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Climate technology investment and innovation: potential benefits of CO_2 capture from the air

Abstract

The purpose of this paper is to provide insights into technological innovation and investment for CO_2 reduction with focusing on the concepts of carbon capture and storage (CCS) and CO_2 direct air capture (DAC) technology. The paper initially argues the necessities and motivations for technology innovation as an effective approach for addressing climate change problem. Then, it undertakes investigations to track the main features, technical progresses, and potential benefits of CO_2 air capture over conventional methods. Finally, economical aspects and cost feasibility issues associated with this technology are discussed. The study approves air capture as an effective and feasible investment for climate change mitigation, subject to extensive commitments and strong policy supports.

Keywords: climate change, technology innovation, investment, economic feasibility, CCS, CO_2 air capture, DAC.
JEL Classification: O31, O32, O33.

Introduction

It is widely accepted that global warming is happening due to the increased atmospheric concentrations of greenhouse gases of which CO_2 from the combustion of fossil fuels is the largest contributor. The dominant role of CO_2 as an anthropogenic greenhouse gas, has led to increasing interest in characterizing the possible mitigation and adaptation measures (Canadell et al., 2009). A common and main barrier in mitigating climate change in both developed and developing countries is the long-lived infrastructure of energy and associated consumption patterns; meaning that for an effective mitigation action many types of energy infrastructure changes will be required that may take over a timescale of decades (McAllister, 2011). Stabilizing CO_2 concentrations will eventually involve deep reductions with “radical transformation of energy systems”, that is a matter of “when” and “how”, rather than “whether” (Battelle Memorial Institute, 2001). Particularly in developing countries, where greenhouse gas emissions “will likely surpass those from developed countries within the first half of this century” (Chandler et al., 2002, p. 3) massive investments will be required for the necessary infrastructure changes in order to achieve low-carbon climate-resilient growth.

The continued economic development requires an absolute increase in total energy production and consumption, while reducing CO_2 emissions would slow down the growth rate under current growth patterns and technological context (Yousefi-Sahzabi et al., 2011a). Nevertheless, “technological innovation” is regarded to be an approach to tackle climate change with minimum negative effect on economic growth. Yet, it is widely acknowledged that there is a large technology gap between usable carbon-neutral energy with current technologies and the amount required for climate stabilization (Galiana and Green, 2009). Given this context, this paper provides an overview of CCS technology and its limitations for significantly redacting the atmospheric levels of carbon dioxide. Then it explores the concept of CO_2 air capture, an innovative and emerging CO_2 reduction technology, as a method to compensate the limitation of conventional CCS systems. The paper includes a technology description and assessment as well as discussions on the potential benefits and feasibility of this technology for climate change mitigation.

1. Technological innovation and CO_2 reduction

There is a growing concern that the current international climate agreements and policies at worst are about to failing and at best are likely to take a considerable length of time to achieve the desired outcome (IMechE, 2011). There is a severe need for alternative strategies with potentials of immediate impacts on the climatic situations, among which a technology-oriented strategy can have the greatest contribution (Barrett, 2012). With technological innovation it can be ensured that CO_2 emission can be addressed without compromising economic growth (OECD, 2011). Various studies have employed energy and economic models to emphasize the role of technological change in climate mitigation strategies (van der Zwaan et al.,

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2002; Kypreos and Bahn, 2003; Gillingham et al., 2007; Popp et al., 2009; Moss et al., 2010). The IPCC Forth Assessment Report has mentioned, as well, about this fact, though with some caution (IPCC, 2007a, p. 20): “There is high agreement and much evidence that all stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are currently available or expected to be commercialized in coming decades”.

Later studies, however, clearly demonstrate that current approaches to stabilizing climate will not work because of the lack of readiness of the required energy technologies (Galiana and Green, 2009).

1.1. Motivations and incentives for investment. The initial costs of technology innovation and diffusion is believed to be much lower than the estimated costs of “inaction”. In fact, the benefits of reducing GHG emissions are the avoided damages that would occur through the business-as-usual path (Shrum, 2007; Goulder and Pizer, 2006). Studies showed that the costs of “inaction” on climate change further than a certain level will be huge due to the higher frequency and intensity of natural hazards, and declining in agricultural yields (OECD, 2008). Many economists agree that the environmental effects of CO_2 emissions create considerable risks to the national economies across the world (West, 2012). The economic value of improvements in the current CO_2 reduction technologies and deployment of newer and more advanced technologies was approved by many studies (IPCC, 2007b). The significance of advanced technology development is realized when one takes into account that each degree of warming in global system will raise the risk of critical climate events, causing large and irreversible damages worldwide (OECD, 2008). The estimated benefits of emission reduction vary widely ranging from -$10 to $350 per ton of carbon (Goulder and Pizer, 2006). If we look at the risks and costs of inaction, ambitious investment plans to reduce CO_2 emissions will make economic sense (OECD, 2008).

On the other hand meeting the primary capital needs for investment in technological innovation is possible by initiating broad range of international policy and regulatory instruments (OECD, 2008). It is vitally important that climate policies and regulations provide appropriate incentives for the development and diffusion of climate-friendly technologies (OECD, 2011). For example setting a global price for CO_2 and other GHGs through the tax measures, efficient regulations, and market forces can make significant contributions (Hodgson et al., 2008). A small tax on each ton of CO_2 can raise tens of billions of dollars globally. Galiana and Green (2009, p. 23) showed that “$5.00 per ton CO_2 tax would raise $30 billion a year in the US, about the same in China, almost as much in the EU, and lesser, but significant amounts in Russia and India; and as much as $150 billion per year could be raised in this way worldwide”. Earlier studies have also estimated the revenue potential of carbon taxes as high as 2% of national GDP in some developing countries (Shah and Larsen, 1992). Taking the most advantages of such high potentials would make it possible to meet ambitious targets by directing massive investments to climate technology innovation and adoption.

2. CO_2 capture and storage (CCS): a key option with constraints

It is already approved that the increasing energy efficiency, expansion of renewable resources, and development of cleaner energy technologies such as “clean coal technology”, beside having many environmental benefits such as emitting less sulfur dioxide, nitrogen oxides, and particulate matters, have great potentials in CO_2 emission reduction (Yousefi-Sahzabi et al., 2011b; Amanollahi et al., 2012; Amanollahi et al., 2013; Rubin, 2013). However, on the other hand, it is also acknowledged that “no single solution exists, and therefore, a portfolio of carbon dioxide reduction technologies and methods will be needed to successfully confront rising emissions” (Almendra et al., 2011, p. 1). According to the IEA (2009), carbon capture and storage (CCS) is “an important part of the lowest-cost greenhouse gas mitigation portfolio” and without it, the overall costs to halve emissions by 2050 rise by 70%. In its latest edition of “Technology Roadmap: carbon capture and storage”, IEA (2013) indicates that “CCS is an integral part of any mitigation scenario where long-term global average temperature increases are limited to significantly less than 4 C, particularly for 2 C scenarios”.

A typical CCS system may use one of available methods for capturing CO_2 from a point source, namely post-combustion, pre-combustion, and oxy-fuel combustion; among which the post-combustion capture using solvent scrubbing is one of the more established technologies. There are currently several facilities that use amine solvents to capture considerable flows of CO_2 from the flue gas streams (IEA, 2009). The captured CO_2 then must be transported to a suitable storage site that is at a distance from the emission source. Pipelines are preferred for transporting large amounts of carbon dioxide for distances up to around 1,000 km, and for amounts smaller than a few million tons of CO_2 per year or for larger distances overseas, the use of ships, could be economically attractive (IPCC, 2006). The final component of CCS system is injecting CO_2 into a geologic formation i.e. a depleted petroleum reservoir, a deep saline reservoir, or an unmineable coal seam. Saline formations, however, have the greatest storage capacity, followed by petroleum reservoirs.

2.1. Limitations of conventional CCS for CO_2 mitigation. The global CO_2 storage capacity has been estimated to be in the range of 400 to 1,800 giga-tons carbon, and by considering the current annual global CO_2 emissions rate of 6.6 giga-tons carbon from fossil fuel combustion, there is still significant global capacity for geological storage of CO_2 in the future (Sivaraman, 2009). When considering CCS capacity for a deep CO_2 reduction and effective climate mitigation, the problem extends beyond storage capacity, and instead; the "capture capacity" remains as the main issue of concern. CO_2 capture in the conventional CCS is limited to large stationary emission sources such as power plants and industrial units which are today responsible for 20-40% of global emissions (House of Commons, 2008). For this reason some studies predicted that the conventional CCS potential for reducing future emissions from fuel energy will only be 20% (Dooley et al., 2006).

In addition, the capture of power plant CO_2 is limited to those plants that are close to storage sites accounting for a small fraction of the total anthropogenic emission of CO_2 (Kheshgi, 2006). Moreover, a considerable number of current power plants particularly in developing countries are not technologically suitable to be retrofitted with capture equipment (Gibbins and Chalmers, 2008; Markusson, 2008). Therefore considering the long operating life of fossil fuel power plants which can reach beyond 50 years, a considerably high initial capital cost will be required to replace or change the current energy infrastructure. On the other hand, the concept of "capacity" for CO_2 reduction may not be limited to the current and future emissions, but could also be extended, as well, to the past emissions, the so called "cumulative and historical emissions"; the emissions that have already started and have roughly doubled since the early 1970s (OECD, 2008). Conventional CCS with the best available technology and maximum economy of scale and efficiency will only offset a portion of "future emissions" but has nothing to do with "historical emissions".

3. CCS with CO_2 capture from the air: an additional approach

In conventional CCS methods CO_2 is captured from large industrial and energy-related sources. However CO_2 can also be captured from ambient air, after its emission to the atmosphere, mitigating emissions from distributed sources and reducing atmospheric concentrations of CO_2 when emissions have already been dispersed. The latter is an under development and near commercialization technology which is called direct air capture (DAC). Although IPCC 2005 CCS Report and its 2007 Fourth Assessment Report "has mentioned to air capture only in passing", the technology is receiving more attention every year (Pielke, 2009, p. 1) and the idea that it will eventually be needed to meet lower stabilization levels is finding more advocators (Jones, 2009).

3.1. What is direct air capture? There are two categories for direct removal of CO_2 from the air including biological and industrial approaches. Biological CO_2 reduction becomes possible through a number of ways including expanding natural photosynthesis by afforestation and reforestation (Sohngen and Mendelsohn, 2003), using biomass with CO_2 capture (Uddin and Barreto, 2007), and fertilizing iron-limited regions of the oceans which stimulates the growth of phytoplankton and causes the surface water to extract CO_2 from the air in order to restore chemical balance (Barrett, 2012; Lampitt et al., 2008). Other examples could be terrestrial ecosystem sequestration, biochar, and enhanced weathering.

Another approach is the industrial method, the so-called "air capture" method. This approach is in particular important for the "already sparked high levels of research and development, in part reflecting the potential scale of the market resulting from the apparent flexibility of the techniques" (McLaren, 2012, p. 16). Air capture removes CO_2 from the atmosphere just like ecosystems carbon sequestration, but it is through the large-scale industrial processes (Keith and Ha-Duong, 2003). As illustrated in Figure 1, the process uses a chemical sorbent that selectively removes CO_2 from the ambient air (stream 1) and releases it as a concentrated stream for disposal (stream 2), while the chemical sorbent is regenerated and the CO_2-free air is returned to the atmosphere (stream 3) (Socolow et al., 2011).

Source: House et al. (2011, p. 3).

Fig. 1. CO_2 air capture industrial process

3.2. Background and earlier applications. Back in the 1930s, CO_2 was first commercially removed from the air for preventing the equipment of cryogenic oxygen plants from fouling and clogging (Greenwood and Pearce, 1953). The CO_2 removal through this process was achieved by formation of the dry ice, however, this method was changed during the years and currently the modern air separation plants use molecular sieves for this purpose (House et al., 2011). Therefore, the technology has been in use for almost 80 years, during which there have been many other industrial applications for it. Removing CO_2 from the air inside the spacecrafts is among the other important applications of air capture. Since human emit CO_2 at the rate of 1 kg/person/day, the concentration of CO_2 can increase quickly in the space shuttle (Heinrich, 2003). The first generation of spacecrafts such as the Mercury, Gemini and Apollo used Lithium Hydroxide (LiOH) for this purpose, but because of some important disadvantages associated with this chemical, the method was later replaced with a four bed molecular sieve system (Ranjan, 2010). Recently NASA is considering other metal hydroxides for air removal purposes that are easily regenerable such as Silver Hydroxide (AgOH) (Heinrich, 2003).

Another important application of CO_2 removal from the air was in the life support system of submarines. Submarines were first widely used during World War I and II, and now figure in many large navies. Since there was not enough energy to power air purification systems, Soda Lime and Lithium Hydroxide (LiOH) were used to absorb CO_2 (Ranjan, 2010). Soda lime is a variable mixture of sodium and calcium hydroxides that react with CO_2 and form carbonates (Grogan, 1998). It uses a chemical reaction to absorb carbon dioxide from air and by-products are water and heat (Ranjan, 2010). The current modern submarines are using electronic power systems for removal of carbon dioxide.

The above applications for CO_2 removal were developed for other purposes than climate stabilization, where the overall cost, scale, and capacity of the process significantly differs. The possibility of industrial CO_2 capture for climate purposes was first suggested by Lackner in 1999 (Lackner et al., 1999).

3.3. Advantages over conventional capture methods. *3.3.1. Offsetting emissions from all sectors.* In order to stabilize atmospheric levels of CO_2, it is necessary to not only deal with CO_2 emissions from power plants and large point sources, but from all emission types including distributed, mobile sources such as automobiles or small stationary sources such as residential buildings (Lackner et al., 2001). Air capture can ensure that various emission source types from all sectors will potentially be mitigated.

3.3.2. Potentials for negative emissions. Unlike other problems caused by environmental emission such as acid rain, urban smog, and particular matters (Amanollahi et al., 2012; Amanollahi et al., 2013), climate change is not happening due to any year’s emissions but by accumulated historical emissions (Lemoine, 2007). Removing the CO_2 directly from the air means that any emissions can be compensated; even the emissions that happened in the past (e.g. decades ago) and theoretically the emission levels can be returned to the pre-industrial level (280 ppm) while ongoing the use of fossil fuels (Lackner, 2010). Jones (2009) points out in a Nature article that there are potentially no limitations to how much CO_2 can be extracted by air capture method: “name an atmospheric concentration you’d like to end up with” (Jones, 2009, p. 1095). Although these expressions could obviously be considered very optimistic which contain so many assumptions and optimistic projections; however, it is evident that air capture may at least be a helpful approach to “buy time” for such difficult and complex changes to our energy, agriculture and resource systems in general to take place, as pointed out by McGlashan et al. (2012).

3.3.3. Continued reliance on fossil fuel. Fossil fuels are of great importance because they produce significant amounts of energy per unit mass. Despite the growth in renewable energy development fossil fuels remain dominant in the global energy mix and will continue to dominate global energy use (IEA, 2012). They will account for around 85% of the increase in world primary demand over 2002-2030 and their share in total demand will increase slightly, from 80% in 2002 to 82% in 2030 (Bilen et al., 2008). It will not be possible to abandon fossil fuel energy consumption, which are plentiful and cost-effective energy source for the human, while the air capture method is the only practical option to maintain access to oil-based energy products (Lackner, 2010). In addition, air capture has potentials to be an integral element of “closed cycle” hydrocarbon synthesis that could bridge the gap between renewable energy and liquid fuels.

3.3.4. Being decoupled from existing infrastructure. Air capture enables the decoupling of CO_2 capture from the existing energy infrastructure “easing the constraints that arise when new energy technologies must be integrated into the existing infrastructures” (Keith et al., 2010, p. 108). Air capture technology does not require abandonment of the existing manufacturing or energy infrastructure, i.e. it is not necessary anymore to wait for phasing out of existing and older infrastructures before addressing

CO_2 emissions problem (Lackner et al., 2001). This brings great cost benefits which otherwise will require massive investments for the necessary infrastructural changes.

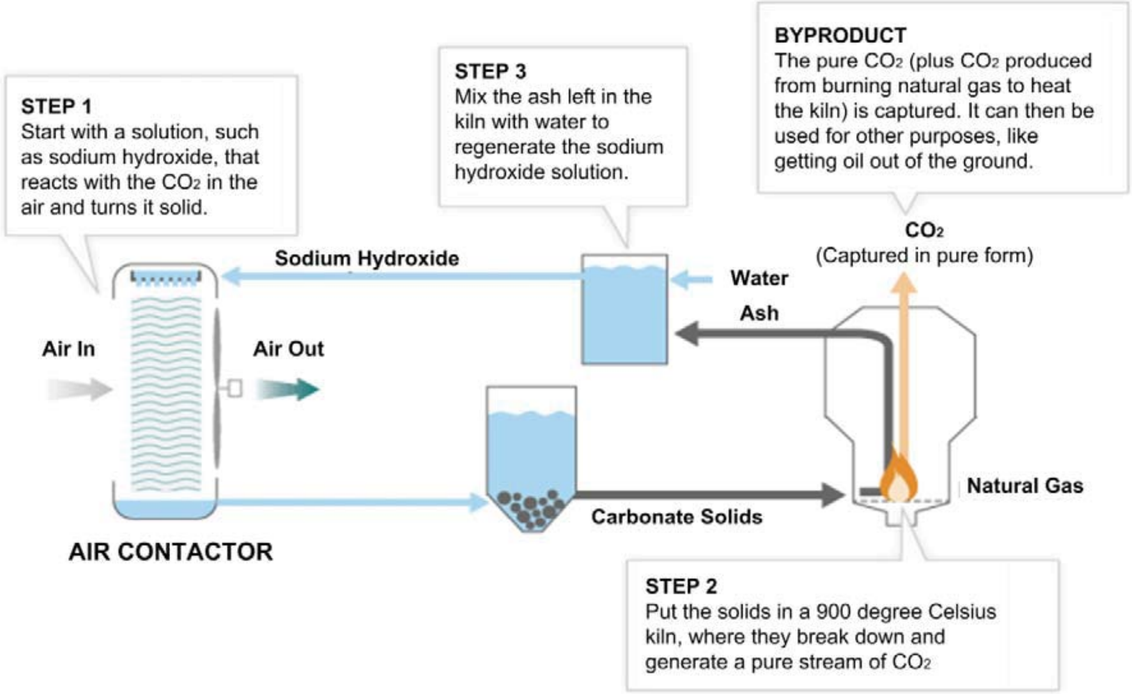
Another advantage of being decoupled from existing infrastructure as noted by Stolaroff (2006) might be realized in the context of a future worst-case climate scenario (p. 3): "consider a future climate change scenario where a sudden shift in the climatic system severely raises concern and demand for action; since air capture is decoupled from the rest of the energy system, it can be deployed more quickly than other reduction tools".

3.3.5. Flexibility in the selection of capture location. Since CO_2 is removed from the ambient air, there is great flexibility on the selection of the capture locations, i.e. CO_2 can be captured from the atmosphere of the favorable storage site and therefore it would not have to construct costly pipelining system between the CO_2 sources and sinks (Lackner et al., 2001). Therefore much higher flexibility of air capture location compared to power plant capture will avoid increasing costs due to the CO_2 transport and saturation of individual reservoirs (Nemet and Brandt, 2012). Additionally this feature of air capture technology provides partial freedom to construct the capture units where it is cheaper and it can bring more cost favorability (Jones, 2009; Lackner, 2009).

4. Emerging technologies for CO_2 air capture

The air capture process for CO_2 reduction from the atmosphere involves a technology that brings air into contact with a chemical sorbent. This chemical sorbent absorbs CO_2 from the air, and the industrial process then separates the CO_2, recycles the sorbent, and transfers the captured CO_2 to the geologic storage. This process is followed by various technology developers; however one approach to categorize different methods is to consider the form of chemical sorbent, i.e. liquid sorbent and solid sorbent. The examples of a real-world and well established methods for each group could be Keith et al. (2006) who are developing a liquid sorbent based technology, and Lackner (2011) who is working on solid sorbent processes.

A prototype system developed by Keith et al. (2006) is among well-known air capture systems that uses sodium hydroxide and lime to remove carbon dioxide from the air. The development of this system is led by Professor David Keith, who built a carbon capturing machine based on the mentioned system. His carbon capturing machine which is housed by Calgary based "Carbon Engineering" company, uses a three-step process (Figure 2) as well as some chemistry know-how to filter the ambient air and extract the CO_2 from the atmosphere (Harris, 2011).



Source: Carbon Engineering; carbonengineering.com.

Fig. 2. Schematics of Keith's CO_2 capturing machine

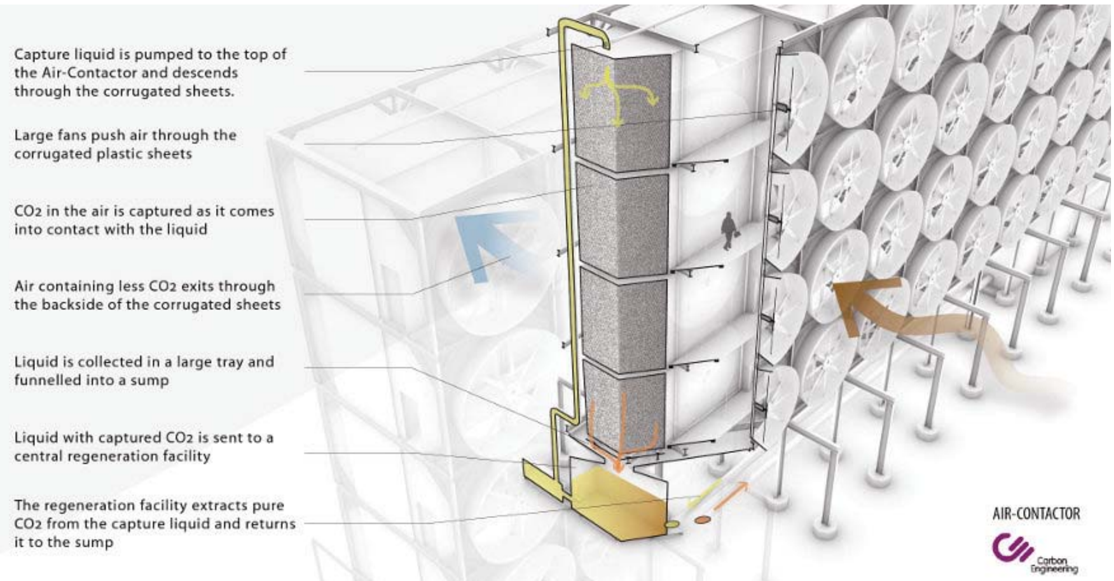
The first important component of the Carbon Engineering air capture machine is its fans, which draw ambient air through a 31-foot-long chamber that is filled with wavy plastic material (Figure 3). Then water laced with sodium hydroxide runs down that plastic and reacts with CO_2 to separate it from the air

(Harris, 2011). Overall, the technology uses two processes consisting of an air contactor and a regeneration cycle: the solution with CO_2 moves to a regeneration-cycle that extracts CO_2 and regenerates the chemical solution for re-use in the contactor (Mader, 2012).

After air is entered to the contactor, it passes through small channels containing a high-surface-area material named "structured packing" which has channels wetted by a CO_2-absorbent liquid (a water-based solution that absorbs CO_2) and while air is passing through the contactor, much of its CO_2 component is removed (Gunther, 2012). The contactor generates a liquid stream which contains the absorbed pure CO_2 for geological disposal (Figure 4).

Source: Carbon Engineering; carbonengineering.com.

Fig. 3. A rendering of Carbon Engineering's air contactor



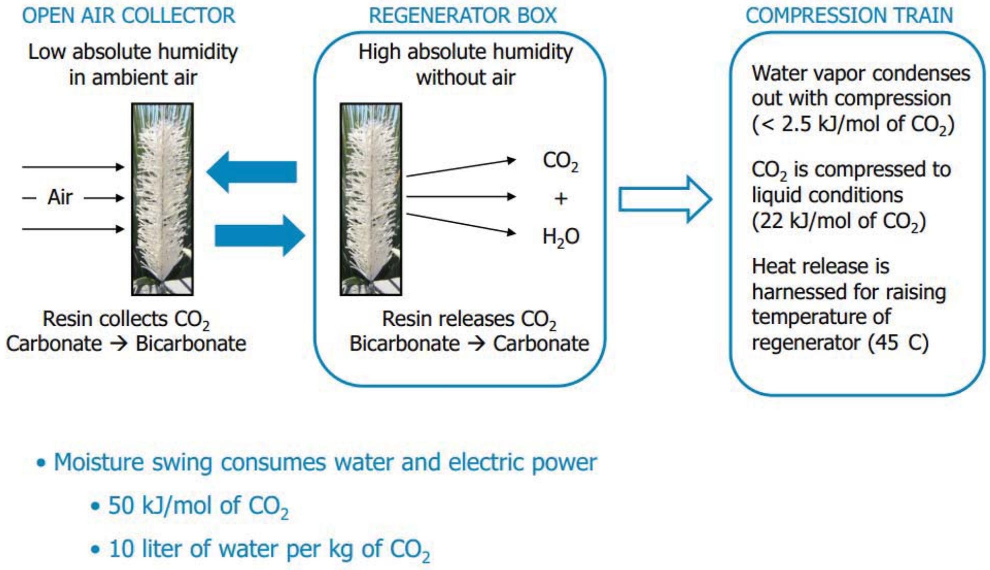
Source: Carbon Engineering; carbonengineering.com.

Fig. 4. A drawing of the Carbon Engineering contactor's inside components

Another promising technology is developed by Professor Klaus Lackner from the Earth Institute at Columbia University. This technology which is hosted by Kilimanjaro Energy (www.kilimanjaro-energy.com) captures CO_2 from the air using a commercially available wet resin. This material shows different behavior in wet and dry environment; in the former it turns CO_2 into the carbonate, and in latter, it turns the CO_2 into bicarbonate (Mader, 2012). When the resin becomes exposed to water (moisture) in a relative vacuum, the created bicarbonate changes back to carbonate and release CO_2 and water vapor which becomes pressurized to change to the water (Mader, 2012). This process is named "moisture swing absorption" (Figure 5).

This novel system mainly requires water and electricity to collect CO_2 from the air. For creating moisture the saline water can also be used and the energy consumption for the capture process is such that only 21% of the CO_2 captured would be released again at a distant power plant that produces the electricity required in the process (Lackner, 2010). Therefore almost 80% of the captured CO_2 is a real reduction from the atmosphere. Professor Lackner has imagined huge 'farms' featuring thousands of these devices that could capture billions of tons of CO_2 from the atmosphere (Jones, 2009) similar to the prototype shown in Figure 6.

Other alternative methods are under development but because of being near to commercialization, the details are not published yet due to the proprietary issues (Pielke, 2009). There are, however, various ranges of technologies being explored for air capture, making significant progresses toward final development in coming years (Jones, 2009). In 2007, entrepreneur Sir Richard Branson, along with judges including Al Gore, the former US vice president, created a $25 million prize for scalable and sustainable ways of removing greenhouse gases from the atmosphere, which is one of the largest 296 science prizes on offer, of 11 current finalists from over 10,000 entries (Heffernan, 2007) (www.virginearth.com). Currently, the main technical challenge ahead for all research and development efforts seems to be how to cope with higher costs of direct air capture.



Source: Lackner, 2011a; p. 35.

Fig. 5. Moisture swing absorption (single step) technology

Source: Stonehaven Productions; www.stonehaven.ca.

Fig. 6. A rendering of air capture farm

5. Cost issues of air capture climate mitigation

Although there are not yet large-scale technologies that achieve air capture in scalable conditions, previous studies suggested that it will be comparatively easy to develop such technologies on the timescales relevant to climate policy (Keith and Ha-Duong, 2003). According to Keith (2009) there are two factors which make air capture more difficult than exhaust streams: first, the lower concentration of CO_2 in the air which results in higher thermodynamic barriers; and second, the cost of energy and materials for moving large quantities of air through the absorbents. More recent studies have shown that the technology is in the final stage of readiness; and the UK's Institution of Mechanical Engineers (IMechE) stated that the technology can be rolled out by 2018 based on their successful small-scale demonstration project (REUTERS, 2011). Other estimations have already anticipated that the technology will be deployable by 2015 (Jones, 2009). In particular, during the past couple of years the technology has become more and more matured every year; what made air capture advocates to emphasize that any feasibility assessments must be based on the most recently achieved progresses. For example a technical assessment by the American Physical Society (APS) arguing against cost feasibility of air capture, received critics for being based on the concepts developed in the first days of air capture research, more than 5 years ago; while novel and highly efficient technologies were evolved during the last few years (Climeworks LLC, 2011). Lackner (2011b) accused APS's assessments by stating that the cost estimates of new technologies have often been wrong because these technologies present moving targets while the costs can significantly drop as technology develops. Using very similar economic assumptions as used by the APS report, Holmes and Keith (2011) suggested an optimization method through which the total contactor costs of air capture can be estimated as 75% lower than those from APS's estimations.

In short, the economic feasibility of air capture was hotly disputed in the past years. Keith (2009) has suggested that the cost of air capture will not be determined by the current small-scale studies and recommended the "pilot-scale process development" as the only way to make the costs evident. Other studies have suggested that air capture could be a useful technology which has implications for climate policy and deserves to be among the policy options in international debates (Pielke, 2009; Lemoine, 2007; Stolaroff, 2006).

5.1. Cost estimations in the absence of scale effect. While some air capture opponents claim that this technology's costs are considerably high (i.e. \$1000 per ton of CO_2), the advocate researchers and DAC developers indicate that the technology could be achieved by lower costs. For example, Professor Keith says his technology can currently extract CO_2 from the air at a cost of less than \$250 per ton (Isaacson, 2014). Barrett (2012) believes the marginal cost associated with CO_2 air capture range from \$100 to \$200 per ton of carbon that exceeds current estimates of the social cost of carbon (ranging about \$7 to \$85 per ton of carbon). He believes these estimated costs are lower than estimations of the cost of meeting a 2° C temperature change target by means of abatement technology by around 2100 (Barrett, 2009). Several studies have suggested that air capture could be a viable climate mitigation technology because it costs no more than a few hundred dollars per ton of CO_2 avoided (House et al., 2011). Pielke (2009) showed that the calculation of air capture costs in global climate policy is simply possible by multiplying the expected capture cost per ton of carbon by the integral of the difference between projected emissions and emissions under air capture. By assuming the net carbon dioxide emissions from 2008 to 2100 to be 880 gigatons of carbon and the annual global GDP growth rate to be 2.9% he calculated the cumulative costs of air capture over the periods 2008-2050 and 2008-2100 by considering the cost ranges of air capture per ton of carbon as below: (a) The highest value suggested by Keith et al. in 2006 of \$500 per ton of carbon; (b) The lower value suggested by Lackner and Keith in 2006 and 2007, respectively, of \$360 per ton; and (c) The lowest value by Lackner in 2006 of \$100 per ton.

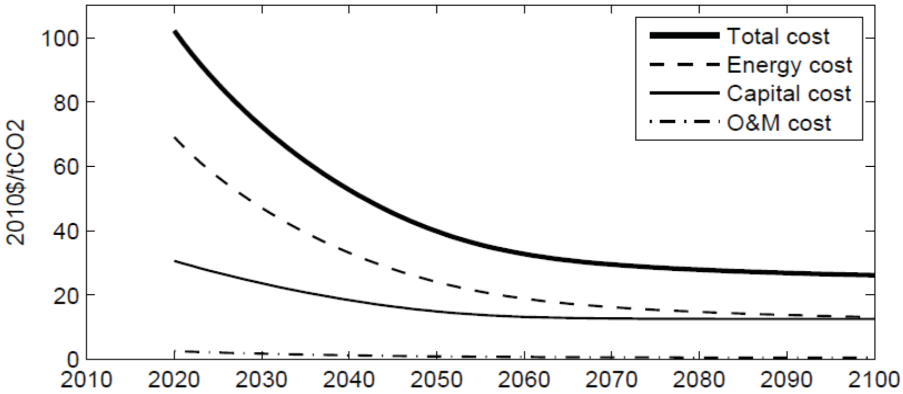
The above estimations can be compared with the potential costs of inaction – the worsening damages that will result from allowing climate change to continue. A report for FOE (Ackerman and Stanton, 2006) indicates that the first 2° of warming will have numerous destructive and costly impacts for northern countries and most developing countries will experience greater costs. This report continues that Beyond 2° of temperature change in the second half of 21st century, the effects of additional warming – which will certainly happen in the absence of ambitious mitigation efforts – will be much more dangerous and all potential benefits from CO_2 emission will vanish. Pielke (2009) showed that the projected costs of inaction over the 21st century in terms of global GDP that ranges from 5% to 20%, as estimated by IPCC and Stern's Economic Review (Stern, 2007), is higher than the costs of CO_2 air capture based on the various scenarios (Table 1); hence it should receive the same attention as other climate mitigation approaches. Some studies have also approved the viability of air capture by comparing it with other costly mitigation approaches. For example Lackner et al. (2001) believe air capture cost efficiency is higher than shifting transportation infrastructure to non-carbonaceous fuels.

Table 1. Cost of air capture as a percentage of global GDP (Source: Pielke, 2009, p. 222)

	$500/tC	$360/tC	$100/tC
450 ppm cost to 2050	2.7%	1.9%	0.5%
550 ppm cost to 2050	0.0%	0.0%	0.0%
450 ppm cost to 2100	2.1%	1.5%	0.4%
550 ppm cost to 2100	1.5%	1.1%	0.3%

It must be noted that all the above estimations are based on the current prices for air capture; without considering the scale effect. However, experience with technological innovation suggests comparatively declining of the marginal costs over the time (Beinhocker, 2008).

5.2. Consideration of the "economy of scale". Economy of scale is defined as the "decline of average costs (per unit of product) with an increase of production volume per unit of time, where production capacity is variable" (Nooteboom, 2004, p. 258). The majority of air capture cost arguments are based on "limited production volumes" without considering the economy of scale. For example compare the costs of making a hand-made car with the cost of its mass production in a factory. Now consider that air capture will use a single technology for offsetting CO_2 emissions of all kind of emitter from all sectors in a global scale. This means a huge economy of scale, because identical capture units will be produces in large numbers in a given period. By considering the economy of scale, Lackner (2010) estimated a long term cost of air capture as \$30/ton of CO_2, though it seems to be a rough estimation that may involve some certain levels of uncertainty. Nevertheless, it is reasonable to say air capture worth to be investigated as a mitigation options with great potentials of economy of scale for future climate change mitigation. Beside the scale effect, Lackner (2011b) draws attentions to the "dynamic of cost reduction via learning" as an important fact that can dramatically affect the production costs of air capture equipments; the same could be seen in the development and mass production of other technologies such as computer hardware, solar panels and gas turbines. Figure 7 illustrates the cost trends of air capture in the context of "time" suggested by Nemet and Brandt (2011; 2012); showing higher costs in the initial periods while dramatic shrinkage by the time; an indication of the scale effect and cost reduction via learning.



Source: Nemet and Brandt, 2011, p. S8; 2012.

Fig. 7. Air capture cost components

Summary and conclusion

After several years of attempts to limit future atmospheric CO_2 growth, it is eventually approved that international leaders are failing in their fight against global warming (Satter, 2013); a fact that could be end up with severe damages on global economy and environment. Kyoto protocol has already failed and "even if the countries honor their promises ... by 2020 emissions will exceed the trajectory for keeping warming under 2°C" (The Economist, 2011). Evidently, the reductions demanded by the climate protocols are far less than what would ultimately be required to stabilize CO_2 concentration. Moreover, those demanded goals are too ambitious to be achieved by using current mitigation technologies. For practical stabilization of CO_2 levels, it is necessary to invest in novel approaches with greater and short-term potentials. This will not be achieved without addressing emissions from all sectors, rather than focusing on power plants. Even by doing so, yet the issue of historical emissions will remain as a source of concern. For preventing CO_2 concentrations from reaching critical levels, there may be little choice but to extract some of the CO_2 already in the atmosphere (Jones, 2009). Having all these features and considering the recent advancements, air capture deserves to be among the policy options. Several attempts for commercialization of the technology are on the way and demonstration projects are advancing, though there is a lack of strong policy supports. It is asked whether, given the current level of international policy support for CCS, policymakers could do more to consider and integrate support for investment in DAC systems as well; as despite the discussed uncertainties, further resources into this promising but undercapitalized area could be an important step on the journey to achievable and sustainable ways of meeting emissions reduction targets through continued mitigation with technological innovation and the removal of greenhouse gases from the atmosphere.

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