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Environmental Sciences Division

CONSIDERATIONS FOR THE DESIGN OF A GAS TRANSPORT SYSTEM FOR CO-LOCATION OF MICROALGAE CULTIVATION WITH CO_2 SOURCES

Susan M. Schoenung[1]
Rebecca A. Efroymson[2]
Matthew H. Langholtz[2]

[1]Longitude 122 West, Inc.
[2]Oak Ridge National Laboratory

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DOE	U.S. Department of Energy
EGU	electricity-generating unit
NG	natural gas
O&M	operations and maintenance
USEPA	U.S. Environmental Protection Agency

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ABSTRACT

Co-locating microalgae cultivation facilities with sources of waste CO_2 may present opportunities for cost savings that could benefit the algal biomass industry and industries or utilities that have incentives to manage carbon emissions. However, the cost savings have not been quantified. We compare the cost of utilizing CO_2 from flue gas transported to 405-ha, base-case, open-pond microalgae facilities to the commercial purchase price of CO_2. Sources of CO_2 include coal- and natural gas-fired power plants and ethanol, ammonia, and cement production plants in the United States. The transport of CO_2-containing gases to the microalgae cultivation facility requires infrastructure and electricity. This engineering analysis explores the parameters that affect the infrastructure and transport distance over which emitted flue gases can be cost-effectively transported to microalgae cultivation facilities, compared to the cost of commercially purchased CO_2 (i.e., the break-even distance). Parameters that are varied include size of facility pond area, productivity, and daily duration of waste CO_2 emissions that are transported to algae. Under our assumptions and under all cases in this study, cost savings can be achieved by co-locating microalgae facilities near waste CO_2 sources. The break-even distance, which is estimated here to range from under 2 to 80 km, depends primarily on the concentration of CO_2 in flue gas, algae productivity, facility size, and pipeline system design considerations. Greater break-even distances are simulated if electricity cost is minimized, rather than if capital cost is minimized.

1. INTRODUCTION

The U.S. Department of Energy's (DOE) *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* [1] presents microalgae as a viable source of biomass for biofuel in the United States, but at substantially higher prices than terrestrial biomass, due in part to different nutrient, infrastructure (e.g., pond liners), and energy requirements (e.g., paddlewheels), compared to inputs for agriculture. Strategies are needed to reduce operational costs of microalgae biomass cultivation used for biofuels and bioproducts. Carbon is a required nutrient for microalgae growth, and the purchase of compressed CO_2 to allow high-productivity microalgae cultivation can contribute up to 40% of the raw material cost [2] or cost $101/tonne algae biomass (ash-free dry weight) [3].

Co-location strategies that pair a cultivation system, such as an engineered open pond, with an existing industrial facility allow the emitter to potentially reduce waste management costs, while providing reduced-cost gas delivery to the microalgae producer, as well as the potential for waste heat utilization in cooler climates. Potential advantages of co-locating microalgae biomass cultivation facilities with point sources of waste CO_2 have been demonstrated at pilot plants and at commercial scale [4-9, 2 4]. Some variables affecting greenhouse-gas-emissions life-cycle analysis from utilities co-located with algae facilities, such as facility size and CO_2 concentration in waste gas, have been explored [10]. However, the cost of transporting bulk flue gas in quantities sufficient to support high-productivity, commercial-scale algae development, as well as cost-effective transport distances, has not been estimated and published in the past two decades (see the 4.8-km assumption for flue gas in [11]) for any algae cultivation system. Venteris et al. [12] and Quinn and Davis [13] note that costs associated with delivering flue gas and cost-effective transport distances are needed for techno-economic analyses and resource assessments for microalgae biofuel production. Beal et al. [14] assert that the "proximity and quality of the carbon source is one of the most important parameters for algal biofuel production." In techno-economic analyses, the uncertainty regarding the cost-effective transport distance for CO_2-containing gases has been handled by assuming a baseline, lower bound and upper bound value, as in the distances of 4.8 km, 1.6 km, and 16 km, respectively, used in Quinn et al. [15] to represent distances for transport of co-located waste CO_2 emitted at a variety of concentrations. Lundquist et al. [16] considered algae co-location distances of 1.6, 3.2, and 4.8 km from power plants.

The U.S. emits more than 3.0 billion tonnes of CO_2 per year from point sources that could potentially be used in algal biomass cultivation [17], over 2 billion tonnes of which is from the electric power sector [18]. The vast majority of this waste resource is not used, though CO_2-enhanced oil recovery utilizes more than 50 million tonnes of CO_2 per year.

The primary objective of this study is to explore the design considerations for sizing and costing a system to transport waste, CO_2-containing gas over some distance to the algae cultivation facility. The overall concept for co-location is shown in Figure 1. Feasible CO_2 transport distance results for power plants and ethanol production plants were used to estimate U.S. national potential microalgae resource availability in the *2016 Billion-Ton Report* [1], and this analysis builds on the engineering cost simulations for that work by adding CO_2 sources, alternative project cases, installation costs, and additional infrastructure costs.

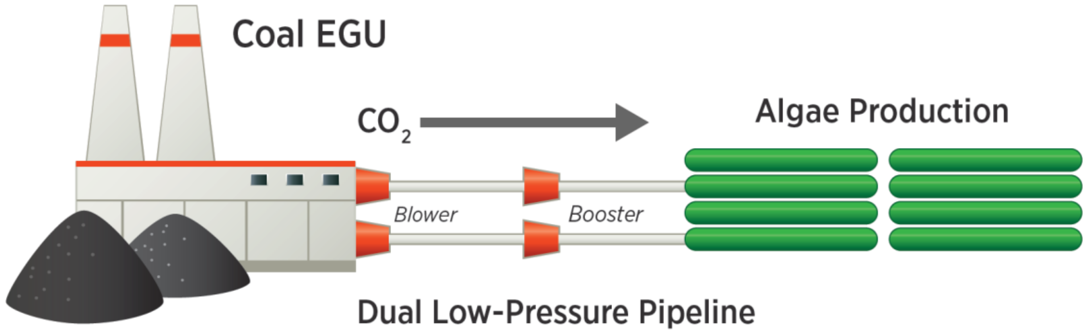

Figure 1. Illustration of co-location strategy to use CO_2 emissions from a power or process plant. In this figure, the source is a coal-fired power plant (EGU=electricity-generating unit). The number and size of blowers and pipelines vary with gas volume.

2. RESOURCES AND ALTERNATIVE CASES

The co-location strategies focus on major classes of emitters of CO_2 with different concentrations of CO_2 in the waste gas stream, i.e., coal (14%) and natural gas-fired power plants (5%) [19], ethanol production plants (99%) [20], ammonia production plants (97%) [21] and cement manufacturing plants (24%) [22]. The emissions from the cement kiln (47% CO_2) were analyzed, as well as the combined emissions from the cement plant, which mixes flue gas from the kiln and heat plant together. These sources represent a large range of volumetric concentrations of CO_2 in emitted gas, as indicated in Table 1, leading to a large range of estimated pipe sizes and resulting transport costs.

Table 1. Waste Resources

Waste Resource	CO_2 Concentration, %
Ethanol plant	99
Ammonia plant	97
Cement kiln (part of cement plant)	47
Cement plant	24
Coal-fired power plant	14
Natural gas-fired power plant	5

The following base case parameters were established: a microalgae cultivation facility with 405 ha (1000 acres) of open ponds operated at 30-cm depth. The base case assumes a moderate annual average biomass productivity of 13.2 g $m^{-2}d^{-1}$, which corresponds to national mean annual average productivities assumed in previous studies to be achievable under currently available technologies using available strains [23, 1]. A CO_2 uptake value of 82% is used, as assumed in other modeling studies [12, 1]. In addition to the base case, three alternative cases aimed primarily at understanding scaling issues are compared with the base case. With six CO_2 resources and the base case with three cases with altered cultivation parameters, a total of 24 cases of CO_2 transport to algae facilities are evaluated in this study.

The base case, a single 405-ha (1000-acre) microalgae cultivation facility, calls for 107 tonnes of CO_2 per day on average, or over 36,400 tonnes per year. This is a fraction of the emissions from a typical ethanol production plant, which releases over 227,000 tonnes of CO_2 per year, or a coal-fired power plant, which releases 1.36 to 18 million tonnes of CO_2 per year [24]. Thus, scaling to larger cultivation facilities would be possible with these resources.

Three alternative cases are modeled (Table 2). A smaller, 202-ha (500-acre) facility is considered because contiguous parcels of 405 ha may not be located near some of the CO_2 sources. A future higher annual average productivity of 25 g m^{-2}d^{-1} is an additional case, consistent with a targeted productivity rate used in a recent U.S. microalgae pond design study and in the *2016 Billion Ton Report* [3, 1]. The base case and these two alternative cases assume CO_2 is captured for an average of 12 hr/day while the ponds are sunlit and productive. Costs for an alternative case that assumes an innovative technology allowing 24-hour capture and storage of CO_2 are also estimated. In that case the microalgae use the CO_2 emitted during both day and night for growth in daylight. Based on a concept used by Global Algae Innovations [25], the CO_2 is removed from the waste gas using a packed-bed wet scrubber (specially designed packing medium wetted with liquid through which the gas flows) and storage pool for the dissolved CO_2, Water with dissolved CO_2 is fed directly to the algae pond when needed. Line-packing, whereby CO_2 is stored within the pipeline itself by closing valves and increasing pressure at select locations [26], is not considered in this study. The four alternative cultivation cases are summarized in Table 2.

Table 2. Alternative case study parameters

Case	Productivity g m^{-2}d^{-1}	Algae facility size, hectares (acres)	Average hours of waste gas capture/day	Required CO_2, tonnes per year*
Base case	13.2	405 (1000)	12	43,343
Smaller farm	13.2	202 (500)	12	21,739
Higher productivity	25	405 (1000)	12	82,345
24-hour CO_2 capture	13.2	405 (1000)	24	43,343

* Based on uptake rate of 82%, as assumed in [12] and [1]

3. ENGINEERING APPROACH AND TRADE-OFF ANALYSIS

The engineering approach involves sizing and costing the gas transport system, which consists of pipelines and gas blowers (i.e., devices for moving volumes of gas with a moderate increase of pressure). Figure 1 shows a representative depiction of the system design. Flue gas is captured at the plant and transported as relatively low-pressure gas (144.8 kPa) through a pipeline to the microalgae cultivation facility. Depending on the distance and flowrate, either a single pipe or a series of pipes with one or more blower stations is sufficient to move the gas to the cultivation site. The engineering analysis is used to determine the size and costs of the pipe, blowers and energy requirements for each of the 24 cases. The governing equation for gas flow is as follows (SPE 2015)[27])

$$P_1^2 - P_2^2 = 0.205\ [(SQ_g^2 ZTfL) / d^5] \tag{1}$$

Where

P_1 = upstream pressure, kPa,
P_2 = downstream pressure, kPa,
S = specific gravity of gas, dimensionless
Q_g = gas flow rate, Sm^3/hr,
Z = compressibility factor for gas, dimensionless,
T = flowing temperature, °K
f = Moody friction factor, dimensionless,
d = pipe internal diameter, cm,
L = length, m

The Moody friction factor is a function of Reynolds number.

For the case of a series of blowers, the upstream pressure is 144.8 kPa (21 psia) and the pressure drop between blowers is a maximum of 13.8 kPa (2 psig). Properties for either carbon dioxide or gas mixtures are used. The flow is fully turbulent.

The required gas flowrate, Q, is determined by the assumed productivity of the microalgae, pond area, and the concentration of CO_2 in the flue gas, such that adequate CO_2 is available for the microalgae during the growing period in each day. As seen in Equation 1, the pipeline diameter, *d*, is an important variable in determining the pressure drop along the pipe, and this dominates the decision for selecting design parameters to reduce the overall cost of the transport system for a given distance from the emission source. There is a trade-off between the cost of pipe, which increases nonlinearly with diameter, and the cost of blowers, the number of which depends on the pressure drop between stations. The costing analysis computes the capital cost of pipeline and blowers plus the operating cost for electricity. For the 24-hour CO_2 capture case, a scrubber and pool are added in sequence following the pipeline and immediately before the algae pond. The gas distribution system within the pond is not costed in this study and would vary for different cases, such as for facilities of different sizes or locations with different productivities. The capital cost is computed as in Equation 2.

$$C_{cap} = C_p \text{ x } L + C_b + C_{sp} \tag{2}$$

Where:

C_{cap} = Capital cost, \$
C_p = Cost of pipe, \$/m (See Figure 2)
L = Pipe length, km
C_b = Cost of blower(s), \$
C_{sp} = Cost of scrubber and pool, \$ (optional)

Table 3 indicates the cost assumptions used in this study. The pipe cost (per linear dimension) is estimated from an engineering handbook [28] and updated to 2014 dollars. Because PVC is less expensive than steel, as shown in Figure 2, the former material is used in the pipeline design wherever possible. Furthermore, smaller parallel pipes are selected over fewer larger steel pipes for the same reason.

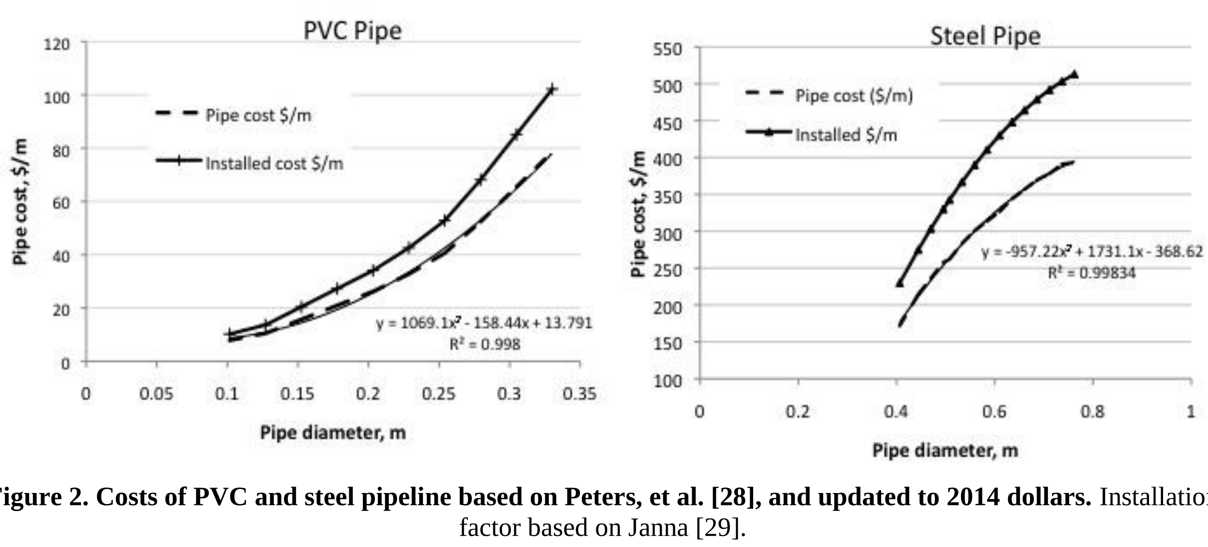

Figure 2. Costs of PVC and steel pipeline based on Peters, et al. [28], and updated to 2014 dollars. Installation factor based on Janna [29].

The cost of the blower system is estimated from discussions with industry, and the electric power requirement for the blower is estimated from industrial literature [30]. Similar to the approach used in previous techno-economic analyses of algae production [31-33], an installation factor is applied to determine the total capital investment. To estimate the installation factor for the pipeline in this study, the material cost is compared to the installed cost of steel pipeline in Janna [29]. Based on this comparison, the installation factor is set to 1.3 and applied to the capital costs in this study. Valve and fitting estimates are derived from Peters et al. [28]. Earth works for the pipeline are not included in the cost, nor are sensors or potential needs for SO_x control or NO_x control for power plant flue gas [9]. The capital and operating cost assumptions for the 24-hr capture and storage case are derived from U.S. Environmental Protection Agency (USEPA) literature [34] and verified in discussion with industry [25]. The fixed operations and maintenance (O&M) cost of 4% of capital per year is based on engineering experience for power plants [35]. In addition, the approximate cost of a small quantity of buffer storage is included to hold 10 minutes of the daily flow of gas. The purpose of the buffer storage is to respond to dynamics in the flow as the gas reaches the pond, either from the source or from the gas entering into the pond distribution system.

To minimize capital cost, a trade-off is made between the cost of selected blower equipment and the cost of pipeline. An example of this trade-off is shown in Figure 3, where pipe cost dominates for larger pipes, but blower cost increases with smaller pipes. The latter is due to greater pressure drop along the smaller pipes, thus requiring more blower stations. Figure 3 also shows the blower-related electricity cost, which scales with the number of blowers.

Table 3. Cost Assumptions for CO_2 Transport System

Item	Cost	Notes
	Capital Cost	
PVC Pipe	See Figure 2.	Used for pipe diameters up to 38 cm
Steel Pipe	See Figure 2.	Used for pipe diameters from 38 to 76 cm
Blower	Scales from \$25,000 for 5340 Nm^3/hr	Atlas Copco model ZM88 (890- 8010 Nm^3/hr); max P=144.8 kPa [30]
Valves / fittings	Ranges from \$1310 to \$13,100 per each depending on pipe size [28]	One valve system for each blower
Scrubber and pool	\$56.2 \$/Nm^3/hr	Based on discussion with industry, and comparable to USEPA values [34]
	O&M Costs	
Fixed O&M (annual)	4% of total capital cost	Consistent with power plant engineering economics [35]
Electricity	8 cents/kWh	Consistent with other DOE studies [35]
Scrubber consumables (annual)	11.2 \$/Nm^3/hr	Based on [34] and consistent with industry experience [25]
	Installation Costs	
Installation factor	1.3	Factor by which capital costs are multiplied [29]

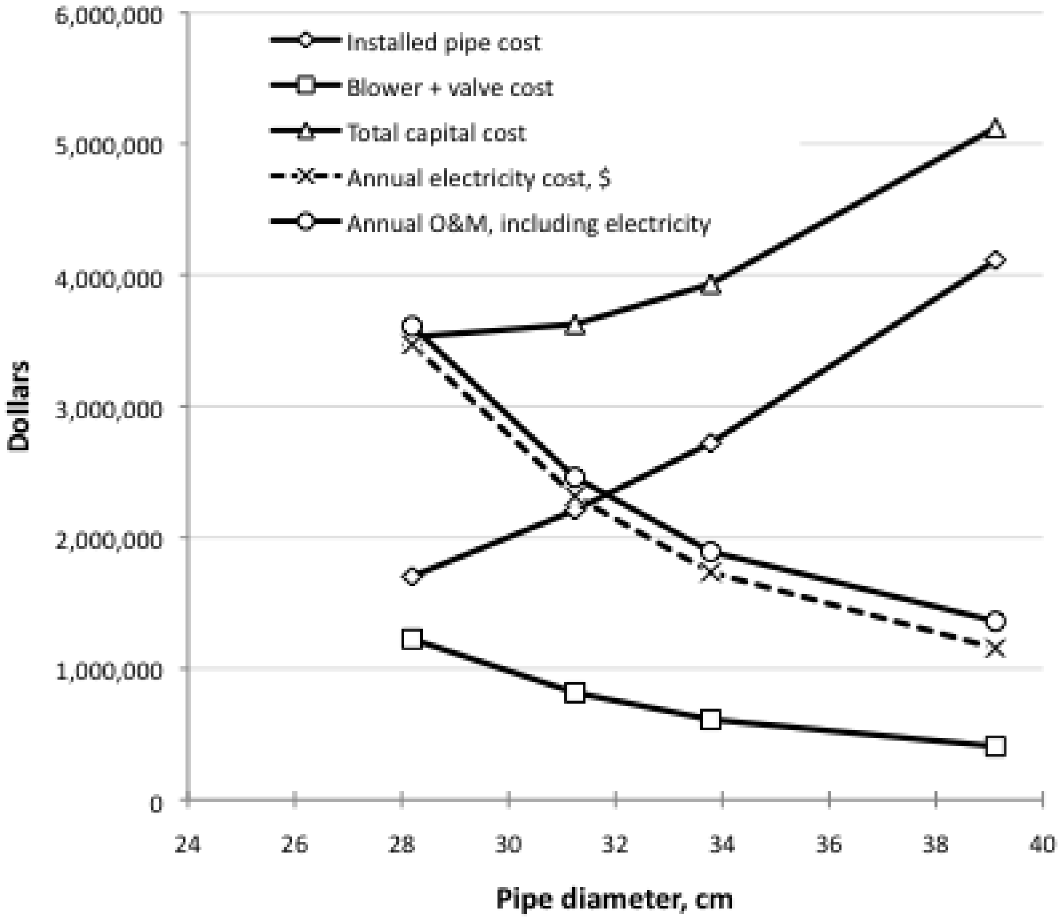

Figure 3. Example of cost trade-off of capital components and electricity cost as functions of pipe diameter for the base-case algae cultivation assumptions with the CO_2 source (coal power plant) co-located 8 km from the ponds. This configuration uses 3 pipes in parallel. O&M is operation and maintenance.

The benefit of the 24-hr CO_2 capture approach with respect to gas transport is a smaller, less expensive pipeline and blower system, because the required amount of gas is carried over a longer period of time. This savings is offset, however, by the additional capital and operating costs of the packed-bed wet scrubber and storage pool for dissolved CO_2, costs which are considered for the 24-hr CO_2-capture cases.

The life-cycle cost of the gas transport system is calculated so that a further trade-off can be made between capital cost and operating (e.g., electricity) cost. The economic parameters for the life-cycle cost are listed in Table 4. The annual cost is summed as in Equation 3. An example of the annualized value of capital cost plus electricity and O&M is shown in Figure 4. Note that this study did not estimate greenhouse gas emissions through a life-cycle analysis; however, selecting a system that reduces the electricity usage will also reduce emissions.

$$\text{Annual cost} = \text{Annualized cost of capital equipment and installation} + \text{annual cost of electricity} + \text{annual O\&M} \quad (3)$$

Table 4. Parameters used in economic analysis

Parameter	Value
Purchase price of CO_2	$44/tonne
Price of electricity	$0.08/kWh
Life time for annual calculation	30 years
Interest rate	10%
Average daily duration of CO_2 capture	12 hr/day (base case)

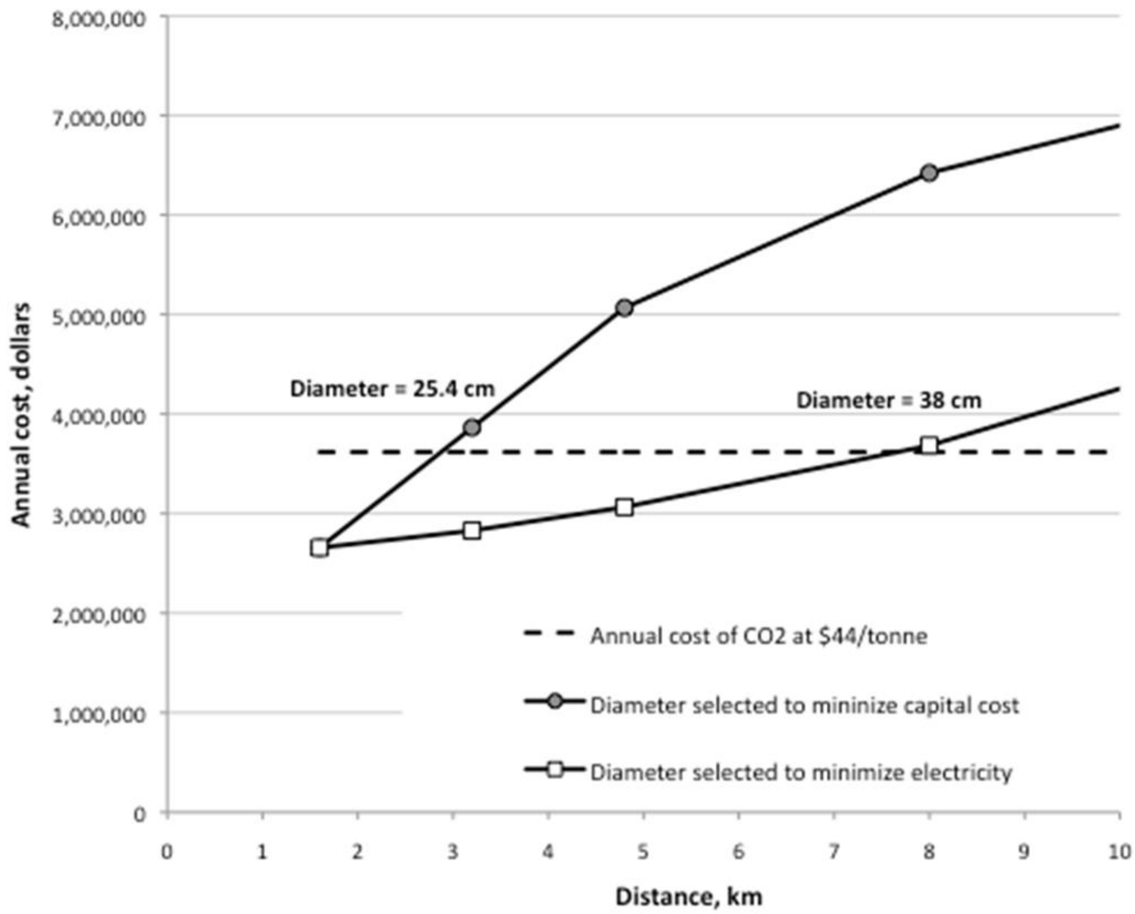

Figure 4. Example of trade-off in annual cost between selecting a pipe diameter to minimize capital cost or to minimize electricity cost for a case in which a coal power plant was the CO_2 source for the 405-ha set of open algae ponds, and high algae productivity was assumed. For this case, 6 parallel pipes were selected.

The estimated break-even transport distance is determined by comparing the annualized costs of capital plus operations to the cost of purchased CO_2. For this study, the commercial purchase price of CO_2 was assumed to be $44/tonne, a cost assumed in other recent studies [35, 36]. Other assumptions include a 30-year life of the transport system, 10% interest rate on capital, and 8 cents/kWh for electricity [23]. The method for determining the break-even gas transport distance for the coal-fired power plant source is illustrated in Figure 5, where the annualized cost crosses the $44/tonne line.

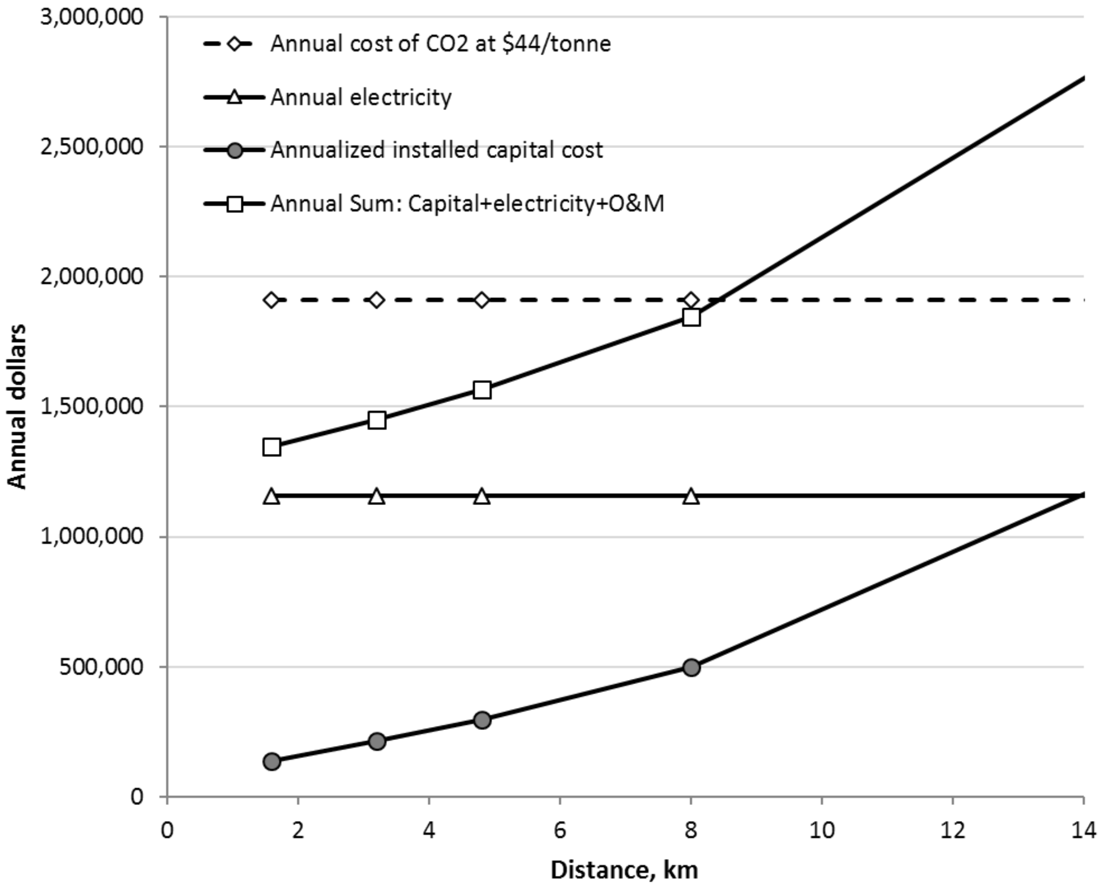

Figure 5. Method for determining break-even transport distance of waste gas from the source to the algae production facility. The break-even distance occurs where the curve of annual cost of capital plus O&M expenses cross the curve depicting cost of purchased CO_2 (at $44/tonne). This example is for the case of flue gas from a coal-fired power plant, including three sets of pipelines with one blower each, to a 405-ha set of open ponds under base case conditions.

4. RESULTS AND DISCUSSION

CO_2 is a greenhouse gas that is emitted by various utilities and industries. Existing and incipient commercial enterprises, such as the algal biofuel industry, view waste CO_2 as a resource. This study investigated the costs of using waste CO_2 transported to algae facilities as a resource for growing biomass, compared to the cost of purchasing the nutrient.

Cost-effective transport distances for CO_2-containing waste gases from the six utility and industrial sources under base-case cultivation conditions and assumptions are shown in Figure 6. Beyond these distances, purchased CO_2 would be less expensive than the use of waste CO_2. The gray bars in the chart indicate the distance at which capital cost for the CO_2 transport system is minimized by using smaller pipe at the expense of greater electricity cost. The black bars indicate the distance where electricity costs to transport the required CO_2 are minimized by spending more capital on larger pipes. Also shown at the top of the bars on the chart is the concentration of CO_2 in the waste gas from the source. For the high CO_2 concentration cases (ethanol and ammonia), fairly long cost-effective distances of more than 40 km are possible, under our assumptions. Clearly, the lower the concentration of CO_2, the greater is the gas volume required to produce the algae and the closer the source must be to reduce transport costs. For a 405-ha set of ponds at an 8-km distance from a coal-fired power plant, savings of $65,000/year over the costs of CO_2 purchase are realized under the assumptions described here. For ponds fed by CO_2-

containing gas from an ethanol production plant at the same distance, the savings is over $1.5 million/year.

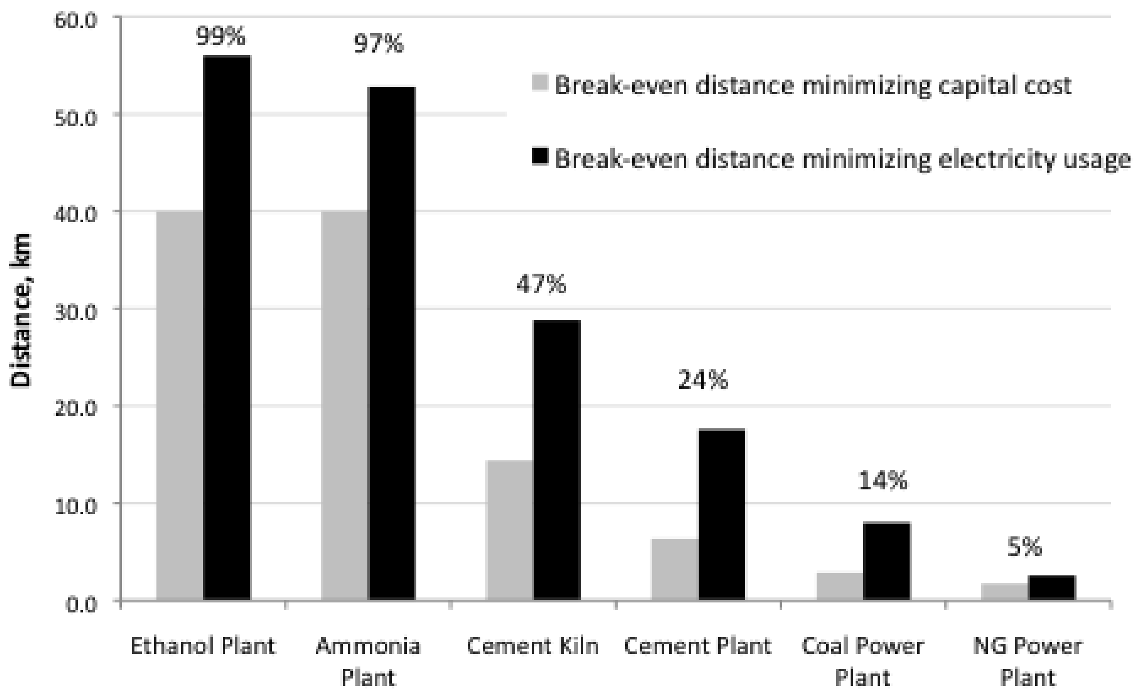

Figure 6. Cost-effective CO_2 transport distances (relative to $44/tonne CO_2) for the resources considered under base-case conditions. Gray bars depict the break-even distances for the configuration that minimizes capital cost of the transport system to the algae facility at the expense of more electricity, while black bars correspond to configurations that minimize the additional electricity cost for transporting CO_2 at the expense of greater capital cost. The percentages above each bar depict the concentration of CO_2 in the waste gas. NG is natural gas.

The results for a selection of the alternative cases are shown in Figure 7. These cases compare cost-effective CO_2 transport distances for natural gas and coal power plants and ethanol and cement production plants under the base case with results for the alternative cases (a smaller total pond area in each facility, higher productivity, and 24-hour capture of $CO_{2)}$ to highlight the effects of these changes to the base-case parameters. Break-even distance results for CO_2 gas transport from the ammonia production plant cases are similar to those from the ethanol production source. Results for the cement kiln cases fall between those for the ethanol production plant and the cement plant case, as in Figure 6.

Three general conclusions apply that are not necessarily intuitive. 1) Slightly longer break-even transport distances are associated with the smaller-area (202-ha) facility because less gas is needed to supply the microalgae. A smaller pipe system can be used and, since costs do not scale linearly with pipe diameter, a relatively less expensive transport system results. 2) Microalgae cultivation at higher productivity than the base case (25 $g\,m^{-2}d^{-1}$) presents a challenge for CO_2 transport because more gas and a higher-capacity, more expensive transport system are needed to provide sufficient CO_2. The increased expense is associated mostly with the larger, more expensive pipes. Somewhat shorter break-even CO_2 transport distances from the source to the algae cultivation system, therefore, result from this increase in productivity. 3) For the flue gases containing higher concentrations of CO_2 (ethanol and ammonia), the 24-hr capture leads to even longer break-even distances (or less expensive transport systems), as expected. However, for the more dilute CO_2 resources (power plant flue gases), 24-hr capture is not necessarily less expensive than 12-hr capture in the base case. The cost of operating the scrubber scales with flowrate [34], and the high cost of scrubbing the more voluminous, dilute CO_2-containing gas can outweigh the savings on the capital cost of the pipeline. A comparison of the results for 12-hour and 24-hour operation with the coal power plant as a source at an 8-km distance from the 405-ha ponds is shown as an example in Figure 8. 4) For natural gas power plants supplying CO_2 to high-productivity (25 g m^{-2}d^{-1}) algal ponds, only a very short pipeline distance (1.6 km) gives a cost-effective solution for a 405-ha algae pond. Thus, as improved technologies facilitate higher algal productivities, especially in warm, sunny locations, sources of dilute CO_2 will become less desirable for co-location with commercial-scale microalgae production facilities. The steadily increasing annual CO_2 emissions from natural gas facilities in the U.S., transitioning from coal [12, 37] are not as useful for high-productivity algae production as more concentrated sources of CO_2.

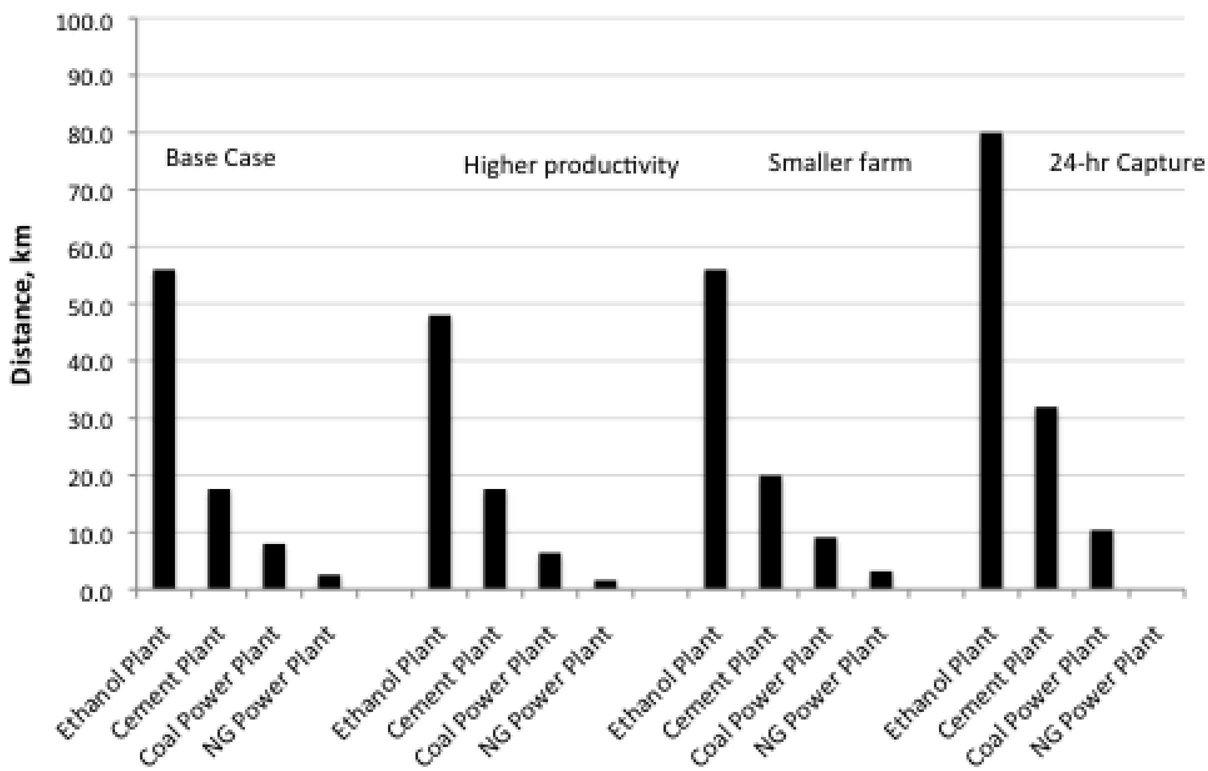

Figure 7. Cost-effective CO_2 transport distances (relative to \$44/tonne CO_2) for the resources considered under base-case, higher-productivity, smaller-facility, and 24-hr-CO_2-capture conditions. These results correspond to a configuration that minimizes the electricity cost at the cost of greater capital expense. NG is natural gas.

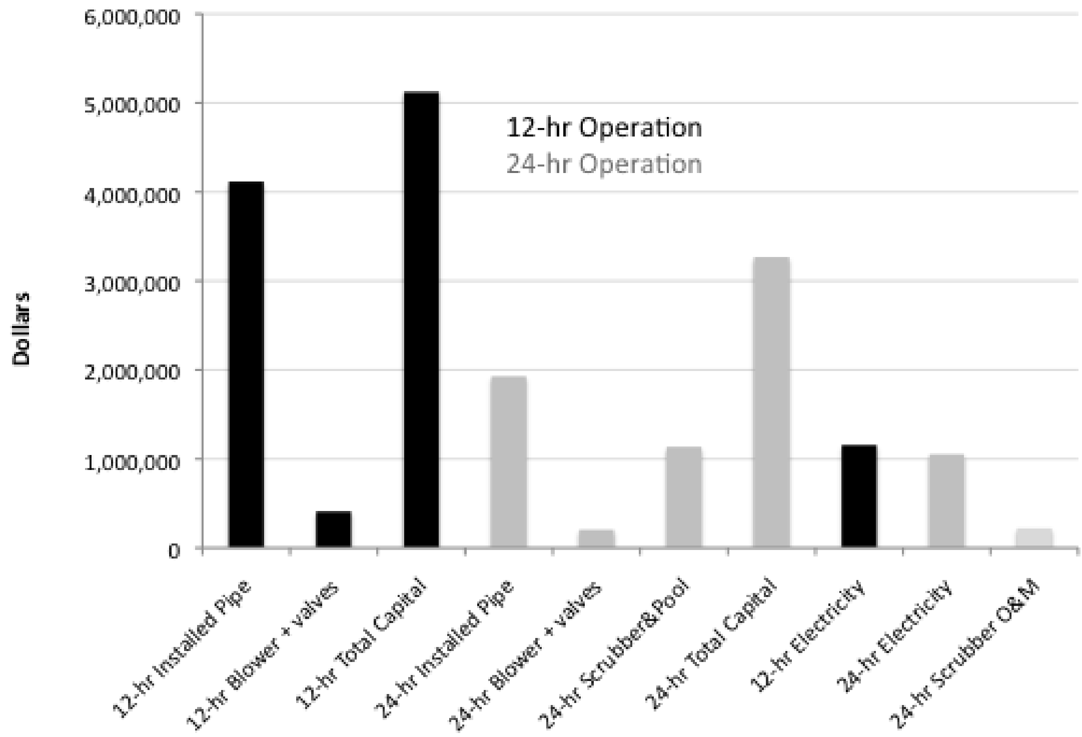

Figure 8. Comparison of costs for 12-hour base-case CO_2 transport with the 24-hr CO_2-capture case for a coal power plant at an 8-km distance. The difference between sum of the first two bars and the third is the approximate cost for a storage buffer for the gas as it reaches the ponds (see text).

The break-even CO_2 transport distances (i.e., at which estimated annual costs of transport of CO_2 equal annual costs of purchased CO_2) range widely, from 1.6 km to 80 km, depending on the assumptions for the case (Table 5). Distances are based on annual cost comparison results for all 24 cases and configurations that minimize either capital or electricity costs. While the lower bound distance (1.6 km) matches that assumed in Quinn et al. [15], the upper bound of 80 km for ethanol and ammonia plants with 24-hour CO_2 storage is higher. Table 5 also shows the number of parallel pipes and the pipe diameter for each case at the break-even CO_2 transport distance.

Table 5. Cost-effective CO_2 transport distances for the base case and cases with alternative algae cultivation parameters.

	Total Gas flow, Nm^3/hr	Number of parallel pipes	Break-even distance minimizing capital cost, km	Related Pipe diameter, cm	Break-even distance minimizing electricity usage, km	Related Pipe diameter, cm
Base Case						
Ethanol Plant	5,106	1	40.0	23.6	56.0	43.2
Ammonia Plant	5,263	1	40.0	21.6	52.8	43.2
Cement Kiln	10,863	1	14.4	29.0	28.8	50.8
Cement Plant	21,273	2	6.4	27.9	17.6	42.7
Coal Power Plant	36,473	3	3.2	28.2	9.6	39.1
NG Power Plant	102,127	8	1.8	28.7	2.6	32.8
Higher Productivity						
Ethanol Plant	9,672	1	32.0	27.7	48.0	53.1
Ammonia Plant	9,968	1	32.0	27.7	48.0	53.1
Cement Kiln	20,573	2	12.8	28.4	27.2	48.5
Cement Plant	40,290	4	6.4	29.0	17.6	41.1
Coal Power Plant	69,076	6	2.9	25.4	8.0	38.1
NG Power Plant	193,421	10	1.6	34.0	1.6	34.0
Smaller Farm						
Ethanol Plant	2,553	1	48.0	16.3	56.0	32.0
Ammonia Plant	2,632	1	48.0	16.3	56.0	32.0
Cement Kiln	5,431	1	19.2	21.1	30.4	40.1
Cement Plant	10,638	2	6.4	20.3	20.0	32.3
Coal Power Plant	18,236	2	4.8	27.2	9.1	34.5
NG Power Plant	51,063	8	2.1	21.8	3.2	24.9
	Total Gas flow, Nm^3/hr	**Number of parallel pipes**	**Break-even distance minimizing capital cost, km**	**Related Pipe diameter, cm**	**Break-even distance minimizing electricity usage, km**	**Related Pipe diameter, cm**
24-hour Capture						
Ethanol Plant	2,553	1	52.8	16.3	80.0	40.4
Ammonia Plant	2,632	1	52.8	16.3	80.0	40.4
Cement Kiln	5,431	1	20.8	22.1	43.2	41.7
Cement Plant	10,638	2	11.2	21.3	32.0	35.6
Coal Power Plant	18,236	2	2.6	20.8	10.4	34.5
NG Power Plant	51,063	8	0.0	18.3	0.0	18.3

Notes: Base Case: Productivity of 13.2 $g\,m^{-2}d^{-1}$, 405 ha, 12hr/day
Higher Productivity: 25 $g\,m^{-2}d^{-1}$
Smaller Farm: 202 ha
24-hour capture: base case parameters

Overall, the results show a break-even CO_2 transport distance (minimizing capital costs) of 40 km for waste gases containing CO_2 at high concentration under the base case assumptions. For more dilute CO_2

emissions from power plants under the same assumptions, the distances are much shorter, i.e., 1.8 to 3.2 km, and they could be shorter still, once the costs of distributing dilute flue gas across the ponds, compared to costs for pure CO_2, are considered. Some producers and pilot plants choose to co-locate facilities adjacent to CO_2 sources to reduce costs [5-7]. Previous research had concluded that only shorter transport distances for CO_2 transport to microalgae facilities would be cost-effective. For example, Benemann and colleagues estimated distances between 2.4 and 4.8 km for transporting CO_2 from power plants, but for larger, 1000-ha microalgae cultivation facilities, where the gas demand is higher [11]. Quinn et al. [15] and Lundquist [16] also used a 4.8-km as their greatest co-location distance from a CO_2 source. Our analysis suggests that transport distances for CO_2-containing gas of greater than 4.8 km can be feasible under specific production assumptions, such as the use of CO_2 of high purity, lower-productivity cultivation systems (13.2 $g\,m^{-2}d^{-1}$), and/or 24-hr CO_2 storage.

Many annual carbon utilization efficiencies in the literature are measured or assumed to be lower than the assumption of 82% here. Recent reports are that sparging CO_2 in traditional raceways results in a utilization efficiency of less than 50% [38]. Some of the lower measured carbon utilization efficiencies in ponds or raceways are 25% [39] and 26% [40]. Wilson et al. [9] achieved a 44% CO_2 utilization efficiency in a photobioreactor. An 83% carbon utilization efficiency was achieved in an open pond system through the use of a bubble column to increase the area of contact for gas exchange [41]. Although the CO_2 utilization efficiency was not employed directly as a sensitivity parameter in this study, the effect of changing the efficiency can be qualitatively considered by examining the variations of other parameters in this study that involve increased CO_2 requirements. For example, a lower utilization efficiency would mean more CO_2 required for all cases, just as higher productivity requires more CO_2 than the base case. Thus, decreasing the CO_2 utilization efficiency from 82% to 44% (as in [9]) might be expected to have the same effect on break-even CO_2 transport distance as the approximate doubling of productivity considered here. However, the effect of chemical components of the flue gas on utilization efficiency would need to be studied, as well as the effect of closed versus open cultivation systems.

Additional costs that could vary from those assumed here are the cost of purchased CO_2 (now and in the coming decades), the costs of materials used for pipelines (e.g., Quinn et al. [15] assumed concrete instead of PVC), the rate of amortized capital costs [42], the installation cost factor, and the local cost of electricity. An additional factor that could increase transport cost is a large variation in production with season; a larger pipe diameter or different system could be needed to accommodate the CO_2 requirements for high productivity days. Costs of earth works were not included. Venteris et al. [12] highlight the importance of the distance to rail lines for determining material transport costs. Additional waste CO_2 sources with different purities would have different costs as well. Maintenance costs may be more related to blowers and compressors than to capital costs, as assumed here. Carbon utilization policy incentives would also affect cost-effective CO_2 transport distances and profitability [43]. Moreover, an additional factor that could increase transport cost is large variation in production with season; a larger pipe diameter or different system could be needed to accommodate the CO_2 requirements for high productivity days.

Given the constraint of cost-effective waste CO_2 transport distance that would be added to the constraint of land or location suitability (topography, water availability, climate), the question of how much algae could be grown at national scale using bulk flue gas transport is still an open one. In the *2016 Billion Ton Report*, annual algae biomass potential was estimated at up to 42 million tonnes from *Chlorella sorokiniana* (a freshwater species) or at up to 78 million tonnes from *Nannochloropsis salina* (a saline water species) under mean national productivities close to that which was assumed here (i.e., current productivity assumptions) [1]. However, that analysis had some overlap between the supply areas of CO_2 sources, did not fully consider short-term water availability, did not consider industrial CO_2 sources, and did not consider some of the cost considerations in this analysis. Middleton et al. [18] identify vast areas in the U.S. where there is no access to waste CO_2 at an "industrially relevant scale (i.e., >25 kt/yr)." Pate et al. [44] argue that CO_2 requirements, including siting considerations near waste CO_2 streams, "appear to be the most significant challenge to algae biofuels scale-up," given the lack of a widely networked CO_2 capture and transport infrastructure. And the purest industrial CO_2 sources (e.g., ethanol plants) are not always located in high-productivity regions; in the *2016 Billion Ton Report* the economic gains from increased productivity in warmer locations outweighed the CO_2 cost savings differential from the higher-purity CO_2 from ethanol plants [1]. More economical methods of carbon capture [45] may be available in the future, and these may obviate the cost-saving assumption here that CO_2-containing gas must be transported by pipeline.

5. CONCLUSIONS

Cost savings can be achieved by co-locating open-pond microalgae production facilities near waste CO_2 sources. The break-even CO_2 transport distance (i.e., distance at which the annualized cost of transporting CO_2 to the facility is equivalent to the cost to purchase CO_2) depends primarily on the concentration of CO_2 in the waste stream and on the amount of microalgae biomass that requires the CO_2, which is determined by algae productivity and facility size. Additionally, trade-offs between capital and operating costs based on pipe and blower sizing affect the overall cost-effectiveness and break-even co-location distances. This study shows that the concentration of in flue gas also is an important determinant of cost and cost-effective transport. Sources of lower concentration CO_2, such as natural gas power plants, may have limited utility for co-location with algae cultivation, as shown here from a CO_2 transport cost perspective, and as shown by Rickman et al. [10] from the perspective of mitigation of CO_2 emissions. This study also shows that potential utilization of nighttime CO_2 storage is an important contributor to cost reduction and that as productivity increases, the scaling up of pipelines may reduce the cost-effective CO_2 transport distances. Further study is needed to integrate these costs with techno-economic analyses, to include costs of distributing CO_2 to the algae farm (which should be lower for smaller farms and purer sources of CO_2) and to consider tradeoffs between the cost savings of scaling up most system components and the nonlinear scaling, higher costs of transporting higher quantities of CO_2-containing gas. As carbon policy evolves, an awareness of this utilization potential by algae will be important for both emitting industries and the for national assessments of algae biomass potential and costs.

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