Daybreak Alpha: Aerostatic Infrastructure for Direct Air Capture of Carbon Dioxide

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Abstract

Global temperature rise due to radiative forcings from the greenhouse effect, primarily caused by increasing concentrations of carbon dioxide (CO_2, represents an existential threat to humanity. Carbon removal technologies are currently undergoing active research and if deployed on a global scale, can limit temperature rise to 1.5°C. One of the most promising areas, direct air capture of CO_2, offers the possibility of lowering atmospheric CO_2 concentrations to preindustrial levels. However, issues with cost and scalability limit its potential.

Daybreak is a proposed infrastructure for direct air capture projects with the goal of enabling extremely affordable and rapid deployment of air capture technologies using a network of aerostatic balloons.

This work introduces the Daybreak infrastructure, explores the preliminary design, and describes several components in detail. Additional use cases, operating costs, and interfaces with other systems are also discussed. Useful feedback is welcome, and should be directed to @slipstreamterra on Twitter.

Contents

1 Background

As of April 2019, the current concentration of atmospheric carbon dioxide (CO_2) hovers around 410 ppm. It is commonly stated that even an immediate switch to 100% renewable energy sources would do little to mitigate the damaging effects of climate change [1]. Therefore, it is important to not only end the burning of fossil fuels, but also to develop negative emissions technologies that remove enough CO_2 from the atmosphere to limit global warming to a safe level of 1.5°C.

The simplest carbon dioxide removal technique is reforestry, although direct air capture, an emerging technology, is becoming of particular interest. Commonly known as "artificial trees", air capture, if developed at an industrial scale, would require substantially less resources than a forest, and also creates the opportunity for carbon-neutral fuel production. Current air capture projects suffer from a multitude of issues, most prominently:

1. Capture cost per tonne (estimated to be $400-$600 USD per tonne [2])
2. Scalability (large-scale, industrial capture has yet to be proven [3])
3. Energy (the process is extremely energy-intensive [4])

In order for atmospheric CO_2 capture to have any material impact on the climate, it must be performed on the gigaton scale. For context, annual global carbon emissions are nearly 40 Gt [5]. One of the largest air capture plants, operated by Climeworks, is only able to remove 900 metric tonnes per year [6]. For air capture to be performed on a gigaton scale, the number of direct air capture plants must increase. Enabling the scaling of air capture devices requires a novel system that must be:

1. Affordable, keeping costs below $100 USD per tonne of CO_2 captured
2. Extremely quick to deploy; installing air capture infrastructure should take minutes, not months
3. Completely passive, utilizing ambient winds and solar energy to keep operating costs at an absolute minimum (possibly bringing the entire system off-grid)
4. Location-flexible; the system can be deployed anywhere in the world (even offshore)

We propose the Daybreak project to democratize access to air capture infrastructure and increase the number of air capture projects worldwide, based on the principles outlined above.

2 Daybreak Air Capture Infrastructure

Daybreak is a proposed system for enabling affordable, rapid deployment of infrastructure for direct air capture of carbon dioxide. The two primary components of the infrastructure include:

1. **Aerostatic contactor**: We propose a global network of tethered kytoons to provide a cheap and flexible infrastructure for air capture.

2. **Regeneration module**: We show how a regeneration process independent from the contactor would enable rapid, continuous adsorption and desorption cycles.

Operation of a Daybreak system occurs as follows:

1. An air contactor consisting of a CO_2-adsorbent material is launched to an altitude of 600 meters via a tethered kytoon.

2. Once the adsorbent material is fully saturated with CO_2, the kytoon is winched down into a regeneration chamber.

3. In the regeneration chamber, the balloon is quickly refilled/replaced, and the saturated adsorbent is swapped out with a new one.

4. The kytoon, now with a fresh adsorbent, is launched back into the air, while the used adsorbent is sent to be regenerated via solar power.

The remainder of the paper is organized as follows. We motivate, define, and present individual components of the Daybreak air capture system in this section. Section 3 provides a brief roadmap, and we end with a discussion of future work.

2.1 Aerostatic Contactor

An important feature of the Daybreak infrastructure is the use of a network of kytoons, which has two functions. Airborne direct air capture devices give us access to consistent, high-velocity winds, which lowers operating costs. A balloon-based system also allows for reduced capital costs and enables flexibility in deployment location.

2.1.1 Motivation

At 0.04%, the concentration of carbon dioxide makes up a relatively low percentage of the gases in the ambient air. This requires we move extremely large volumes of air through a contactor in order to capture a meaningful amount of carbon dioxide.

There are two approaches to accomplishing this: increase the area of the inlet of the contactor and place it in a stream of low wind speed air, or force high-velocities of air through a small inlet.

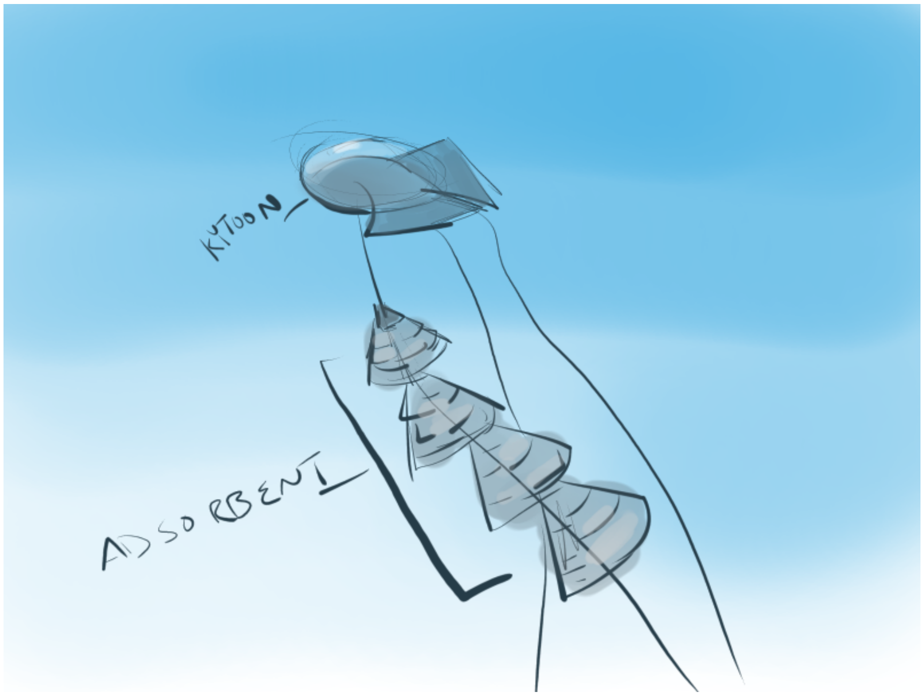

Figure 1: Conceptual sketch of a Daybreak kytoon, carrying modular air contactors.

Most direct air capture projects utilize the second approach, as they have found that capital expenditure makes up a significant enough portion of the overall capture cost per tonne to justify using a consistent, high-velocity flow of air[7].

However, balloons would allow for a reduction in capital costs, while also providing the necessary consistent, high-velocity air by taking advantage of the natural wind gradient, thus eliminating the need for fans.

The vertical profile of wind speeds can be modeled by a wind profile power law to estimate wind speed at a given height:

$$v = v_r(\frac{z}{z_r})^\alpha$$

with v and v_r being the velocities at a height, z and a reference height, z_r, respectively. α is the wind shear exponent, a coefficient that varies depending on atmospheric stability. The power law shows that wind velocity increases with height.

A balloon/kytoon-based infrastructure also reduces capital costs, as there is no need to build tall structures to reach a desired altitude. Balloons can also be launched offshore, there is access to higher-quality winds.

2.1.2 Kytoon

Operating a balloon in high-wind conditions requires we utilize a tethered kite balloon (kytoon) in order for our contactor to be directionally stable in strong winds.

FAA regulations require airborne wind devices to fly within a maximum height of 2000 ft, or about 600 meters. Therefore, we anticipate our balloons to fly at a height of around 500 to 600 meters above the ground, where we will have access to consistent, high-velocity airflow. Each balloon can be made of a strong, yet flexible, latex or rubber material.

The balloon can be raised or lowered to a desired altitude via a winch. The lift gas for each balloon would most likely be helium. However, deploying balloons offshore also creates the opportunity for producing lift gas in-situ via electrolysis of seawater, where hydrogen formed from water splitting may be used as the lift gas.

2.1.3 Contactor Geometry

Carried by each kytoon would be a string of modular air contactors. The string of air contactors would be made of a CO_2-adsorbent material, and would be launched into the air via the lift force provided by the kytoon.

Assuming the wind would not always be coming from a singular direction, the contactor must be open on multiple sides to compensate for variable-direction windflow. We propose a contactor geometry similar to that of a pinecone or toilet brush, where "leaves" of adsorbent material extend outwards from a central axis.

Each contactor must also be easily detachable at its base, in order to facilitate rapid replacement during the regeneration phase. A magnetic coupling mechanism is of particular interest.

2.1.4 Adsorbent Material

Solid sorbents would be attached to each balloon for CO_2 removal. The adsorbent material used for each balloon would most likely be a polyamine-modified honeycomb support, as amine-based sorbents are currently used in most commercial air capture plants. These amine-based sorbents operate via a thermal swing, where heat is used to release the carbon dioxide [8].

However, a cheap, nontoxic alternative to volatile amines would consist of an activated carbon foam loaded with sodium carbonate (Na_2CO_3). When reacted with CO_2 in the air, Na_2CO_3 forms the corresponding bicarbonate. Potassium carbonate (K_2CO_3) has also been shown to be a viable alternative to Na_2CO_3 [9]. Although the carbonation rates of carbonates such as Na_2CO_3 are slow, they can be sped up greatly by loading them over a porous matrix [10], hence the activated carbon foam.

2.1.5 Flight Equipment

In addition to its primary function of removing carbon dioxide from ambient air, Daybreak also has the potential to collect and process vast amounts of data via an array of sensors.

2.2 Regeneration Module

The regeneration module has two purposes: replace the used adsorbent in a balloon, as well as repair any potential leaks in the balloon.

2.2.1 Motivation

Modular direct air capture devices go through cycles of adsorption and desorption, where they are either removing carbon dioxide from the air or releasing it. For example, in the contactors proposed by Klaus Lackner, which operate on a moisture swing, the adsorbent material (an ion-exchange resin) must be immersed in water to release the CO2. During the desorption phase, those devices are unable to further absorb any more CO2 from the air.

Decoupling the desorption phase from the contactor, a concept used by Carbon Engineering, allows for the contactor to operate continuously, and continue to remove CO2 without interruption from the desorption cycle.

2.2.2 Adsorbent Replacement

Each adsorbent "pinecone cartridge" must be continuously swapped out with a new, regenerated adsorbent for minimal interruption to the adsorption process.

Some embodiment of a robotic end effector might be used to perform the "swapping." However, assuming magnets are used to connect the cartridge to the kytoon, a simpler approach would be to position the magnetic part of the kytoon over a chain of sorbents.

2.2.3 Concentrated Solar Thermal Regeneration

Sodium Bicarbonate decomposes into water, carbon dioxide, and sodium carbonate when heated to temperatures above 120°Celsius [11]. This allows us to pump out the CO_2 for further processing, as well as the water, which might be able to be used for electrolysis to generate hydrogen to refill the kytoons. The regenerated adsorbent, sodium carbonate (Na_2CO_3) is then able to be redeployed for further CO_2 capture and regeneration cycles. 120°C is also a temperature that could be easily reached through concentrated solar power, and has been successfully proven to be viable for use in air capture regeneration [12], thereby further lowering energy requirements and costs.

A possible regeneration module would consist of placing the fully saturated sorbent material inside a sealed container, and then placing an array of mirrors, such as parabolic reflectors or heliostats, around said container. Another possible design is to replicate the solar collector in a solar updraft tower, which consists of a wide greenhouse-like collector to trap heat around the container.

Heat can be stored for regeneration at nighttime or in unfavorable conditions by utilizing a saltwater thermal sink or similar heat-absorbing material. The regeneration module could also incorporate solar photovoltaics for additional heat and power output.

Captured CO2 can be stored underground in geological storage sites.

2.2.4 Balloon Deployment

Regeneration modules have the unique ability of being somewhat mobile, and are able to change their deployment location if conditions are deemed more favorable elsewhere.

Helium, the lift gas of choice, is lost at a rate of 0.5 percent each month. Once the adsorbent material is replaced, the balloon can be refilled/replaced if needed, and redeployed in less than thirty minutes. We expect each kytoon to last four to six months before needing Each regeneration module would contain a compressor and pumps to supply necessary additional lift gas to the balloon.

3 Roadmap

We can split the development of Daybreak into four distinct phases: scale model testing, open-environment testing, main system launch, and scale-up.

3.1 Scale Model Testing

The first version of Daybreak will be a scale model, primarily for testing the feasibility of an airborne air capture system. We expect to release the results of a feasibility study and open-source some aspects of the design.

3.2 Open-Environment Testing

A demonstration-scale version of Daybreak will be tested in open-environment conditions. Additional implementations of the following will be open-sourced:

- Kytoon design
- Adsorbent material
- Control mechanisms for regeneration

After the open-environment testing milestone has been reached, further improvements will be released on a rolling basis leading up to a public launch of the main system.

3.3 Main System Launch

The first full-scale, industrial deployment of the Daybreak infrastructure will commence once testing implementations of Daybreak are deemed successful. The infrastructure will be deployed on an industrial scale and begin removing and storing atmospheric carbon dioxide.

3.4 Scale-Up

Daybreak would be ready to scale once extremely rapid, affordable (<$100 USD/tonne) has been demonstrated on industrial scales.

All functional components of the Daybreak infrastructure will be open-sourced for community projects.

4 Future Work

Due to the open-source nature of the Daybreak project, community contributions are highly-encouraged.

We anticipate adding the following features to the Daybreak project on top of the features described above.

1. A precise plan for geological storage of the captured CO_2
2. A detailed analysis of cost and energy requirements
3. Further expansion on the control mechanisms for each system
4. An analysis of the impact of Daybreak balloons on volant animals

Daybreak is a work in progress, and any useful feedback is welcome. Consider DM-ing us on Twitter with feedback at @slipstreamterra.

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