Many refer to this as: the *Azolla* event, and some enthusiasts have long speculated on the potential of inducing such event again in an effort to remove atmospheric CO_2. Unlike algae, *Azolla* is not a halophytic plant and thereby can only grow on the surfaces of freshwater. This makes the use of *Azolla* for gigaton carbon removal challenging, since it will compete with other industries that also need freshwater.

Ideally, one would engineer salt tolerance in *Azolla*, which would make it able to grow in all oceans. However, salt tolerance is a polygenic trait controlled by quantitative loci and requires multiple levels of molecular engineering (Ismail & Horie, 2017). Two high level constraints with this approach are the limited amounts of genetic tools to genetically engineer *Azolla* and also the release of genetically modified organisms (GMO) in an ecosystem comes with many ethical constraints and is likely never going to be possible (Tsatsakis et al., 2017). Another approach would be to find a pathway to adapt *Azolla* to salt water through classical breeding or non-GMO mutagenesis. However, as already mentioned, the polygenic nature of salt tolerance as a trait would turn this challenge into a time consuming one, ranging anywhere from 50yrs to never. Another challenge remains the actual storage of *Azolla*. Predictions showed that Azolla was buried, thereby encapsulating the organic matter in an anoxic form where no microbial activity could cause the release of carbon back into the atmosphere (Speelman et al., 2009). Emulating this burial, comes with many questions including the location of this permanent storage, MRV and other environmental constraints such as disturbance in the carbon and nitrogen cycle that can cause unprecedented hazards to ecosystems.

Failed opportunity areas

The goal of Marble is to create cutting edge, high impact companies that come with a different angle than conventional ways of looking at building a company. This process requires truly out of the box thinking with still a realistic approach to evaluating technologies. During my internship, I scoped for multiple opportunity areas that showed clear indications that they were not at a mature stage to be able to further consider as a company. This included, the already mentioned use of soil as a NET. Furthermore, there were two other opportunity areas that are currently not at a mature stage to be interesting. I'd like to highlight that although my research showed that they were not impactful, they still remain opportunities that could become impactful in the near future.

Biomineralization

Biomineralization is an interesting concept that is ancient and has major potential for NETs. It is in line with geochemical NETs, the concept of using alkaline minerals to remove CO_2 from the atmosphere(Maesano et al., 2022). There are multiple organisms that are able to precipitate carbonate and thereby store CO_2 for long periods of time. These organisms range from cyanobacteria and diatoms to more primitive organisms such as coccolithophores and brachiopods. Many organisms that are capable of biomineralizing, have never been cultivated in a laboratory, resulting in some key scientific and ethical concerns that have not been answered yet. Next to technological readiness, the land that is required to grow these organisms and the time that is needed for them to sequester one gigaton of carbon is a major bottleneck. Furthermore, there are many open questions on the amounts of minerals and other Earth elements that are required for sequestration of carbon. Lastly, there are major concerns on the ecosystem impacts these technologies may have as they can influence the carbon cycle and cause deleterious effects to our ecosystem. In short, biomineralization is currently not at a mature state to be a good enough opportunity area. However, we remain optimistic on this area and greatly stimulate more incentive to do academic research to understand more how they may be applied in technology.

Microalgae for CDR

Cultivation of microalgae for CDR has often been seen as a promising method. Currently, microalgae can be cultivated in open ponds or in photobioreactors (Chiu et al., 2009). Open pond cultivation uses lots of land and is prone to contamination that causes cultures to crash and reduced growth of algae and photobioreactors are not economical since they require a carbon supply, supplemental lights and allot of maintenance and optimization (Chiu et al., 2009; Hepburn et al., 2019). Many researchers have strongly suggested that utilization of microalgae is only economically viable for production of high-value compound such as the pharmaceutics, β-carotene and astaxanthin that range in costs starting $1700.000/ton (Hepburn et al., 2019; Shukla & Kumar, 2018). In short, there are multiple bottlenecks on algae cultivation and its down costing. Next to that, there are also multiple concerns on the storage of microalgae. Currently, there are two options to store microalgae: algae burial, in order to get it in a state where microbial activity makes it unable to breakdown or deep-sea sinking, the process of throwing algae in the ocean, which allows it to get to the deep-sea and permanently get stored (Chiu et al., 2009). Both these methods could result in disruption of the nitrogen cycle or changing of an ecosystems food-chain, which may lead to other effects that may accelerate climatic changes. Next to that, there are concerns whether storage of one gigaton of CO_2 will deplete nutrients, particularly phosphorous. We believe microalgae may have massive impact in other decarbonizing efforts such as biofuels, but focusing on it for CDR might not be the best approach from both a costs perspective (down costing to $100/ton) as well the potential environmental constraints.

Overview

This table is meant to represent my personal rating of all current projects and scoped opportunity areas in terms of their climate impact, scalability and scientific risk. In the first three rows, the climate change strategies, namely, mitigation, adaptation and carbon removal are highlighted. According to the IPCC report, all three strategies are equally important, however, decarbonizing emitting industries requires significant more capital investment than adaptation and carbon removal. Next to that, the impact of a company that will stop dependency on fossil fuels is more impactful to our climate than a company that removes 1Gt of CO_2. For this reason, I allocated the impact factor 60:20:20 (Mitigation:Adaptation:Removal). I worked with three scores: Low (L), Medium (M) and High (H). A high score is given to the mitigation strategy a project or opportunity area is intended for (Eg: Atmocooling is first and foremost an adaptation company). A medium score is when evaluations have shown that a certain technology has a clear potential in this domain (Eg. Atmocooling can reduce GHG-emissions from transportation and can also terraform desserts thereby removing CO_2 directly). A low score is given when this technology does not impact a sector by any means. From there the initial impact factor is calculated. There are companies that have multiple climate impacts synergistically and this table accounts for that in their climate impact. Furthermore, I added two additional criteria, namely land use and power source as a means to evaluate the actual climate impact of a project or opportunity area. If a company requires significant amount of land, that will compete with other industries, it is given a H score, and thereby 10 points are removed from its impact factor. If the impact is limited and not a bottleneck, it is given an M and only 5 points are deducted and when there is no effect, it is given an L. The power source can either be photosynthesis (P) or renewables (R). When a company mentions that they will be powered by renewable energy, 10 points are deducted, since this system does not operate on life's principles and will be competing with other industries that use renewable energy as their decarbonization strategy.

Lastly, this table takes into account scientific and engineering risks, by removing points to the impact factor when there is a high or medium risk. Given that scientific risks are much more challenging to deal with, we added that a high science risk in a project, will lead to a deduction of 20 points.

Price competitiveness is not taken into account in this table, since we do not have data for the TEAs and at this stage we are only interested in the opportunity and climate impact rather than the competition and its costs.

Interestingly, from this table we see that most NETs struggle to be an impactful company if they do not have additional effects beyond carbon removal. Additionally, it's important to look at the impact factor of a company in order to evaluate its long-term potential if cutting edge technology de-risks some key constraints there are in their deployment.

Project or Opportunity	Mitigation (60%)	Adaptation (20%)	Removal (20%)	Impact factor	Land use (-10)	Power source (- 10)	Science risk (-20)	Engineering risk (-10)	Full Score
Atmocooling	M	H	M	73	L	R	M	M	53
Afforestation/reforestation	L	H	H	40	H	P	L	L	30
Augmenting photosynthesis	L	H	M	53	M	P	M	M	33

Synthetic autotrophs	H	L	M	80	M	P/R	H	M	45
Zfuels	H	L	L	73	L	R	M	H	43
Cell-free bioproduction	H	L	L	73	L	R	M	H	38
Whole-Cell, heterotrophs bioproduction	H	L	L	73	L	R	M	M	48
Whole cell, Autotrophs bioproduction	H	L	L	73	L	P/R	M	H	48
Geothermal hydrogen production	H	L	L	73	H	R	L	H	43
Carbonic anhydrase	M	L	H	67	L	R	M	H	38
Azolla event	M	L	H	67	H	P	M	M	42
Soil carbon sinks	L	M	H	53	H	P	H	H	23
Biomineralization	L	M	H	53	H	P	M	M	28
Microalgae CDR	L	L	H	40	H	P/R	L	M	20
Microalgae biofuels	H	L	L	73	H	P/R	H	H	38

Conclusion

In this research, we looked at the influence of emulating nature, as a model for solutions for mass industry decarbonization. During this process, I looked into a wide range of species, starting from highly conserved and primitive organisms that arrived on Earth 3.5 billion years ago, to other species that have recently adapted to our changing climate.

Our general knowledge on how non-model organisms sustain themselves on Earth is limited to basic understanding of their abilities to acquire food and their means of reproduction. This is very logical since allocation of funding to do research hardly touches upon species that have never been cultivated in a laboratory. Looking into nature for solutions in climatic change is thereby challenging, since most literature only touch upon superficial aspects of some of the most interesting organisms in terms of their metabolic networks.

This is particularly the case in finding NETs that are inspired by nature. The massive carbon drawdown that took place during Earths history, was mediated by species that remain extant. However, given their complex nature, most of them are not well studied and thereby utilizing them in an attempt to create a NETs company has too many unproven scientific questions. The next wave of fundamental research with these organisms should have clear hypothesis that can push the science and innovation of what we know and what we could create with what is known forward. Next to that, we need to remain cautious that many biological systems did not have time constraints when performing their activities and have had carbon drawdown occur over a course of millions of years. Humans however, need to remove gigatons of carbon in less than 30 years and we thereby need to constantly think about how we should accelerate these slow naturally occurring processes. One proposed method, is to partner with experts from other fields, namely, engineers who have been able to rapidly deploy technological innovations with creative approaches. But this is only possible if human incentives get to a point where we focus on the biggest problems collectively. Fortunately, we have seen multiple events whereby there was a collision of many expert domains. One example was getting humans to the moon. More recently, we saw the major revolution of computer technologies becoming the most dominating market and completely changing the way our world functions. Combining biology with engineering would allow biological systems to be perceived in a way that is beyond deductive reasoning and thereby might allow for novel insights that can make biology work faster and more efficient.

Currently, we see that many nature-based ideas that propose to massively decarbonize emitting industries, rely on synthetic biology to improve their systems. I believe synthetic biology on itself is an opportunistic domain that has shown massive improvements in bioproduction as well as adaptation for plants, however, we should be cautious that we don't overestimate what it can do within a timeframe. Nonetheless, it is important to question the possibility of using synthetic biology within any system, since sometimes an improvement in production can be just one point-mutation away.

In conclusion, the impact biological systems may have in our road to net-zero is enormous and we already see many novel technologies that operate by harnessing the power of nature. The drive to get more individuals in the climate tech space is already visible, but not near enough. It is evident however that at this point in time, getting an idea acquired in a laboratory to a product on a market offers the highest amounts of success because of the high incentive of investments taking place to create new, net-zero industries.

What makes a successful venture

Part of my research was to find a new way to define the success of a venture within the climate deep tech space. First and foremost, a success of a venture within the climate space should be directly correlated with its potential climate impact. It is thereby a priority for all groups (whether it's a large-scale investment firm or a small venture builder), that are investing equity towards creating new climate technology, have a board of experts within the domain of a technologies output, that are able to critically analyze each technology and their short- and long-term impact to all ecosystems. LCAs are a good measure for the impact of a product, but often relies on generalized data and don't address long-term impacts. Emulating nature will elucidate better what the long-term impacts of a technology is, since we can look at the emulated organisms and how they sustain themselves in an ecosystem as a measure for any overlooked effects. Particularly NETs require nature-based models, since there is no market yet that exists for CDR and there is thereby no clear guideline on what there needs to be delivered in terms of ecosystem impacts and carbon storage permanence.

After evaluating a ventures climate impact, we need to look at the risks of actually deploying this company since this also greatly influences the success of the venture. Most ideas or scoped opportunity areas at Marble are theoretical concepts backed by lab-scale prototypes or simulations. In other words, in most cases there is a risk that a proposed technology does not actually work when assembled together. In order to get funding for such technological insecurities, we need to ensure that the market risk, that is, the demand of such innovative technology on the market, is low. Ideally, we are looking at a technology that has a market size/TAM of roughly $1Billion. After that, we need to know what the risk-reward ratio of a venture is. If the expected gains of a given investment outweighs the risks of the loss of this investment, a company and their proposed model is venture backable. Lastly, it remains of critical importance that we can see that when an FIR is allocated to a co-founder, there is a significant stimulation in their work outputs. Their dynamics are critical for the success of their company.

Personal reflection

When I applied as an intern at Marble, I was in a period whereby I was discouraged and unmotivated by the way our academic system worked. I failed to see how current academic research is helping with mitigating climate change, since most research was not transferable to an industrial setup and in addition, there was minimal incentive for anything related to tech transfer. My internship at Marble offered me the opportunity to research technologies in a different way, namely, how they can become a company rather than defining a new hypothesis that can be tested in a laboratory. This led me to get inspired by how nature functions and what could be improved using biological systems. At Marble, we have individuals who have worked in multiple sectors including consulting and other venture studios and they thought me allot on the process of building a company and the markets that need to be infiltrated with that. I especially realized that fundamental research is pivotal for our fight to decarbonize all industries since there remains allot to be unexplored in biology. Although it seems that we will likely not decarbonize all industries by 2050, I am optimistic about what Marble and other companies in the climate deep tech space do to bring experts together to work on solutions that can have massive impact.

Acknowledgments

During my 6 months internship I had the opportunity to completely emerge myself in the climate deep tech space and learn extensively how companies are build and opperate at Marble. I would like to give a huge thank you to the entire team at Marble for making my internship so meaningful and unique. I especially acknowledge my supervisors Lipsa Nag and Benjamin Tincq for guiding me in my work on the biology for climate roadmap and their constructive criticism on how we can create technologies from concepts and ideas. I also want to thank all founders in residence that I had the pleasure of working with and wish them the best of luck in creating their companies.

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