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Energy Procedia 4 (2011) 2893–2900

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

Systems Analysis and Cost Estimates for Large Scale Capture of Carbon Dioxide from Air

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Abstract

This paper explores the resource intensity and major cost elements of direct air capture of carbon dioxide. The levelized cost of carbon removal is calculated as the sum of costs resulting from interdependent capture devices, energy supplies, water supplies and sequestration resources. The analysis considers "generic" air capture technology characterized only by its energy use, capture footprint, and water use. Capital costs dominate the analysis, followed by energy efficiency. Four dedicated energy resources are considered: wind, enhanced geothermal, natural gas combined cycle (NGCC), and NGCC with 90% carbon capture. Nearly carbon-free energy is critical to keeping overall cost of carbon mitigation low. The analysis shows that high second law capture efficiencies (on the order of 10%) and relatively inexpensive capture devices (on the order $0.5M for an individual device capturing one tonne CO_2/day) must be achieved if the cost of air capture is to approach $300/tonne-$CO_2$. Reaching those goals is likely to require substantial research into the kinetics and thermodynamics of capture chemistry which, respectively, keep the capital and energy costs as low as possible.

Keywords: Direct Air Capture; Carbon Dioxide; Systems Analysis; Economics; Negative Emissions.

1. Introduction

Recent carbon cycle research by Solomon et al. (2009) and Hansen et al. (2007) has resulted in increased interest in technologies that can accomplish a "negative emissions" effect. Such technologies would be capable of removing at least enough carbon dioxide from the global atmospheric system to diminish accumulated emissions from fossil fuels. Engineered direct capture of carbon dioxide (CO_2) from air is one such technology. Other concepts include biomass energy with carbon sequestration, direct burial of bio-carbon or bio-char, and acceleration of mineral weathering. This paper examines the factors that will dictate the cost of engineered air capture.

Pielke (2009) has described the macro-scale economic playing field for air capture, while others (Mahmoudkhani and Keith, 2009, Lackner et. al, 2001, Zeman, 2007) have begun research into specific technologies capable of removing CO_2 from the air. The authors of this paper acknowledge that air capture is, at best, one of many options that might be deployed AFTER both significantly improving the efficiency of the global energy system AND capturing or eliminating CO_2 emissions from nearly all major stationary sources.

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doi:10.1016/j.egypro.2011.02.196

The motivation for this study is to evaluate the *interdependent* energy, water and sequestration resources that comprise the balance of an air capture system. For air capture to succeed at scale, dedicated energy resources must be provided, or abundant low carbon energy must be available on a nearby utility. Furthermore, in the likely event that an aqueous solvent is used for capture, air capture will consume significant quantities of water. Delivery and treatment of that water will, in turn, require more energy. Finally, captured CO_2 must be injected into the subsurface, and the compression of CO_2 to injection conditions will create further demand for energy.

It is not the intent of this study to predict an absolute cost for air capture. The authors are keenly aware of claims and studies that predict air capture costs between \$30 and \$1000 per tonne CO_2. Rather, it is the authors' goal to illuminate the interdependence of cost drivers in a framework flexible enough to accommodate the broadest range of assumptions about the costs and efficiencies of the underlying sub-systems.

2. System Description

Figure 1 is an energy, water and carbon flow diagram for a generalized air capture system. The components of the system are described below.

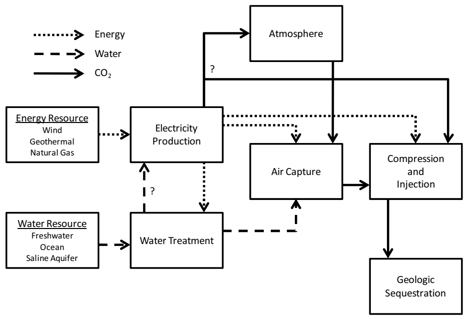

Figure 1. Energy and material flows for a generalized air capture system. The two question marks (?) indicate that electricity production may produce CO_2 which could be emitted or sequestered and that electricity production may also consume water.

2.1. Air Capture

This analysis assumes that CO_2 is captured from the air by an array of modular devices, each capable of capturing approximately 1 tonne per day of CO_2. The cost of a single module, which is an input to the overall analysis, includes the capture device itself as well as the associated connections (plumbing) to the other systems. The specific design of capture devices was not considered – however, their size is consistent with industrial cooling tower assemblies which typically handle enough air that if 10% of the CO_2 in that air was removed, the 1 tonne/day (CO_2) target would be reached. The value of 10% was chosen because at that low level of separation, it may be possible to use inexpensive contacting strategies (packing, spray nozzles or solid sorbents) and to achieve low pressure drop. The minimum work of separation for CO_2 from air at 10% recovery is 0.452 GJ/tonne-CO_2. In this analysis, electricity is used as a surrogate for all of the energy inputs to the system components[2].

2.2. Energy

This analysis considered four different energy resources to drive the entire air capture system. There must be enough electricity to drive the air capture devices, the water treatment system and the CO_2 compressors. The four resources are:

- **Wind:** Commercially available 1.5 MW wind turbines could be deployed as a wind farm in conjunction with an air capture array. This analysis compensates for the low capacity factor of wind turbines (estimated to be 35%) by installing enough turbines to supply the capture system's energy use over the course of a year[3].

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[2] Most proposed CO_2 removal systems are driven by a combination of electricity and heat. Estimation of the thermodynamic efficiency of these systems takes into account the low exergy value of the heat.

[3] The analysis does not take the logistics of intermittency into account; capture technologies that require uninterrupted power would push the cost of the wind-driven system higher. Alternatively, capture and regeneration systems designed to accommodate wind's intermittency would be ideal.

- **Geothermal:** Specifications for advanced geothermal systems as outlined in MIT's geothermal report (2006) were used in this study. . Geothermal plants consume significant quantities of cooling water because of their low intrinsic thermal efficiency.
- **Natural Gas Combined Cycle:** NGCC systems used to power air capture systems would require cooling water and would emit carbon, offsetting some of the capture effort. They would also require fuel, whose price might be independent of the natural gas market if an otherwise stranded resource were accessed.
- **Natural Gas w/CCS:** Even under the circumstances where a NGCC system could power an air capture system large enough to offset its own emissions, it would likely be more economical to capture the CO_2 generated during electricity production at the stack. The NGCC system with CCS behaves similarly to the unsequestered NGCC system, albeit with higher capital cost, fuel consumption and water consumption rates.

This analysis does not explicitly consider other energy resources, although the methodology could easily be extended to solar photovoltaic, solar thermal, nuclear, coal and generalized "grid mixtures" of electric power. Air capture powered by electricity from co-located biomass energy with CCS (BECS) presents a potentially synergistic combination of technologies. However, analysis of the water, fuel and soil resource intensity of BECS is beyond the scope of this paper.

2.3. Water

If carbon dioxide is captured in an aqueous solution, or even if it is adsorbed onto a hygroscopic solid (Lackner and Wright, 2009), there will be significant consumption of water by air capture devices. Early prototypes (Zeman, 2008) consume water at the rate of 90 tonnes-H_2O per tonne-CO_2. While it is assumed that a fully developed air capture device could be far more water-efficient, it is clear that a large air capture installation will require a dedicated water treatment and delivery facility. Purified water (from a surface supply, groundwater or saline supply) must be delivered to the air capture units and, in some cases, the power plants that drive those units. Because it is assumed that air capture will take place in locations where there is a good sequestration resource, and the largest sequestration resources are expected to be saline aquifers (Orr, 2004), this analysis assumes that salt water is available on site. The energy intensity of water treatment is a variable in this analysis.

2.4. Sequestration

Compression and sequestration of carbon dioxide is the fourth and final major component of the air capture system. CO_2 compression technology is very mature, and the energy and capital requirements for compressors are well known. The minimum work required to isothermally compress CO_2 to injection conditions (13.8 MPa) is 0.225 GJ/tonne-CO_2, and thermodynamic efficiencies are generally around 60% (RDS and Alstom Power, 2007). Electricity to run the compressors must be supplied via the power plants described above.

Sequestering the volume of carbon dioxide produced by an array of air capture units would require about one hundred 10,000 tonne/yr wells to be drilled. While there is ongoing research regarding reservoir management for carbon sequestration, the costs of drilling and maintaining the injection sites is well understood. If the energy resource used to run the air capture system captures its own carbon, enough additional sequestration capacity must be added to accommodate that flow.

3. Assumptions and Analysis

The flow rates of energy, CO_2 and water between each of the unit operations are linearly dependent on the scale of those operations. The interdependency of some of the operations (e.g., it takes electricity to produce water and it takes water to produce electricity, etc.) requires the simultaneous solution of several algebraic equations to calculate, for example, the total quantity of electricity required for the entire system (See Table 1 for Equation 1 variable definitions).

$$E_{tot} = \frac{c_{cap}(e_{water}w_{cap}+e_{inj}+e_{cap})}{1-(w_{elec}e_{water}+e_{inj}ccf_{elec}c_{elec})} \quad (1)$$

Table 1. Variable descriptors in the calculation of electricity consumption

E_{tot}	*GJ/yr*	*Electricity required to run the entire system (incl. sequestration and water)*
C_{cap}	tonnes-CO_2/yr	Gross carbon removal rate from atmosphere by capture devices
e_{water}	GJ/tonne-H_2O	Water supply system's specific electrical demand
w_{cap}	tonnes-H_2O/tonne-CO_2	Capture devices' specific water consumption
e_{inj}	GJ/tonne-CO_2	Compression and sequestration systems' specific electricity demand
e_{cap}	GJ/tonne-CO_2	Capture devices' specific electricity demand
w_{elec}	tonnes-H_2O/GJ	Power production systems' specific water demand (N/A for Wind)
ccf_{elec}	(none)	Fraction of CO_2 produced by electricity system that is captured
c_{elec}	tonnes-CO_2/GJ	Gross specific CO_2 production of the power generator

Table 2 lists all of the input parameters for a reference case estimate of the total system cost. The reference case used in this study is composed of costs and efficiencies that the authors estimate would be attainable with significant research. Optimistic ("best case" scenario) and pessimistic (likely attainable with today's technology) estimates were generated in order to bound the analysis (Table 3). The analysis assumes that all capital equipment has a service lifetime of 30 years, and that capital costs are amortized over a 30 year period at 10% interest.

Table 2. Reference case costs, efficiencies and other parameters.

Air capture devices	***Units***				
Nominal size	tonnes-CO_2/yr	400			
Second law efficiency of capture	%	10%			
Water consumption	tonne-H_2O/tonne-CO_2	30			
Capital cost	$/unit	$500,000			
O+M	% of capital/yr	2.5%			
Capacity factor	%	90%			
Water treatment					
Nominal size	liters/min	500			
Electricity consumption	J/liter	2500			
Capital cost	$/unit	$700,000			
O+M	% of capital/yr	2.5%			
Capacity factor	%	90%			
Carbon sequestration					
Nominal size	tonnes-CO_2/yr	100000			
Second law efficiency of compression	%	60%			
Compressor capital cost	$/unit	$3,000,000			
Well capital cost	$/well	$100,000			
Well flow rate	tonnes-CO_2/yr per well	10000			
Compressor O+M	% of capital/yr	2.5%			
Wellfield O+M	% of capital/yr	1.5%			
Long term monitoring + verification	$/tonne-$CO_2$	$6.00			
Capacity factor	%	90%			
Electricity generation equipment		***Wind***	***Enhanced geothermal***	***Nat. gas w/o seq.***	***Nat. gas w/seq. (90% capture)***
Nominal size	MWe	1.5	150	40	40
Thermal efficiency	%	100%	15%	40%	30%
Fuel	--	None	Geofluid	Nat. gas	Nat. gas
Fuel heating value	GJ/tonne (MJ/kg)	0	0.33	50	50
Fuel CO_2 potential	kg-CO_2/kg-fuel	0	0.0001	2.75	2.75
Fuel price	$/GJ	$0.00	$0.00	$4.00	$4.00
Water consumption	tonne-H_2O/GJe	0	0.7	0.25	0.5
Carbon capture fraction	%	100%	0%	0%	90%
Capital cost	$/unit	$2,000,000	$450,000,000	$30,000,000	$40,000,000
O+M	% of capital/yr	4.0%	7.5%	2.5%	2.5%
Capacity factor	%	35%	90%	90%	90%

Table 3. Range of variation for model inputs.

Air capture devices	***Units***	***Optimistic***	***Reference case***	***Pessimistic***
2nd Law Capture Efficiency	--	0.2	0.1	0.05
Water consumption	tonne-H_2O/tonne-CO_2	10	30	90
Capital cost	$/unit	$250,000	$500,000	$1,250,000
O+M	% of capital/yr	1.5%	2.5%	3.5%
Water treatment				
Electricity consumption	J/liter	1500	2500	7500
Capital cost	$/unit	$300,000	$700,000	$2,000,000
O+M	% of capital/yr	1.5%	2.5%	5.0%
Carbon sequestration				
Compressor capital cost	$/unit	$1,500,000	$3,000,000	$4,500,000
Well capital cost	$/well	$50,000	$100,000	$200,000
Compressor O+M	% of capital/yr	1.0%	2.5%	4.0%
Wellfield O+M	% of capital/yr	1.0%	1.5%	3.0%
Long term monitoring	$/tonne-$CO_2$	$3.00	$6.00	$10.00
Electricity - Wind				
Capital cost	$/unit	$1,000,000	$2,000,000	$3,000,000
O&M	% of capital/yr	2%	4%	10%
Capacity factor	--	60%	35%	25%
Electricity – Geothermal				
Water consumption	tonne-H_2O/GJe	0.525	0.7	1.4
Capital cost	$/unit	$337,500,000	$450,000,000	$810,000,000
O&M	% of capital/yr	5.0%	7.5%	12.5%
Electricity – Nat. Gas.				
Fuel Price	$/GJ	$2.00	$4.00	$8.00
Water Consumption	tonne-H_2O/GJe	0.15	0.25	0.4
Capital Cost	$/unit	$20,000,000	$30,000,000	$40,000,000
O&M	% of Capital/yr	1.5%	2.5%	3.5%
Electricity – Nat. Gas./CCS				
Thermal Efficiency	%	30%	30%	30%
Fuel Price	$/GJ	$2.00	$4.00	$8.00
Water Consumption	tonne-H_2O/GJe	0.25	0.5	0.75
Capital Cost	$/unit	$30,000,000	$40,000,000	$60,000,000
O&M	% of Capital/yr	2.0%	2.5%	4.0%

4. Results

Microsoft Excel[4] was used to calculate the total and unit-specific flows of electricity, water and carbon dioxide. A capture array sized to capture 1 million tonnes of CO_2 per year from the air was used to normalize all of the systems relative to one another. This normalization forced all systems to have exactly the same number of air capture units. But because some of the systems use energy resources with intrinsic carbon emissions and others use energy resources that sequester additional carbon, the net carbon removal rate varied, as did the total number of injection facilities required. Table 4 lists the energy and mass flow results of this analysis as well as the number of units of each system component that are required for the 1 million tonne per year capture array.

Table 4. Scale of operations for a 1,000,000 tonne/yr capture system.

Scale of operations		***Wind***	***Enhanced geothermal***	***Nat. gas w/o seq.***	***Nat. gas w/seq. (90% capture)***
Total quantity of electricity produced	GJ/yr	4969833	4978546	4972941	5304536
Total quantity of water consumed	tonnes-H_2O/yr	30000000	33484982	31243235	32652268
Total CO_2 injected	tonnes-CO_2/yr	1000000	1000000	1000000	1875248
CO_2 emissions	tonnes-CO_2/yr	0	10058	683779	97250
Net rate of CO_2 removal	tonnesCO_2/yr	1000000	989942	316221	902750
# electricity plants	--	273	1.06	4.0	4.0
# capture towers	--	2,778	2,778	2,778	2,778
# water processing plants	--	127	141	132	138
# CO_2 compressors	--	11.1	11.1	11.1	20.8
Total overnight capital cost	$	$2,067,698,672	$2,009,800,861	$1,645,095,380	$1,727,948,759

[4] For a copy of the excel spreadsheet please contact the author at ajsimon@llnl.gov.

The total estimated cost for air capture using each of the four energy resources discussed above are shown in Figure 2. The stars represent the levelized cost of capture using the reference case (Table 2) assumptions and system parameters delineated in Table 3. The red (light) bars represent the cost under a worst case scenario (low efficiencies, high costs) and the blue (dark) bars represent the extent to which costs might be reduced if highly efficient and inexpensive technology could be developed. Note that the reference case is fairly aggressive with regard to efficiency (10%) and capital costs for 1 tonne/day capture units ($0.5M). Note also that under the pessimistic assumptions of lower thermodynamic efficiency, higher water use, higher energy demand for water purification, etc., that the cost of CO_2 removal, on a per-net-tonne basis, is not calculated for the unsequesterd NGCC-fired system. Such a system, if operated, would have a net-negative CO_2 removal rate, i.e., its gross emissions of CO_2 from power production would be greater than the gross rate of CO_2 removal from the air at the capture devices. The possibility of designing such a system underscores the need for air capture to be driven by low- or zero-carbon emitting energy resources.

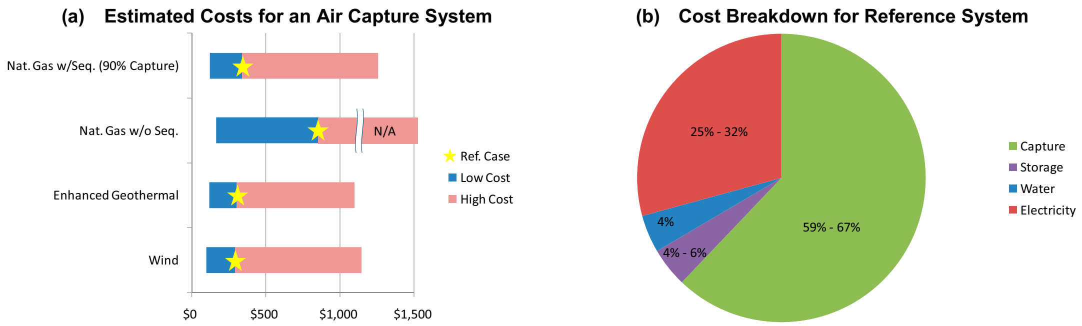

Figure 2. (a): Levelized cost of carbon capture from air. The stars represent the reference case (see Table 2), and the overall range of the horizontal bars represents the uncertainty band between the optimistic and pessimistic cost estimates (see Table 3). (b): Contribution of each of the subsystems to the total cost under the reference case assumptions (see Table 2). The ranges listed correspond to the differences between energy supplies.

Under the reference case assumptions about the cost of capture devices, it appears that the biggest cost center in an air capture system is the capture array itself, accounting for 2/3 of the levelized cost of capture. The energy system is the second largest contributor to cost, accounting for 25 – 33%. Water treatment and CO_2 sequestration account for approximately 5% each. Table 5 lists the dollar costs per net tonne CO_2 captured for each of the systems. While the cost of air capture technology is still very much unknown, the costs for the balance of system (electricity, water, sequestration) are all comparable to current utility costs per service ($/kWh, $/gal, $/tonne-$CO_2$), even though this analysis does not rely on the connection of the air capture system to any utility grids.

Table 5. Levelized cost of capture by system component.

System Component		*Wind*	*Enhanced geothermal*	*Nat. gas w/o seq.*	*Nat. gas w/seq. (90% capture)*
Capture	$/tonne-$CO_2$	$182.05	$183.90	$575.72	$201.67
Storage	$/tonne-$CO_2$	$11.71	$11.83	$37.05	$18.79
Water	$/tonne-$CO_2$	$11.63	$13.11	$38.30	$14.02
Electricity	$/tonne-$CO_2$	$87.64	$96.19	$211.70	$105.46
Total	**$/tonne-$CO_2$**	**$293.04**	**$305.04**	**$862.76**	**$339.95**

Figure 3 shows the sensitivity of the system cost to the capital cost of the capture device. This cost is the one of the least well quantified parameter of this analysis, and one of the most sensitive to technological advancements in the field of carbon capture. The specific design of chemical processes, catalysts, solvents, sorbents and contactors will, in large part, determine the cost of carbon management, independent of the economic relevance of engineered air capture.

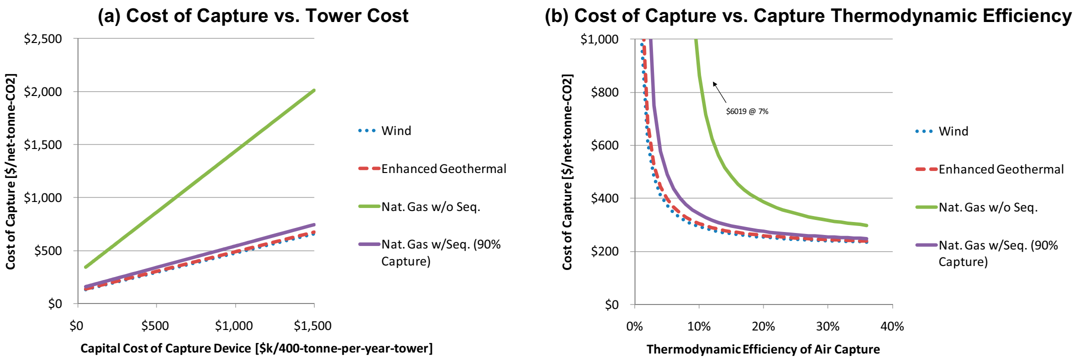

Figure 3. Cost of air capture as a function of (a) capture device capital cost and (b) capture device thermodynamic efficiency. All other parameters, including efficiency in (a) and capital cost in (b), were held to their reference values (see Table 1).

Energy plays a smaller role than capture device capital cost, but if the thermodynamic efficiency of real devices falls far short of the reference-case assumption, the energy cost can increase dramatically. While holding all other inputs fixed at the reference case values, the thermodynamic efficiency of the capture devices was varied between 5% and 40%. Figure 3b shows that as efficiency drops below 10%, costs can rapidly increase beyond $400/tonne. While not shown, it is clear that if less optimistic values for the other system parameters are used, much higher costs as a function of efficiency loss would be seen. On the other hand, efficiency increases beyond 20% have a very small effect on the overall cost. This is because of the dominance of the cost of the capture devices on the overall system cost.

It is relatively clear that under a consistent set of assumptions about the costs of capture devices, water resources and sequestration systems, the differences in the projected costs of air capture between low-carbon-energy-powered systems are small. Carbon emitting systems, on the other hand, are notably higher in cost, even in the reference scenario. The logic behind this trend is straightforward: the cost of capture is calculated as the total system expenses divided by the net quantity of carbon removed from the atmosphere. As the denominator in this expression decreases (due to unsequestered carbon emissions from the energy system), the cost increases up to the point of engineering infeasibility. The NGCC reference case without capture corresponds to a carbon efficiency approximately equal to that of the current U.S. electric grid. Even though it might be possible for air capture systems powered by grid-based electricity to be formally carbon negative, the costs will be prohibitive until such time as the electricity system is essentially decarbonized.

It likely possible to engineer real devices that use energy in multiple forms (electrical and heat) and that take advantage of natural conditions in ways that can lower the overall cost of an air capture system. The assumptions of electric-only energy with no explicit system integration should not be interpreted as a recommended design, and integrated systems should be considered under any research program that investigates negative emissions. This approach does, however, place realistic bounds on the total energy efficiency that such an integrated system would have to achieve.

5. Conclusions

The material and energy flows for a system capable of air capture of CO_2 were estimated and calculated in a flexible framework that allows adjustments to the consumption of various utilities by each of the components of the air capture system: capture devices, energy resources, water treatment and compression/sequestration systems. Furthermore, preliminary cost estimates were applied to these systems in order to calculate a levelized cost of carbon capture over a 30-year period. Calculations were performed for a reference scenario as well as for optimistic and pessimistic sets of input parameters for systems powered by wind, enhanced geothermal, natural gas combined cycle and natural gas combined cycle with carbon capture.

Under the reference case assumptions dominated by 10% thermodynamic efficiency and capture unit cost of $0.5M for a one tonne /day unit, capture devices are the largest cost center, followed by the energy system. Water and sequestration systems account for a little over 10% of the system cost. Under the reference assumptions, the cost

of capture is likely to exceed \$300/tonne, and the most expensive system is the unsequestered NGCC system. The cost per tonne mitigated is tied to the carbon intensity of the power source. As the carbon and resource intensities of the systems grow, the unsequestered system becomes clearly uncompetitive. It is unlikely that fossil fueled energy systems without high degrees of capture, including grid power, could be effectively used to power air capture systems. While the challenge of providing enough carbon-free energy to an air capture system may sound daunting, it is prudent to remember that air capture will be deployed only after the power needs of the global population are met by carbon-free electricity.

An example of an advanced, self-contained air capture facility powered by natural gas (with carbon capture) corresponding to our reference case and capable of removing one million tonnes of CO_2 per year from the atmosphere would include: about 2800 capture devices similar in size to industrial cooling towers, a 160 MW-e NGCC w/capture power plant, a 100 million-liter-per-day water plant, a desorption and compression plant, and a geologic storage system capable of accepting 1.87 million tonnes of CO_2 per year. The capture devices would, by far, require the largest area foot print in this example. The total capital cost of such a system could be around \$1.7 billion.

Two research and development targets are clear from this analysis. Development of capture systems (principally the chemical system) should be targeted toward fast absorption kinetics to minimize the overall size of capture devices, and also targeted at optimizing system thermodynamic efficiency by minimizing regeneration energy and fluid handling losses. These two goals address the two largest cost centers (capture device capital cost and energy system overall cost) respectively. This is a challenge because fast absorption chemistries tend to also be the most energy intensive. Our analysis suggests, however, that at efficiencies of 10% and capital costs similar to conventional cooling towers, air capture could be conducted well below \$500/tonne-CO_2, making air capture a potential contributor to the ultimate decarbonization of the global energy system in a future where all prudent and less costly mitigation options (increased conservation and efficiency, maximum deployment of zero-carbon and carbon-managed electricity and elimination or capture of CO_2 from all major stationary sources) have been fully deployed. Air capture is also one of the only technologies (alongside biomass based solutions) that could be put to use in a negative emissions program.

References

Barker, T.I. et.al, Mitigation from a cross-sectoral perspective in Climate Change, 2007. Contribution of Working Group III to the Fourth Assessment Report of the IPCC.

Hansen, J. et al., 2007. Climate change and trace gases. Philosophical Transactions of the Royal Society A. 365 (1856), 1925-1954.

Lackner, K. S et al., 2001. Capturing carbon dioxide from air. Proceedings of the First National Conference on Carbon Sequestration in Washington, DC.

Lackner, K. S. and Wright, A. B., May 2009. USA Patent No. 12/265556.

Mahmoudkhani, M. and Keith, D. W. 2009. Low-energy sodium hydroxide recovery for CO_2 capture from atmospheric air--Thermodynamic analysis. International Journal of Greenhouse Gas Control. 3 (4), 376 - 384.

McKinsey & Company, 2009. Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve.

MIT, 2006. The Future of Geothermal Energy available at: http://www1.eere.energy.gov/geothermal/egs_technology.html.

Orr, F. M., 2004. Storage of Carbon Dioxide in Geologic Formations. Journal of Petroleum Technology. 56 (9), 90 – 97.

Pielke, R. A., 2009. An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. Environmental Science and Policy. 12 (3), 216-225.

Pittner, G. A., 1992. The Economics of Desalination Processes, in: Amjad, Z. (ed.), Reverse Osmosis. Van Nostrand Reinhold, New York, pp. 76-103.

RDS, LLC and Alstom Power, 2007. Final Draft Report Report No. DOE/NETL-401/110907

Solomon, S et al. 2009. Irreversible climate change due to carbon dioxide emissions. PNAS 106 (6).

Zeman, F., 2007. Energy and Material Balance of CO_2 Capture from Ambient Air. Environmental Science & Technology. 41 (21), 7558-7563.

Zeman, F., 2008. Experimental results for capturing CO_2 from the atmosphere. AIChE Journal 54 (5), 1396-1399.