A Pathway Toward Reducing CO$_2$ Emissions from the Industrial Sector

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Abstract

It is well documented that a concerted effort is required to reduce the threat of climate change. One vital component in this portfolio of solutions – carbon capture and utilization – has been stalled by significant economic and technical barriers. To overcome these obstacles, it is necessary to identify economically viable capture opportunities – targets that can serve as a driver to lower life cycle costs, increase commercialization efforts and provide an impetus for development in the utilization arena. This study presents a methodology for assessing the levelized cost of CO_2 capture, compression, and transport from industrially-sourced capture to regional utilization (sink) opportunities. Industrial sources are targeted over coal and gas-fired power plants given industrial sources often have exhausts with higher CO_2 purity, a factor that lends to a lower minimum work of separation and, hence, lower cost of capture. The greater concentration in CO_2 results from combination of process emissions with those associated with stationary combustion. These industrial sources, together with a full inventory of geo-referenced utilization opportunities, serve as inputs to a robust cost model that accommodates for differences in source exhaust composition, flow rate, and source-sink geographical relationships. A case-study conducted for the US state of Pennsylvania yields a cost-based ranking of 47 industrial sites, whereby steel and cement manufacturing dominated the least levelized cost options, anchored by high CO_2 exhaust content (14 – 33% CO_2). Further, we find truck transport is cost-competitive with pipeline for small volumes (< 100 kt CO_2/a); such small volumes dominate non-EOR based utilization demand.

Significance Statement

This work represents a techno-economic analysis of CO_2 emissions from industrial processes, identification of regional CO_2 utilization opportunities, and a method to estimate the levelized cost of CO_2 capture, compression, and transport. Targeting industrial CO_2 emissions allows for the exploitation of exhaust streams typically richer in CO_2 content than those found in power generation – a factor that lends to lower separation costs. A thorough geo-inventory of CO_2 emission supply and demand, combined with a cost model that accommodates for site, size, and process-dependent inputs can relate information pertaining to the region-specific economic viability of CO_2 capture. The method and results presented here can assist industry leaders and policy makers alike in the development of early strategies for CO_2 capture integration.

1. Introduction

In 2013, the US industrial sector emitted approximately 1.4 gigatonnes of carbon dioxide (Gt CO_2), or 21% of total US CO_2 emissions – the third highest figure for any economic sector behind transportation (27%) and electricity (31%) (1). These industrial emissions can be categorized as direct (on-site fuel combustion), indirect (attributed to electricity purchased for power and off-site steam generation) and process (CO_2 liberated as a reaction by-product, see Figure S1). Direct and indirect emissions generally constitute ca. 80% of total industrial emissions, with process emissions making up the balance, though the relative contribution of process emissions to total emissions varies by industry. Process emissions constitute a relatively small percentage of industrial emissions (2); they are the by-product of the production of commodities like glass, cement, ammonia and steel – commodities that form the irreplaceable fabric of industrialized nations. Unlike the electricity sector, where mitigation might be achieved

through a transition to technologies that do not emit CO_2 such as wind and solar power, there are no economic pathways that lead to zero CO_2 emissions for most industrial commodity fabrication. Therefore, these irreplaceable industrial processes (IIPs) represent CO_2 emissions that largely cannot be abated. While overall production from such IIPs has declined in the US, it is projected to increase globally 45-60% by 2050 to meet the demands of a rising global population and economic activity (3). Provided that global industrial CO_2 emissions eclipsed 13 Gt in 2010(4), presently, such growth ought to be a cause for concern.

For an industrial process to be considered an IIP, it must meet the following conditions: 1) the process must produce CO_2 as a reaction by-product; 2) there is no economic/industrially relevant alternative routes to production (5); and 3) there either exists no viable product (e.g. cement, steel, glass, etc.) substitute, or the manufacturing of such a replacement results in CO_2 process emissions of an equivalent or greater amount than the original. Based on these criteria, this study identifies and examines the following as IIPs: aluminum, ammonia synthesis, mixed carbonate use, cement, ethanol production, ferroalloys, glass, iron and steel, lead, lime, magnesium, petrochemicals, phosphoric acid, pulp and paper, refining, silicon carbide manufacturing, soda ash production, titanium oxide, and zinc smelting. These IIPs are important for two reasons: 1) process stoichiometry makes CO_2 creation unavoidable, and perhaps more importantly 2) they often yield exhaust streams containing higher CO_2 content than the flue exhausts from fossil-fuel fired electricity production (e.g. coal and natural gas) [*]. Given that the cost of CO_2 separation scales inversely with initial dilution of a mixed feed

stream (6, 7), carbon capture technology retrofits have the potential to efficiently and economically divert emissions from industrial exhaust streams to viable CO_2 utilization opportunities. Such opportunities include enhanced oil recovery (EOR), food processing, refrigeration, and fertilizer production (8). To assess the economic potential of carbon capture applied to irreplaceable industrial processes, this work provides a novel cost analysis across the three major components of the carbon capture supply chain: capture, compression, and transport. Given levelized costs (measured in dollars per tonne of CO_2 captured), this study employs a geo-referencing approach which links industrial sources to current and potential future CO_2 sinks (utilization opportunities) to identify least cost pathways for abatement, given a local mix of supply and demand (9). The aim is to classify these IIPs based on carbon-capture "readiness", which is ultimately a combination of the industry- and site-specific factors listed above. This study provides an approach whereby emissions from irreplaceable industries may be significantly reduced. As the ordering of lowest cost abatement opportunities are identified in a given region, it raises the idea of new entrants within an expanded CO_2 commodity market, potentially displacing carbon dioxide production from natural reservoirs and/or specialty chemical manufacturing facilities. This replacement would have the effect of reducing the net CO_2 emissions from an overall economy (10). While prices from current CO_2 commodity markets are low, public policy would need to play a strong role to provide a signal for investors to build capture facilities at industrial sites.

2. CO$_2$ Utilization Opportunities

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[*] Consequently, the high volume power sector has seen the majority of attention in regards to the implementation of CO_2 abatement technologies.

In 2011, the US EPA estimated the scale of US CO_2 utilization at 67 Mt/a (11), approximately 1% of total US emissions, and 10% of the available CO_2 emissions from the aforementioned IIPs. Currently, the scale of CO_2 utilization is small, limiting its current impact as an emissions abatement strategy. Yet, continued research and development, coupled with expanded demand in current technologies leads to optimistic projections of near to mid-term CO_2 utilization growth (12). For example, the US (and global) CO_2 reuse market is dominated by enhanced oil recovery (EOR), with most within the US Permian basin, the majority of which is located in West Texas (13). Though current demand stands at ca. 62 Mt CO_2/a (101 US operations) some estimates believe this number could rise to as high as 500 Mt CO_2/a (8).

Outside of EOR, CO_2 utilization opportunities are much smaller in scale, numerous and dispersed (Figure 2). Growth in non-EOR applications is anticipated as more captured CO_2 becomes available. For example, CO_2 is currently being explored extensively as a chemical feedstock (a partial listing of the industrial reactions of CO_2, sorted by the free energy of reaction, is provided in Table S2). Another option involves the use of CO_2 as a solvent or technological fluid. In particular, CO_2 has been thoroughly investigated as a replacement for organic solvents, as a refrigerant, in chemical extractions (14, 15), and as a substitute for potentially harmful solvents such as phosgene (16). A detailed discussion of these and other viable CO_2 utilization options is presented in the supporting document.

In most cases, CO_2 is sourced naturally or created intentionally. Unfortunately, these sources offer no direct reduction to CO_2 emissions as it is additive to anthropogenic emissions. A direct impact on emissions abatement could be realized if these natural and intentionally

generated sources were replaced with IIP-sourced CO_2. For example, the CO_2 used for EOR is mainly supplied via natural reservoirs delivered by an extensive CO_2 pipeline network at a collective rate of ca. 145 tonnes CO_2/day (85% of total demand) (17, 18). Jackson Dome and McElmo Dome each supply roughly 20 $MtCO_2$ per year to the Gulf and Permian Basin regions, respectively (Figure S3). Currently, industrial processes account for only 4% of the EOR CO_2 supply chain (CO_2 sourced from natural gas processing accounts for the remaining 11%). Given an average industrial output of approximately 0.8 $MtCO_2$ per year, these natural sources could be replaced with the combined output of 25 such facilities. However, in high-output regions like the Gulf Coast, IIPs from refining and petrochemical production can yield greater than 6 $MtCO_2$ per year , thus as few as three industrial sources could effectively replace the naturally-sourced CO_2.

For the purposes of this study, only existing utilization sites are considered. Further, this study considers only those opportunities where CO_2 demand is directly quantifiable (refer to supplementary information for methodology). The total addressable CO_2 demand market can be split into two groups: first order opportunities (EOR, urea manufacturing, soft-drink manufacturing, soda bicarbonate production, fireproofing and decaffeination) are characterized as mature processes that currently accept CO_2 as a commodity feedstock. Industrial facilities would be motivated to install and operate appropriate capture facilities only if the captured CO_2 is cost-competitive with the incumbent provider.[†] Second-order opportunities (refrigeration, polymers, methanol, gum and wood chemicals and gas manufacturing) can potentially accept CO_2, but additional considerations serve to complicate deployment and may require substantial investment in the receiving facility. For example, CO_2 is known to produce methanol via

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[†] In most cases, a policy mechanism such as a tax credit, carbon tax or other incentive would be required to achieve cost-competitiveness of such captured CO_2.

hydrogenation; however, the CO_2 route to methanol requires one additional mole of H_2 per mole of methanol produced when compared to the CO route. In this case, a reliable low-carbon source of H_2 is necessary to ensure that CO_2 substitution in methanol production is carbon negative. CO_2 in refrigeration applications is another example whereby equipment retrofitting may be required.

3. Industrial CO_2 Capture: Predicting Separation Cost

The chemistry of the IIPs makes CO_2 release unavoidable. An inventory of the reactions for each IIP where CO_2 is a by-product is provided in Table 1. Together, these processes released just short of 400 Mt CO_2 emissions in the United States in 2014, roughly 30% of total emissions from the industrial sector. Typical IIP conditions are summarized in Table 2. When compared to power generation, these industrial processes can produce exhaust streams with higher CO_2 content, a factor that lends to a lower theoretical minimum work of separation. Thermodynamically, this work is defined as the change in Gibbs free energy of product streams (separated CO_2 and residual, B and C) and reactant stream (gas mixture, A) (19):

$$W_{\min} = RT\left[n_B^{CO_2}\ln\left(y_B^{CO_2}\right) + n_B^{B\text{-}CO_2}\ln\left(y_B^{B\text{-}CO_2}\right)\right] + RT\left[n_C^{CO_2}\ln\left(y_C^{CO_2}\right) + n_C^{C\text{-}CO_2}\ln\left(y_C^{C\text{-}CO_2}\right)\right]$$
$$- RT\left[n_A^{CO_2}\ln\left(y_A^{CO_2}\right) + n_A^{A\text{-}CO_2}\ln\left(y_A^{A\text{-}CO_2}\right)\right]$$

This principle was illustrated in the works of Thomas Sherwood, whereby separation cost was shown to scale inversely with target dilution(20). We use this principle to build a cost model based on current capture costs and conditions (Figure 1). Here, the Carnegie Mellon Integrated Environmental Control Module (IECM)(21) is used to first estimate the capital and operating

costs of carbon dioxide capture operation chain for the capture component alone (minus compression, storage and transportation costs) for natural gas combined cycle (NGCC), sub-critical pulverized coal (PC) and integrated gasification combined cycle (IGCC) systems of various capacities (net power outputs). Based on the methodology described in the Supplementary Information, these model output costs are used to determine the levelized cost of carbon dioxide capture (LCOC) for each generation technology, peak capacity and flow rate.[‡] A multi-variate regression is used to express levelized capture costs as a function of CO_2 exhaust dilution, capture efficiency, and gas flow rate. This relationship is applied to each IIP to estimate levelized capture only costs based on known flow rates, assumed capture rates (90% in this study) and assumed CO_2 exhaust dilution (Table 2, column 2). As indicated, IIP costs are strongly correlated to the initial CO_2 dilution which supports the Sherwood approach to cost estimation. Flow rate is expected to play a smaller role as 1) industrial flow rates are comparable in scale and 2) variations in flow rate become less important to cost as the CO_2 concentration increases.

This study has identified and characterized 875 IIPs in the US. Figure 3 displays the geographical spread of US IIPs. The scale and location of these industrial facilities creates regional CO_2 opportunities to be explored in the context of CO_2 utilization (Fig. 2). The majority of these industries (83% by count, representing 79% of all IIP emissions) have exhaust streams

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[‡] The levelized cost of carbon dioxide (LCOC) is similar in concept as the more familiar levelized cost of electricity (LCOE), used to compare the economics of alternative electricity generation technologies. The LCOC unit of measure is cost (in dollars) per unit mass of CO_2 (in tonnes). The LCOC considers the fixed, variable and capital costs, in addition to cost of capital, tax rates and depreciation schedule of systems used to capture, compress and transport CO_2. The LCOC is modular by construction and thus can be calculated for each element the carbon dioxide value chain (capture, compression and transport). The LCOC is essentially a break-even metric, that is, the average price that would need to be received over the lifetime of the system (capture, compression, transport) to yield a net present value (NPV) of zero.

that fall between $0 - 40\%$ CO_2 purity; this range is within that used to derive the adjusted Sherwood plot, lending to more reliable levelized cost estimations. The remaining industries such as ammonia and ethanol production, produce near-pure streams of CO_2 and account for 21% of all IIP emissions. Currently, many of these facilities already sell captured CO_2; for example in 2011, 115 facilities employed carbon capture technologies to produce 16 Mt/a of CO_2 (11). Costs for high purity capture are expected to deviate from the relationship derived in Figure 1, as the separation component typically involves only dehydration and compression (to be addressed later); thus, as CO_2 purity approaches 100%, the cost of separation[§] should approach zero(22, 23).

Figure 4 illustrates the relative CO_2 offset potential for IIPs based on the cumulative utilization demand within a 100-mile radius of the source. A plant 'stranded' geographically in terms of regional sink opportunities is colored blue, while a plant situated to potentially offset all CO_2 emissions via regional pairings is colored red. Naturally, regions of high CO_2 offset correspond with dense clusters of high-demand CO_2 reuse opportunities (EOR, urea, etc.) and carry the potential to form a regional market or exchange.

4. Compression and Transport Cost Elements of the LCOC

[§] The cost of separation here refers to capture only. Costs associated with compression, dehydration, and flow directors are included in the compression estimate.

After capture, CO_2 must be compressed to a level suitable for transport. The two methods of transport considered in this study are pipeline and tanker delivery.[**] The IPCC report on CO_2 transport (24) dismisses tanker delivery, and other similar studies focus mainly on pipeline transport (25, 26). This is likely due to the noted economies of scale related to high volume CO_2 transport via pipeline. However, this assumes a high volume source (power generation, large industries) and high capacity sink (EOR, for example) while failing to account for smaller scale opportunities where pipeline transport may be cost prohibitive. Situations exist where the volume of CO_2 is simply too low to avoid high cost pressurization of the stream. For these low-volume CO_2 applications (< 0.1 Mt CO_2 per year.), trucking is more cost effective for any distance, compared to an appropriately sized piping infrastructure (Figure S4). Therefore, tanker delivery is the preferred choice where CO_2 is to be transported in small volumes to multiple locations. Given the foreseeable low volumes of CO_2 production from IIP capture processes, and the relative dispersion of sources relative to sinks, this transportation method assessed in detail this work. The standard cost model of Berwick and Farooq (27) is used as the basis for trucking transport estimates (a full methodology is included in the supporting document).

For pipeline transport, CO_2 must be compressed to a liquid dense phase, typically at pressures ranging from 9–15 MPa and temperatures between 10–35°C (19). For tanker delivery, liquefied CO_2 is stored in cryogenic vessels and transported by tank trucks with a capacity range of 2-30 tonnes. Here, CO_2 is compressed to 1.7 MPa and -30°C (28). Generally, the theoretical power required to compress CO_2 to a suitable level for transport can be calculated (Table S5).

[**] In the context of transport, tanker indicates both sea (merchant vessel) and land (trucking) modes. Here, we unambiguously define tanker as land (trucking) transport. Please refer to the Supplementary Information for details on the truck transport model.

However, several factors can influence compression costs from case to case, including the volume of CO_2 processed and the assumed electricity prices used in the compression process; thus, it is important to develop a compression model that can scale with plant size (output). Here, IECM baseline data for compression capital expenditures and fixed and variable operating and maintenance costs are inventoried for PC, NGCC, and IGCC processes, similar to the procedure used to determine the capture-only component. A regression is applied such that levelized compression costs (measured in $/tCO_2$) are expressed as a function of CO_2 flow rate.[††]

5. Case-Study: Ranking Irreplaceable Industrial Processes in Pennsylvania

We provide an illustrative example of our cost methodology through an assessment of the levelized cost of source/sink scenarios in a region of Pennsylvania. Pennsylvania has a range of IIPs and sink opportunities, and a geographical mix of urban and rural areas that make it well suited for an example approach which could be generalized to other regions. The average IIP CO_2 output is approximately 800 kt CO_2 per year, while the average sink demand is far smaller (ca. 15 kt CO_2 per year); thus on average ~50 sinks of equal capacity would be required to accept all CO_2 captured. To define these source/sink relationships, a service area encompasses all sink opportunities within a 100-mi *driving* radius. These individual CO_2 transportation routes serve as the input to the transport model, and taken together with the capture and compression cost models, define a physically viable scenario for each IIP (see SI for a full description of the methodology). Locations for all 47 Pennsylvania IIPs, as well as the 772 first- and second-order utilization opportunities within the 100-mile radius are presented in Figure 5. Levelized capture, compression, and transport costs are calculated for delivering captured industrial CO_2 to

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[††] It is understood that the CO_2 product is H_2O saturated and dehydration cost are included within compression.

surrounding utilization opportunities, and the 20 lowest LCOCs are reported in Table 4 (column

8). A large-scale iron and steel plant represents the lowest-cost ($36.77/tCO$_2$).[‡‡] Not surprisingly,

the options with the lowest LCOC correspond to higher CO$_2$ exhaust purities. Some factors act to

increase the LCOC of a source/sink scenario, including the maximum deliverable CO$_2$ for each

100-mile IIP service area (Table 4, column 6). This quantity is limited by either the amount of

CO$_2$ captured or the cumulative sink demand. When this number is small, transport costs can

become quite large, increasing the levelized cost of CO$_2$.[§§] For a given source, the best-case

scenario occurs when all captured CO$_2$ can be sunk, subject to a minimization of transport

costs.[***] We note that in a given region, the CO$_2$ supply with the lowest LCOC would be fully

absorbed by the sink(s), and in the event there is excess sink capacity available, the next lowest

LCOC – subject to transportation constraints and quantity of CO$_2$ produced – would be made

available. To more fully account for supply and demand within a region, and to understand what

opportunities would arise should adjacent regions become available, a dynamic model is

required. Such a formulation is beyond the scope of the current study and should be the focus for

future work.

6. Conclusions

This study introduces a methodology for estimating capture, compression, and transport

costs for CO$_2$ captured from irreplaceable industrial sources of varying exhaust rates and

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[‡‡] The LCOC is based on a given source (in this case an iron and steel plant) being able to fully transfer its supply to the available sink(s) within the defined region.

[§§] Given fewer units of CO$_2$ in which to spread the cost over, the levelized unit cost would increase.

[***] We note that in the case where captured CO$_2$ is not delivered to an appropriate sink, it becomes "stranded" and, assuming no alternative disposal, may be released (curtailed). If it is anticipated that – on average, over the lifetime of the capture unit – a portion of the captured carbon dioxide will not be transferred to a sink, the decision *ceteris paribus*, could be to either (i) idle the capture process or (ii) build a smaller unit at the outset. The result of either could have the implication of higher unit cost of carbon capture.

composition. With robust models that can accommodate industry and site-specific parameters, an order can be generated for any region for the identification of early targets for CO_2 capture installation. The major contributions of this model over previous cost models are as follows: i) this model adds two additional dimensions to the original Sherwood-model: flow rate and capture efficiency. These additional degrees of freedom allow for a more accurate application of the power-plant derived Sherwood curve to facilities with far lower gas flow rates, while the inclusion of capture efficiency is applicable to cases where a tailored approach for capture technology implementation is desired, such as emission targets based on mass opposed to rates; and, ii) a bi-modal approach to transportation allows for the simultaneous consideration of large volume (EOR) applications via pipeline, as well as smaller volume CO_2 transport via trucking. Our calculations indicate that trucking is the cost-effective transportation method for small volumes (i.e. the majority of non-EOR IIP utilization cases) compared to pipeline. The inclusion of truck transport model challenges the conventionally favored pipeline model by showing that truck transport could play a significant role in low volume, short distance transport scenarios. Results from our case study suggest that the LCOC of IIP is meaningfully below that of the power sector, which has received the majority of interest regarding carbon capture technology implementation. This in turn raises the potential of an accelerated timeline for the adoption of carbon capture technologies at scale.

There are several promising avenues for future research. First, an understanding of the supply/demand dynamics within a region with endogenous boundaries would provide greater insight regarding costs and producer behavior. Second, an exploration of how policy mechanisms such as tax incentives or a price on CO_2 could alter source and sink preferences, subject to differing regulations. Third, a study on how existing processes which currently do not use carbon

dioxide as an input may be altered given sufficient supply (and related reduction in lifecycle cost) CO_2.

References

1. US EPA (2015) US GHG Inventory Chapter 2: Trends in Greenhouse Gas Emissions. Accessed January 16, 2016.
2. US EPA (2015) US GHG Inventory Chapter 4: Industrial Processes and Product Use. Accessed January 16, 2016.
3. IPCC (2015) Emissions Scenarios. Available at http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=99 Accessed September 2, 2015.
4. IPCC (2014) Climate Change 2014, Mitigation of Climate Change. Chapter 10 : Industry. Accessed February 27, 2016.
5. Peters M, *et al.* (2011) Chemical technologies for exploiting and recycling carbon dioxide into the value chain. *ChemSusChem* 4(9):1216-1240.
6. House KZ, *et al.* (2011) Economic and energetic analysis of capturing $CO2$ from ambient air. *Proceedings of the National Academy of Sciences* 108(51):20428-20433.
7. Grübler A (2003) *Technology and global change* (Cambridge University Press).
8. Brinckerhoff P (2011) Accelerating the uptake of CCS: industrial use of captured carbon dioxide. *New York*.
9. Solomon S (2007) *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Cambridge University Press).
10. Comello S & Reichelstein S (2014) Incentives for early adoption of carbon capture technology. *Energy Policy* 74:579-588.
11. United States Environmental Protection Agency (2011) Carbon Dioxide Capture and Sequestration, Available at http://www3.epa.gov/climatechange/ccs/. Accessed 11/1/2015.
12. Mikkelsen M, Jorgensen M, & Krebs FC (2010) The teraton challenge. A review of fixation and transformation of carbon dioxide. *Energy & Environmental Science* 3(1):43-81.
13. Melzer LS (2012) Carbon dioxide enhanced oil recovery (CO 2 EOR): Factors involved in adding carbon capture, utilization and storage (CCUS) to enhanced oil recovery. *Center for Climate and Energy Solutions*.
14. Beckman EJ (2004) Supercritical and near-critical CO_2 in green chemical synthesis and processing. *The Journal of Supercritical Fluids* 28(2):121-191.
15. Wai CM, Hunt F, Ji M, & Chen X (1998) Chemical reactions in supercritical carbon dioxide. *Journal of chemical education* 75(12):1641.
16. Sakakura T, Choi J-C, & Yasuda H (2007) Transformation of Carbon Dioxide. *Chemical Reviews* 107(6):2365-2387.
17. DiPietro P, Balash P, and Wallace, M. (2012) A Note on Sources of CO_2 Supply for Enhanced-Oil-Recovery Operations. (Society of Petroleum Engineers).
18. DiPietro P, Murrell, G (2013) North American CO_2 Supply and Developments. *19th Annual CO_2 Flooding Conference.*
19. Wilcox J (2012) *Carbon capture* (Springer).
20. Sherwood TK (1959) *Mass Transfer Between Phases* (Phi Lambda Upsilon, Penn State University, University Park, PA).
21. Rubin ES, Chen C, & Rao AB (2007) Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy policy* 35(9):4444-4454.
22. Dixon T, Herzog H, Twinning S, Gollakota S, & McDonald S (2014) 12th International Conference on Greenhouse Gas Control Technologies, GHGT-12Commercial-scale CCS Project in Decatur, Illinois – Construction Status and Operational Plans for Demonstration. *Energy Procedia* 63:5986-5993.

23. Finley R (2006) Illinois State Geological Survey Evaluation of CO2 Capture Options from Ethanol Plants.

24. Metz B, Davidson O, de Coninck H, Loos M, & Meyer L (2005) Carbon dioxide capture and storage.

25. Hasan MMF, Boukouvala F, First EL, & Floudas CA (2014) Nationwide, regional, and statewide CO2 capture, utilization, and sequestration supply chain network optimization. *Industrial & Engineering Chemistry Research* 53(18):7489-7506.

26. Knoope MMJ, Guijt W, Ramírez A, & Faaij APC (2014) Improved cost models for optimizing CO2 pipeline configuration for point-to-point pipelines and simple networks. *International Journal of Greenhouse Gas Control* 22:25-46.

27. Berwick MD & Farooq M (2003) Truck costing model for transportation managers. (Mountain-Plains Consortium).

28. Omae I (2012) Recent developments in carbon dioxide utilization for the production of organic chemicals. *Coordination Chemistry Reviews* 256(13–14):1384-1405.

29. Tsai IT, Al Ali M, El Waddi S, & Zarzour OA (2013) Carbon Capture Regulation for The Steel and Aluminum Industries in the UAE: An Empirical Analysis. *Energy Procedia* 37:7732-7740.

30. Das SK (2007) Improving Energy Efficiency in Aluminum Melting. Available at http://www.phinix.net/services/Energy_Management/Improving_Energy_Efficiency.pdf. Accessed October 14, 2015.

31. Zakkour P, Cook, G. (2010) CCS Roadmap for Industry: High-Purity CO2 Sources. Carbon Counts Company (UK) Ltd.

32. Anonymous (2012) US GHG Inventory Chapter 4 Industrial Processes. (US EPA).

33. Steele WA (1973) The physical interaction of gases with crystalline solids: I. Gas-solid energies and properties of isolated adsorbed atoms. *Surface Science* 36(1):317-352.

34. Hoenig V, Hoppe H, & Emberger B (2007) Carbon capture technology-options and potentials for the cement industry. *Tannenstrasse: European Cement Research Academy*:96.

35. Rushing SA (2007) Merchant Carbon Dioxide Sourcing: The Ethanol Perspective. *CryoGas International* 45(5):28-29.

36. Intergovernmental Panel On Climate Change (2006) 2006 IPCC guidelines for national greenhouse gas inventories.

37. Holappa L (2010) Towards sustainability in ferroalloy production. *South African Institute of Mining and Metallurgy. Journal* 110(12):703-710.

38. Ladam Y, Tangstad M, Ravary, B (2013) Energy Mapping of Industrial Ferroalloy Plants. *The thirteenth International Ferroalloys Congress*.

39. Díaz-Ibarra O, Abad P, & Molina A (2013) Design of a day tank glass furnace using a transient model and steady-state computation fluid dynamics. *Applied Thermal Engineering* 52(2):555-565.

40. Farla JCM, Hendriks CA, & Blok K (1995) Carbon dioxide recovery from industrial processes. *Climatic Change* 29(4):439-461.

41. Wu JCS (2009) Photocatalytic reduction of greenhouse gas CO2 to fuel. *Catalysis surveys from Asia* 13(1):30-40.

42. Gao F, Liu Y, Nie Z-R, Gong X, & Wang Z (2015) Variation Trend and Driving Factors of Greenhouse Gas Emissions from Chinese Magnesium Production. *Environmental Science & Technology* 49(21):12662-12669.

43. Xu Y, Isom L, & Hanna MA (2010) Adding value to carbon dioxide from ethanol fermentations. *Bioresource technology* 101(10):3311-3319.

44. Efficiency E (2007) Tracking Industrial Energy Efficiency and CO2 Emissions. *International Energy Agency* 34(2):1-12.

45. Romano MC*, et al.* (2013) Application of Advanced Technologies for CO2 Capture From Industrial Sources. *Energy Procedia* 37:7176-7185.

46. van Straelen J, Geuzebroek F, Goodchild N, Protopapas G, & Mahony L (2010) CO_2 capture for refineries, a practical approach. *International Journal of Greenhouse Gas Control* 4(2):316-320.
47. Varghese OK, Paulose M, LaTempa TJ, & Grimes CA (2009) High-rate solar photocatalytic conversion of CO2 and water vapor to hydrocarbon fuels. *Nano letters* 9(2):731-737.
48. Roy SC, Varghese OK, Paulose M, & Grimes CA (2010) Toward solar fuels: photocatalytic conversion of carbon dioxide to hydrocarbons. *Acs Nano* 4(3):1259-1278.
49. Xiong S-F, Yuan Z-F, Cong XU, & Liang XI (2010) Composition of off-gas produced by combined fluidized bed chlorination for preparation of TiCl 4. *Transactions of Nonferrous Metals Society of China* 20(1):128-134.
50. E. Wachs I, J. Dwyer D, & Iglesia E (1984) Characterization of Fe, Fe-Cu, And Fe-Ag fischer-tropsch catalysts. *Applied Catalysis* 12(2):201-217.
51. Elanchezhian C, Saravanakumar L, & Ramnath BV (2007) *Power Plant Engineering* (I.K. International Publishing House).
52. Merkel TC, Lin H, Wei X, & Baker R (2010) Power plant post-combustion carbon dioxide capture: an opportunity for membranes. *Journal of Membrane Science* 359(1):126-139.
53. Frenkel D & Smit B (2002) Chapter 11 - Free Energy of Chain Molecules. *Understanding Molecular Simulation (Second Edition)*, eds Frenkel D & Smit B (Academic Press, San Diego), pp 269-287.

Figure Legends

Figure 1. Adjusted Sherwood plot for the prediction of capture costs from power (black circles) of varying gas flow rates (low to high). This data is used to predict levelized costs of capture for several irreplaceable industries (colored circles and diamonds). Not shown are cost points for streams of 100% CO_2 purity, for which the cost of capture is assumed to approach zero.

Figure 2. National distribution of CO_2 utilization opportunities. Graduated symbology denotes CO_2 demand. Enhanced oil recovery dominates demand but is geographically isolated from industrial emitters in the Northeast and West coast, where smaller scale opportunities may play a more prominent role.

Figure 3. National distribution of irreplaceable industrial processes. Graduated symbology denotes potential CO_2 capture volume (at 90% capture rate).

Figure 4. Offset potential of industrial sources, defined by the volume of CO_2 reuse demand within a 100-mile radius. Red indicates full offset potential; blue indicates reuse-isolated source.

Figure 5. Geographic distribution of IIP sources and viable sink opportunities in Pennsylvania and surrounding markets.

TABLE 1. Chemistry and scale of US irreplaceable industrial processes.[a]

Commodity	Chemistry	CO$_2$ (Mt/a)	
		Process	**Combined[b]**
Aluminum	$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$	2.79	3.33
Ammonia	$0.88CH_4 + 1.26air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$	14.67	24.40
Carbonates	$Ca/MgCO_3 + heat \rightarrow Ca/MgO + CO_2$	0.48	1.48
Cement	$CaCO_3 + heat \rightarrow CaO + CO_2$	65.79	68.22
Ethanol	$C_6H_{12}O_6 + yeast \rightarrow 2C_2H_5OH + 2CO_2 + heat$	40.80	40.80
Ferroalloys	$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$	2.09	2.13
	$Fe_2O_3 + 2MnO + 5C \rightarrow 2FeMn + 5CO$		
	$Fe_2O_3 + 2CrO + 5C \rightarrow 2FeCr + 5CO$		
Glass	various components + heat $\rightarrow CO_2$ + glass	1.18	5.34
Iron and Steel	$2C + O_2 \rightarrow 2CO$	30.71	83.03
	$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$		
Lead	$2PbO + C \rightarrow 2Pb + CO_2$	0.75	1.06
Lime	$CaCO_3 + heat \rightarrow CaO + CO_2$	18.94	38.37
Magnesium	$2MgO + C \rightarrow 2Mg + CO_2$	0.71	0.71
Petrochem.	$C_2H_4 + 3O_2 \rightarrow 2H_2O + 2CO_2$	15.73	80.14
H3PO4	$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$	1.72	2.72
Pulp and Paper	wood organics + $O_2 \rightarrow CO_2$; $CaCO_3 + heat \rightarrow CaO + CO_2$	121.96	143.33
Refining	$CH_{1.33}O_{0.43} + 0.26O_2 \rightarrow 0.65CH_{1.12} + 0.27H_2O + 0.34CO_2$	69.34	188.05
SiC	$SiO_2 + 3C \rightarrow SiC + 2CO$	0.12	0.12
Soda Ash	$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$	1.40	5.44
TiO2	$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$	1.44	2.47
Zinc	$ZnO + CO \rightarrow Zn + CO_2$	0.63	0.69
	Total	391.25	691.84

[a] Source: EPA Greenhouse Gas Reporting Program, 2014

[b] Combined emissions = process + stationary combustion

TABLE 2. Minimum work and Sherwood-derived cost of capture estimations for various industries.

Source	CO$_2$ Content (mol %)[a]	Min. Work (kJ/mol CO$_2$ Captured)[b]	Cost (US\$/tonne CO$_2$ Captured)	Average Emissions (kt CO$_2$/a)[c]	Ref.
Aluminum	4 – 10	8.2 – 10.8	45.8 – 65.6	281	(9, 29, 30)
Ammonia	30 – 100	0.0 – 5.0	0.0 – 29.0	757	(31)
Carbonates	20	6.2	36.0	95	(32)
Cement	14 – 33	4.7 – 7.3	28.1 – 39.2	646	(33, 34)
Ethanol	100	0.0	0.0	399	(35)
Ferroalloys	8 – 10	8.3 – 8.9	46.3 – 50.6	192	(36-38)
Glass	7 – 12	7.7 – 9.3	44.4 – 54.9	67	(36, 39)
Iron and Steel	20 – 27	5.5 – 6.2	31.4 – 34.2	588	(33, 40)
Lead	15	7.1	40.5	80	(41)
Lime	20	6.2	34.4	493	(36)
Magnesium	15	7.1	40.7	71	(36, 42)
Petrochemicals	30 – 100	0.0 – 5.0	0.0 – 28.6	1,173	(40, 43)
Pulp and Paper	8	8.9	48.0	1,173	(44)
Refining	3 – 20	6.2 – 11.7	33.5 – 70.4	1,240	(45, 46)
Silicon Carbide	8	8.9	51.4	110	(47)
Soda Ash	36 – 40	4.0 – 4.4	25.6 – 26.7	1,224	(48)
TiO$_2$	13	7.5	41.2	317	(49)
Zinc	15	7.1	40.2	104	(41, 50)
Natural Gas	3 – 5	10.3 – 11.7	57.2 – 69.9	1,607	(19, 43)
Petroleum	3 – 8	8.9 – 11.7	47.0 – 69.0	2,554	(19, 33)
Coal	10 – 15	7.1 – 8.3	36.5 – 42.7	3,338	(43, 51, 52)

[a] Range in composition due to different processes or different capture points within the same process. When not directly reported, values were estimated from a complete mass balance assuming NG fuel and 15% excess air.

[b] Calculated assuming 99.5% purity and 90% capture, Ref. (19).

[c] Average CO$_2$ emissions reported to the Greenhouse Gas Reporting Program, Ref. (53).

TABLE 3. Statistics and cost estimation (capture, compression, and transport) for Pennsylvania-based irreplaceable industrial sources (top 20 most economical options).

Industry	Output*0.9 (ktCO$_2$/a)[a]	Regional Demand (ktCO$_2$/a)[b] (count)[c]	Average Distance (source to sink) (mi.)	Maximum Deliverable (ktCO$_2$/a)[d]	Levelized Costs (US$ / tCO$_2$) Capture/ Compression	Transport	Total
Iron and Steel	3033.9	43.3 (76)	40.4	43.3	30.58	6.19	36.77
Iron and Steel	342.6	44.9 (78)	41.9	44.9	32.52	6.22	38.75
Iron and Steel	196.9	207.4 (268)	59.1	**196.9**	33.04	6.34	39.37
Cement	622.8	332 (433)	70.3	332.0	31.98	7.75	39.73
Cement	600.5	332.3 (435)	71.0	332.3	32.01	7.78	39.79
Iron and Steel	194.5	43.4 (75)	47.3	43.4	33.05	6.89	39.94
Iron and Steel	234.9	111.1 (145)	67.3	111.1	32.87	7.34	40.21
Iron and Steel	154.0	178.3 (238)	63.8	**154.0**	33.27	7.01	40.27
Cement	606.2	176.4 (256)	69.3	176.4	32.00	8.34	40.34
Cement	374.0	320.9 (410)	71.6	320.9	32.44	7.97	40.41
Iron and Steel	48.5	50.4 (82)	43.3	**48.5**	34.37	6.04	40.41
Iron and Steel	137.0	44.9 (77)	49.3	44.9	33.38	7.06	40.43
Iron and Steel	79.8	50.5 (88)	56.2	50.5	33.89	7.06	40.95
Cement	328.0	286 (394)	73.2	286.0	32.56	8.39	40.95
Cement	120.8	41.1 (73)	53.2	41.1	33.50	7.53	41.03
Iron and Steel	70.3	54.3 (95)	57.7	54.3	34.01	7.05	41.07
Cement	57.5	165 (195)	70.5	**57.5**	34.21	6.90	41.11
Iron and Steel	56.6	52.4 (94)	59.4	52.4	34.22	7.20	41.43
Iron and Steel	33.7	44.6 (76)	39.6	**33.7**	34.73	6.76	41.49
Iron and Steel	59.5	41.4 (73)	54.0	41.4	34.17	7.84	42.01

[a] CO_2 available assuming 90% capture.
[b] Sum of CO_2 demand for all sinks identified within the 100-mile distance matrix.
[c] Number of sink opportunities within a 100-mile radius of source.
[d] Taken as the lesser of Column 2 (90% source output) and Column 3 (Regional Demand). Bold indicates full source offset potential.

CO$_2$ Sinks
- Plastics/Polymers Manufacturing
- Fire Proofing
- Refrigeration
- Industrial Gas Manufacturing
- Beverage Carbonation
- Enhanced Oil Recovery
- Soda Bicarbonate Manufacturing
- Urea Manufacturing
- Gum and Wood Chemicals

Sink Demand (kt CO$_2$ per year)
- < 150
- 150.01 – 600
- 600.01 – 1200
- >1200

Source Output (kt CO$_2$)
- 15,000
- 5,000
- 0.0

Industrial Source

Aluminum	Lime
Ammonia	Magnesium
Carbonate Use	Petrochemicals
Cement	Pulp and Paper
Ethanol	Refining
Ferroalloy	Silicon Carbide
Glass	Soda Ash
Iron and Steel	Titanium Dioxide
Lead	Zinc

Source Output (kt CO$_2$ per year)
- < 500
- 150.01 – 1250
- 1250.01 – 3000
- 3000.01 – 6250
- > 6250

Sink Demand (kt CO$_2$)
- 500
- 250
- 0.0

Industrial Source CO$_2$ Output (kt per year)
- < 500
- 150.01 – 1250
- 1250.01 – 3000
- 3000.01 – 6250
- > 6250

CO$_2$ Offset Potential

$$1 - \frac{(\text{Source CO}_2/a - \Sigma_{(100\,mi.\,r)}\,\text{Sink CO}_2/a)}{(\text{Source CO}_2/a)}$$

- 0.0
- 1.0+

Legend:
- Industrial source (IIP)
- First-order sink
- Second-order sink