

“Climate technology investment and innovation: potential benefits of CO2 capture from the air”

AUTHORS	Amin Yousefi-Sahzabi Debra J. Davidson Kyuro Sasaki Akiya Nagata Hossein Yousefi
ARTICLE INFO	Amin Yousefi-Sahzabi, Debra J. Davidson, Kyuro Sasaki, Akiya Nagata and Hossein Yousefi (2014). Climate technology investment and innovation: potential benefits of CO2 capture from the air. <i>Investment Management and Financial Innovations</i> , 11(4-1)
RELEASED ON	Monday, 15 December 2014
JOURNAL	"Investment Management and Financial Innovations"
FOUNDER	LLC “Consulting Publishing Company “Business Perspectives”



NUMBER OF REFERENCES

0



NUMBER OF FIGURES

0



NUMBER OF TABLES

0

© The author(s) 2024. This publication is an open access article.

Amin Yousefi-Sahzabi (Japan), Debra J. Davidson (Canada), Kyuro Sasaki (Japan), Akiya Nagata (Japan), Hossein Yousefi (Iran)

Climate technology investment and innovation: potential benefits of CO₂ capture from the air

Abstract

The purpose of this paper is to provide insights into technological innovation and investment for CO₂ reduction with focusing on the concepts of carbon capture and storage (CCS) and CO₂ 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 CO₂ 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, CO₂ 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 CO₂ from the combustion of fossil fuels is the largest contributor. The dominant role of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ air capture, an innovative and emerging CO₂ 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 CO₂ 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 CO₂ 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.,

© Amin Yousefi-Sahzabi, Debra J. Davidson, Kyuro Sasaki, Akiya Nagata, Hossein Yousefi, 2014.

Amin Yousefi-Sahzabi, corresponding author, aminyousefi@kyudai.jp, Department of Earth Resources Engineering, Kyushu University, Japan.

Debra J. Davidson, Department of Resource Economics and Environmental Sociology, University of Alberta, Canada.

Kyuro Sasaki, Department of Earth Resources Engineering, Kyushu University, Japan.

Akiya Nagata, Graduate School of Economics, Kyushu University, Japan.

Hossein Yousefi, corresponding author, hosseinyousefi@ut.ac.ir, Department of Renewable Energies and Environmental Engineering, Faculty of New Sciences and Technologies, University of Tehran, Iran.

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 CO₂ emissions create considerable risks to the national economies across the world (West, 2012). The economic value of improvements in the current CO₂ 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 CO₂ 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 CO₂ 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 CO₂ can raise tens of billions of dollars globally. Galiana and Green (2009, p. 23) showed that “\$5.00 per ton CO₂

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. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ from the flue gas streams (IEA, 2009). The captured CO₂ 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 CO₂ 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 CO₂ 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 CO₂ mitigation. The global CO₂ 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 CO₂ emissions rate of 6.6 giga-tons carbon from fossil fuel combustion, there is still significant global capacity for geological storage of CO₂ in the future (Sivaraman, 2009). When considering CCS capacity for a deep CO₂ reduction and effective climate mitigation, the problem extends beyond storage capacity, and instead; the “capture capacity” remains as the main issue of concern. CO₂ 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).

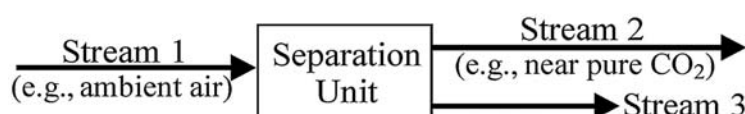
In addition, the capture of power plant CO₂ is limited to those plants that are close to storage sites accounting for a small fraction of the total anthropogenic emission of CO₂ (Kheshgi, 2006). Moreover, a considerable number of current power plants particularly in developing countries are not technologically 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 CO₂ 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 CO₂ capture from the air: an additional approach

In conventional CCS methods CO₂ is captured from large industrial and energy-related sources. However CO₂ can also be captured from ambient air, after its emission to the atmosphere, mitigating emissions from distributed sources and reducing atmospheric concentrations of CO₂ 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 advocates (Jones, 2009).

3.1. What is direct air capture? There are two categories for direct removal of CO₂ from the air including biological and industrial approaches. Biological CO₂ reduction becomes possible through a number of ways including expanding natural photosynthesis by afforestation and reforestation (Sohngen and Mendelsohn, 2003), using biomass with CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂-free air is returned to the atmosphere (stream 3) (Socolow et al., 2011).



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

Fig. 1. CO₂ air capture industrial process

3.2. Background and earlier applications. Back in the 1930s, CO₂ was first commercially removed from the air for preventing the equipment of cryogenic oxygen plants from fouling and clogging (Greenwood and Pearce, 1953). The CO₂ 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 CO₂ from the air inside the spacecrafts is among the other important applications of air capture. Since human emit CO₂ at the rate of 1 kg/person/day, the concentration of CO₂ 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 CO₂ 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 CO₂ (Ranjan, 2010). Soda lime is a variable mixture of sodium and calcium hydroxides that react with CO₂ 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 CO₂ 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 CO₂ 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 CO₂, it is necessary to not only deal with CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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

CO₂ emissions problem (Lackner et al., 2001). This brings great cost benefits which otherwise will require massive investments for the necessary infrastructural changes.

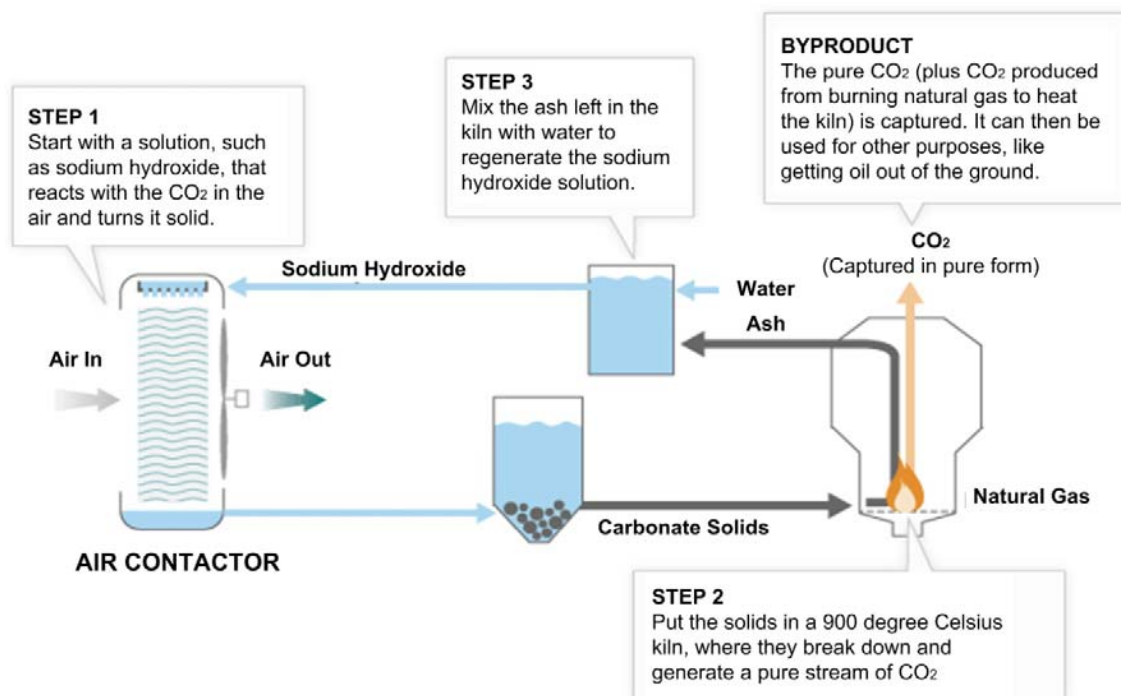
Another advantage of being decoupled from existing infrastructure as noted by Stolaroff (2006) might be realized in the context of a future worst-case climate scenario (p. 3): “consider a future climate change scenario where a sudden shift in the climatic system severely raises concern and demand for 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 CO₂ is removed from the ambient air, there is great flexibility on the selection of the capture locations, i.e. CO₂ can be captured from the atmosphere of the favorable storage site and therefore it would not have to construct costly pipelining system between the CO₂ 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 CO₂ 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 CO₂ air capture

The air capture process for CO₂ reduction from the atmosphere involves a technology that brings air into contact with a chemical sorbent. This chemical sorbent absorbs CO₂ from the air, and the industrial process then separates the CO₂, recycles the sorbent, and transfers the captured CO₂ 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 CO₂ from the atmosphere (Harris, 2011).



Source: Carbon Engineering; carbonengineering.com.

Fig. 2. Schematics of Keith's CO₂ 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 CO₂ 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).

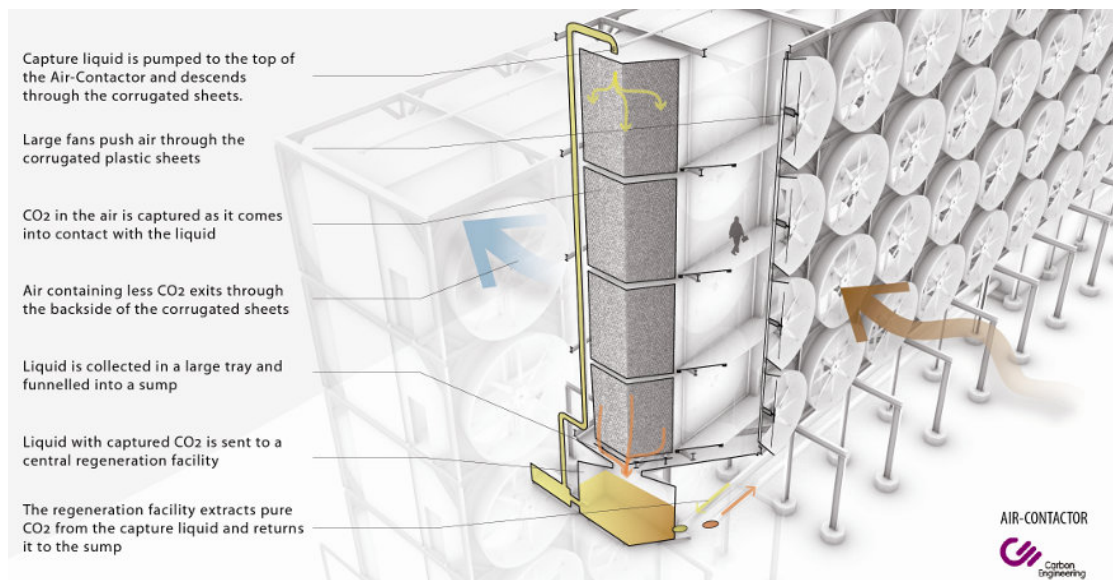
After air is entered to the contactor, it passes through small channels containing a high-surface-

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

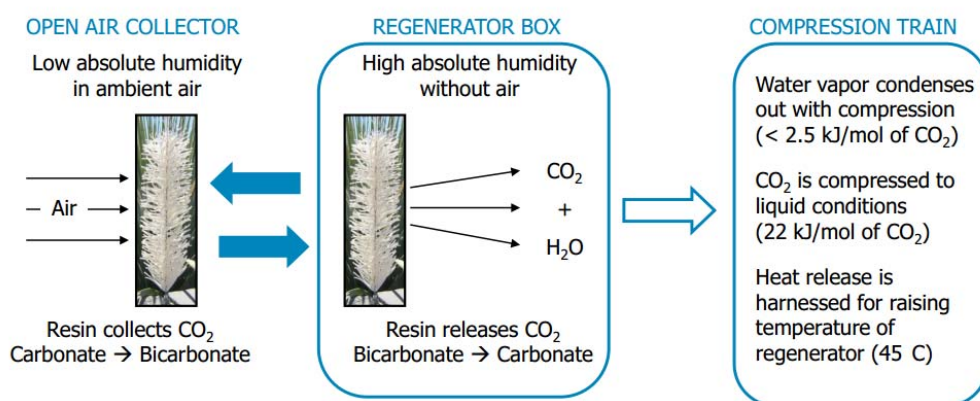
Another promising technology is developed by Professor Klaus Lackner from the Earth Institute at Columbia University. This technology which is hosted by Kilimanjaro Energy (www.kilimanjaro-energy.com) captures CO_2 from the air using a commercially available wet resin. This material shows different behavior 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.



- Moisture swing consumes water and electric power
 - 50 kJ/mol of CO₂
 - 10 liter of water per kg of CO₂

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 CO₂ 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 CO₂), 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 CO₂ from the air at a cost of less than \$250 per ton (Isaacson, 2014). Barrett (2012) believes the marginal cost associated with CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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)

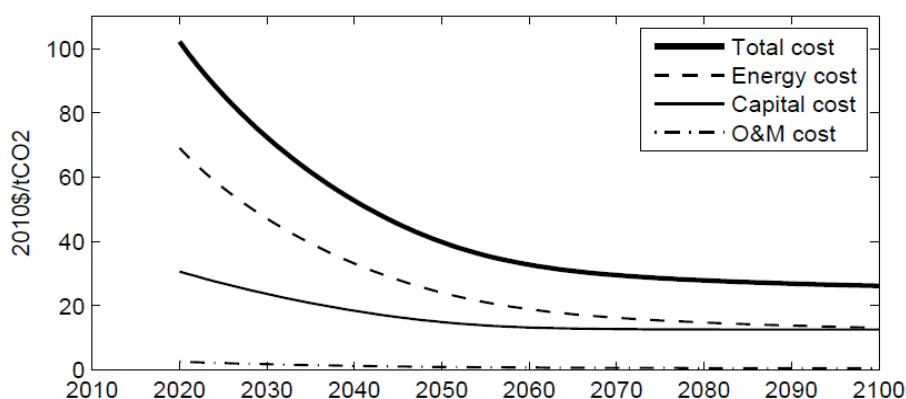
	\$500/tC	\$360/tC	\$100/tC
450 ppm cost to 2050	2.7%	1.9%	0.5%
550 ppm cost to 2050	0.0%	0.0%	0.0%
450 ppm cost to 2100	2.1%	1.5%	0.4%
550 ppm cost to 2100	1.5%	1.1%	0.3%

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 CO₂ 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 CO₂, 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 CO₂ 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 CO₂ concentration. Moreover, those demanded goals are too ambitious to be achieved by using current mitigation technologies. For practical

stabilization of CO₂ 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 CO₂ concentrations from reaching critical levels, there may be little choice but to extract some of the CO₂ 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.

Acknowledgment

The authors are grateful to Professor Klaus Lackner from the Earth Institute at Columbia University for the permission to use the image of his moisture swing absorption technology. Other images provided by Carbon Engineering Ltd. and Stonehaven Productions Inc. are greatly acknowledged. This work was supported by JSPS KAKENHI (Grant-in-Aid for Scientific Research-B), Grant Number 24360372.

References

1. Ackerman, F. and Stanton, E. (2006). *Climate Change – the Costs of Inaction*, Report to Friends of the Earth (FOE), Tufts University: USA. Available online at: <http://www.ase.tufts.edu/gdae/Pubs/rp/Climate-Costs-ofInaction.pdf> (accessed on May 2012).
2. Almendra, F., West, L., Zheng, L. and Forbes, S. (2011). *CCS Demonstration in Developing Countries: Priorities for a Financing Mechanism for Carbon Dioxide Capture and Storage*, Working paper, World Resources Institute: Washington, DC, pp. 1-24.
3. Amanollahi, J., Abdullah, A.M., Ramli, M.F. and Pirasteh, S. (2012). Influences of the window size of moderate resolution imaging spectroradiometer (MODIS) aerosol optical thickness (AOT) values on particulate matter (PM₁₀) motoring in Klang Valley, Malaysia, *Scientific Research and Essays*, 7, pp. 1373-1380.
4. Amanollahi, J., Tzanis, C., Abdullah, A.M., Ramli, M.F. and Pirasteh, S. (2013). Development of the models to estimate particulate matter from thermal infrared band of Landsat Enhanced Thematic Mapper, *International Journal of Environmental Science and Technology*, 10, pp. 1245-1254.
5. Barrett, S. (2009). Climate Treaties and Backstop Technologies, *CESifo Economic Studies*, 58, pp. 31-48.
6. Barrett, S. (2009). The Coming Global Climate-Technology Revolution, *Journal of Economic Perspectives*, 23, pp. 53-75.
7. Battelle Memorial Institute (2001). *A Global Energy Technology Project Addressing Climate Change: An Initial Report on International Public-Private Collaboration*, Joint Global Change Research Institute: College Park, MD.
8. Beinhocker, E., Oppenheim, J., Irons, B., Lahti, M., Farrell, D., Nyquist, S., Remes, J., Nauclér, T. and Enkvist, P. (2008). *The carbon productivity challenge: Curbing climate change and sustaining economic growth*, McKinsey Global Institute: Washington DC, pp. 1-48.
9. Bilen, K., Ozyurt, O., Bakirci, K., Karsli, S., Erdogan, S. and Yilmaz, M. et al. (2008). Energy production, consumption, and environmental pollution for sustainable development: a case study in Turkey, *Renewable Sustainable Energy Rev*, 12, pp. 1529-1561.
10. Canadell, J.G., Raupach, M.R. and Houghton, R.A. (2009). Anthropogenic CO₂ emissions in Africa, *Biogeosciences*, 6, pp. 463-468.
11. Chandler, W., Schaeffer, R., Dadi, Z., Shukla, P.R., Tudela, F., Davidson, O. and Alpan-Atamer, S. (2002). *Climate change mitigation in developing countries: Brazil, China, India, Mexico, South Africa, and Turkey*, Pew Centre on Global Climate Change: Arlington, VA.
12. Climeworks LLC. (2011). Statement Regarding the Technical Assessment “Direct Air Capture of CO₂ with Chemicals” of the American Physical Society, Available online: http://www.climeworks.com/tl_files/climeworks/downloads/CW_statement_APS_DAC_report_2011_05.pdf (accessed on 13 August 2012).
13. Dooley, J.J., Dahowski, R.T., Davidson, C.L., Wise, M.A., Gupta, N., Kim, S.H. and Malone, E.L. (2006). *Carbon Dioxide Capture and Geological Storage: a Core Element of a Global Energy Technology Strategy to Address Climate Change*; Technol. Rep., Global Energy Technol. Strategy Program: USA.
14. Galiana, I. and Green, C. (2009). *An Analysis of a Technology-led Climate Policy as a Response to Climate Change*, Copenhagen Consensus Center: Copenhagen, Denmark.
15. Gibbins, J. and Chalmers, H. (2008). Preparing for global roll-out: A ‘developed country first’ demonstration programme for rapid CCS deployment, *Energy Policy*, 36, pp. 501-507.
16. Gillingham, K., Newell, R.G. and Pizer, W.A. (2007). *Modeling endogenous technological change for climate policy analysis*, Resources for the Future: Washington DC.
17. Goulder, L. and Pizer, W. (2006). *The Economics of Climate Change*, NBER Working Paper, No. 11923; National Bureau of Economic Research: Cambridge, pp. 1-13.
18. Greenwood, K. and Pearce, M. (1953). The removal of carbon dioxide from atmospheric air by scrubbing with caustic soda in packed towers, *Transactions of the Institution of Chemical Engineers*, 31, pp. 201-207.
19. Grogan, P. (1998). CO₂ flux measurement using soda lime: correction for water formed during CO₂ adsorption, *Ecology*, 79, pp. 1467-1468.
20. Gunther, M. (2012). Rethinking Carbon Dioxide: From a Pollutant to an Asset, *Environment*, 360, Yale University, 23 FEB 2012. Available online: http://e360.yale.edu/feature/geoengineering_carbon_dioxide_removal_technology_from_pollutant_to_asset/2498/ (accessed on 14 June 2012).

21. Harris, R. (2011). This Machine Can Suck Carbon out Of the Air. *NPR*, September 15, 2011. Available online: <http://www.npr.org/2011/09/19/140513014/this-machine-can-suck-carbon-out-of-the-air> (accessed on 28 November 2013).
22. Heffernan, O. (2017). \$25 million prize offered to capture carbon, *Nature*, 9 February 2007. Available online: <http://www.nature.com/news/2007/070205/full/news070205-16.html> (accessed on 8 November 2013).
23. Heinrich, J.J. (2003). *CO₂ capture from Air – Current Practices*; Publication No. LFEE 2003-001-WP, Massachusetts Institute of Technology: MA, USA.
24. Hodgson, G., Rhéaume, G. and Coad, L. (2008). *Use Green Taxes and Market Instruments to Reduce Greenhouse Gas Emissions*, The Conference Board of Canada: Ottawa.
25. Holmes, G. and Keith, D.W. (2012). An air-liquid contactor for large-scale capture of CO₂ from air, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Science*, 370, pp. 4380-4403.
26. House of Commons (2012). *Carbon capture and storage*, Ninth Report of Session 2007-08, Authority of the House of Commons London, The Stationery Office Limited: London. Available online: <http://www.publications.parliament.uk/pa/cm200708/cmselect/cmenvaud/654/654.pdf> (accessed on 8 October 2013).
27. House, K.Z., Baclig, A.C., Ranjan, M., Van Nierop, E.A., Wilcox, J., Herzog, H.J. (2011). Economic and energetic analysis of capturing CO₂ from ambient air, *PNAS Early Edition*. Available online: <http://sequestration.mit.edu/pdf/1012253108full.pdf> (accessed on 8 November 2013).
28. IEA (2009). *Technology Roadmap: Carbon Capture and Storage*; International Energy Agency (IEA): Paris.
29. IEA (2013). *Technology Roadmap: Carbon Capture and Storage*; International Energy Agency (IEA): Paris.
30. IEA (2012). *World energy outlook 2012*; International Energy Agency (IEA): Paris.
31. IMechE. *Negative Emissions and Carbon Recycling Air Capture*; Environment Policy Statement; Institution of Mechanical Engineers (IMechE): London, 2011.
32. IPCC (2007b). *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
33. IPCC (2007a). *Fourth Assessment Report. Climate Change 2007: Synthesis Report, Summary for Policy Makers*; Cambridge University Press.
34. IPCC (2006). *IPCC Guidelines for National Greenhouse Gas Inventories; Prepared by the National Greenhouse Gas Inventories Programme*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., (Eds.); IGES: Japan.
35. Isaacson, B. (2014), "Direct Air Capture Makes Pollution a Cash Cow", Available online at: <http://www.newsweek.com/direct-air-capture-makes-pollution-cash-cow-266587>.
36. Jones, N. (2009). Climate Crunch: Sucking It Up. *Nature*, 458, pp. 1094-1097, Available online: www.nature.com/news/2009/090429/full/4581094a.html (accessed on 16 April 2012).
37. Keith, D.K. (2009). Why Capture CO₂ from the Atmosphere, *Science*, 325, pp. 1654-1655.
38. Keith, D.W. and Ha-Duong, M. (2003). CO₂ capture from the air: Technology assessment and implications for climate policy. In *Proceedings of the 6th Greenhouse Gas Control Conference*, Kyoto, Japan, 2003; J. Gale, Y. Kaya, Eds.; Elsevier, New York, pp. 187-197.
39. Keith, D.W., Ha-Duong, M. and Stolaroff, J.K. (2006). Climate Strategy with CO₂ Capture from the Air, *Climatic Change*, 74, pp. 17-45.
40. Keith, D.W., Heidel, K. and Cherry, R. (2010). Capturing CO₂ from the atmosphere: rationale and process design considerations. In *Geo-Engineering Climate Change: Environmental Necessity or Pandora's Box?* Brian Launder and J. Michael T. Thompson Eds., Cambridge University Press, pp. 107-126.
41. Kheshgi, H.S. (2006). Sequestering atmospheric carbon dioxide by increasing ocean alkalinity, *Energy*, 20, pp. 915-922.
42. Kypreos, S. and Bahn, O. (2003). A MERGE model with endogenous technological progress, *Environmental Modeling and Assessment*, 8, pp. 249-259.
43. Lackner, K.S. (2010). Air Capture and Mineral Sequestration – Tools for Fighting Climate Change. Available online: http://science.house.gov/sites/repUBLICans.science.house.gov/files/docume%20nts/hearings/020410_Lackner.pdf (accessed on 8 October 2013).
44. Lackner, K.S. (2009). Capture of carbon dioxide from ambient air, *Eur. Phys. J. Special Topics*, 176, pp. 93-106.
45. Lackner, K.S. (2011a). Synthetic Fuels and Carbon Dioxide Capture From Air. Available online: <http://www.columbia.edu/cu/alliance/documents/EDF/Wednesday/pres.Lackner.pdf> (accessed on 5 November 2013).
46. Lackner, K.S. (2011b). Yes, We Can Afford to Remove Carbon from Air. Available online: <http://blogs.ei.columbia.edu/2011/06/28/response-to-aps-study-on-air-capture/> (accessed on 5 November 2013).
47. Lackner, K.S., Ziock, H.-J. and Grimes, P. (1999). *Carbon Dioxide Extraction from Air: Is It an Option?* In *Proceedings of the 24th International Conference on Coal Utilization & Fuel Systems*, Clearwater, Florida, March 8-11, 1999.
48. Lackner, K.S., Grimes, P. and Ziock, H.J. (2001). *Capturing carbon dioxide from air*, In *Proceedings of the First National Conference on Carbon Sequestration*, Washington, DC.
49. Lampitt, R.S., Achterberg, E.P., Anderson, T.R., Hughes, J.A., Iglesias-Rodriguez, M.D., Kelly-Gerreyn, B.A., Lucas, M., Popove, E.E., Sanders, R., Shepherd, J.G., Smythe-Wright, D. and Yool, A. (2008). Ocean fertilization: a potential means of geoengineering, *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences*, 366, pp. 3919-3945.
50. Lemoine, D. (2007). *Incentivizing Air Capture through Emissions Offsets and Greenhouse Gas Property*; Science, Technology, and Engineering Policy (STEP) 2007 White Paper Competition, Berkeley: USA. Available online: http://step.berkeley.edu/White_Paper/Lemoine.pdf (accessed on 6 December 2013).

51. Mader, B. (2012). CCS Technologies – Air Capture of CO₂. Available online: http://isites.harvard.edu/fs/docs/icb.topic1050197.files/Brigitte_Mader_Direct_Air_Capture_and_CCS_05-09-2012v1.pdf (accessed on 21 August 2012).
52. Markusson, N. (2008). How ready is 'capture ready'? – Preparing the UK power sector for carbon capture and storage. Available online: http://assets.wwf.org.uk/downloads/capture_ready_ccs.pdf (accessed on 21 August 2012).
53. McAllister, L.K. (2011). Adaptive mitigation in the electric power sector, *BYU Law Review*, pp. 2115-2156.
54. McGlashan, N.R., Workman, M.H.W., Caldecott, B. and Shah, N. (2012). Negative Emission Technologies, Available online: <https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Briefing%20Paper%208.pdf> (accessed on 10 October 2014).
55. McLaren, D. (2011). Negatonnes – An initial assessment of the potential for negative emission techniques to contribute safely and fairly to meeting carbon budgets in the 21st century, available online: <http://www.foe.co.uk/sites/default/files/downloads/negatonnes.pdf> (accessed on 10 October 2014).
56. Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M. and Kram, T. et al. (2010). The next generation of scenarios for climate change research and assessment, *Nature*, 463, pp. 747-756.
57. Nemet, G.F. and Brandt A.R. (2011). *Supporting Information for: Willingness to pay for a climate backstop*, La Follette School of Public Affairs, University of Wisconsin-Madison: Wisconsin, United States, pp. S1-S12.
58. Nemet, G.F. and Brandt A.R. (2012). Willingness to pay for a climate backstop: liquid fuel producers and direct CO₂ air capture, *The Energy Journal*, 33, pp. 53-82.
59. Nooteboom, B. (1993). Firm size effects on transaction costs, *Small Business Economics*, 5, pp. 283-295.
60. OECD (2008). *Climate Change Mitigation, What Do We Do?* Organisation for Economic Co-operation and Development (OECD): Paris, France.
61. OECD (2011). Promoting Technological Innovation to Address Climate Change, Available online: <http://www.oecd.org/env/cc/49076220.pdf> (accessed on 21 October 2013).
62. Pielke, R.A.Jr. (2009). An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy, *Environmental Science & Policy*, 12, pp. 216-225.
63. Popp, D., Newell, R.G. and Jaffe, A.B. (2009). *Energy, the Environment, and Technological Change*, Working Paper No. 14832, National Bureau of Economic Research: Cambridge, pp. 1-71.
64. Ranjan, M. (2010). *Feasibility of Air Capture*, Master Thesis, Massachusetts Institute of Technology, June 2010.
65. REUTERS (2011). Air capture technology ready by 2018: UK engineers. Available online: <http://www.reuters.com/article/2011/10/26/us-britain-air-capture-idUSTRE79P40W20111026> (accessed on 29 October 2013).
66. Rubin, E. (2013). Climate Change, Technology Innovation and the Future of Coal, *Cornerstone*, 1, pp. 37-43.
67. Satter, R. (2013). UN official: World failing over climate change. *AP*, Sep. 17, 2013. Available online: <http://bigstory.ap.org/article/un-official-world-not-track-over-climate> (accessed on 29 October 2013).
68. Shah A. and Larsen B. (1992). *Carbon Taxes, the Greenhouse Effect, and Developing Countries Policy Research*, Working Paper Series 957; The World Bank: Washington, DC.
69. Shrum, T. (2007). Greenhouse Gas Emissions: Policy and Economics. Available online: http://www.carbontax.org/wp-content/uploads/2008/03/kansas-energy-council_ghg-review.pdf (accessed on 20 November 2013).
70. Sivaraman, D. (2009). Integrated assessment of using photovoltaic technology in the United States electricity sector. Ph.D. Dissertation, University of Michigan: Ann Arbor, MI, 2009.
71. Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T. and Lewis, N. et al. (2011). *Direct air capture of CO₂ with chemicals: a technology assessment for the APS Panel on Public Affairs*, American Physical Society: College Park, Maryland, pp. 1-91.
72. Sohngen, B. and Mendelsohn, R. (2003). An Optimal Control Model of Forest Carbon Sequestration, *American Journal of Agricultural Economics*, 85, pp. 448-457.
73. Stern, N. (2007). *The Economics of Climate Change: The Stern Review*, Cambridge University Press: Cambridge, UK.
74. Stolaroff, J. (2006). Capturing CO₂ from ambient air: a feasibility assessment, Ph.D. Dissertation, Carnegie Mellon University, August 17 2006.
75. The Economist (2011). The sad road from Kyoto to Durban. Available online: <http://www.economist.com/node/21541028> (accessed on May 2012).
76. Uddin, S.N. and Barreto, L. (2007). Biomass-fired cogeneration systems with CO₂ capture and storage, *Renewable Energy*, 32, pp. 1006-1019.
77. van der Zwaan, B.C.C., Gerlagh, R., Klaassen, G. and Schrattenholzer, L. (2002). Endogenous technological change in climate change modeling, *Energy Economics*, 24, pp. 1-19.
78. West, J. (2012). Stopping Climate Change Is Much Cheaper Than You Think, *Mother Jones*, Apr. 5, 2012. Available online: <http://www.motherjones.com/environment/2012/04/climate-action-cheap-david-kennedy> (accessed on 15 July 2012).
79. Yousefi-Sahzabi, A., Sasaki, K., Yousefi, H. and Sugai, Y. (2011b). CO₂ emission and economic growth of Iran, *Mitigation and Adaptation Strategies for Global Change*, 16, pp. 63-82.
80. Yousefi-Sahzabi, A., Sasaki, K., Yousefi, H., Pirasteh, S. and Sugai, Y. (2011a). GIS aided prediction of CO₂ emission dispersion from geothermal electricity production, *Journal of Cleaner Production*, 19, pp. 1982-1993.