Research article

Carbon dioxide utilization in a microalga-based biorefinery: Efficiency of carbon removal and economic performance under carbon taxation

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A B S T R A C T

Coal-fired power plants are among the major stationary sources of carbon dioxide and environmental constraints demand technologies for abatement. Although Carbon Capture and Storage is the most mature route, it poses severe economic penalty to power generation. Alternatively, this penalty is potentially reduced by Carbon Capture and Utilization, which converts carbon dioxide to valuable products, monetizing it. This work evaluates a route consisting of carbon dioxide bio-capture by Chlorella pyrenoidosa and use of the resulting biomass as feedstock to a microalgae-based biorefinery; Carbon Capture and Storage route is evaluated as a reference technology. The integrated arrangement comprises: (a) carbon dioxide bio-capture in a photobioreactor, (b) oil extraction from part of the produced biomass, (c) gasification of remaining biomass to obtain bio-syngas, and (d) conversion of bio-syngas to methanol. Calculation of capital and operational expenditures are estimated based on mass and energy balances obtained by process simulation for both routes (Carbon Capture and Storage and the biorefinery). Capital expenditure for the biorefinery is higher by a factor of 6.7, while operational expenditure is lower by a factor of 0.45 and revenues occur only for this route, with a ratio revenue/operational expenditure of 1.6. The photobioreactor is responsible for one fifth of the biorefinery capital expenditure, with footprint of about 1000 ha, posing the most significant barrier for technical and economic feasibility of the proposed biorefinery. The Biorefinery and Carbon Capture and Storage routes show carbon dioxide capture efficiency of 73% and 48%, respectively, with capture cost of 139$/t and 304$/t. Additionally, the biorefinery has superior performance in all evaluated metrics of environmental impacts.

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1. Introduction

The world economy is heavily dependent on fossil fuels, generating massive emissions of carbon dioxide (CO2). Coal-fired power plants are among the major stationary sources of CO2 emissions, where Carbon Capture and Storage (CCS) is the leading technology for CO2 management. Besides recognized technical barriers — e.g., existence of geological sites (Cuellar-Franca and Azapagic, 2015), CO2 monitoring for leakage (Cheah et al., 2016) — the absence of revenues imposes relevant economic penalty to the CO2 source processes due to the significant capital investment required.

Alternatively, utilization of CO2 aims to add value to the captured CO2 (Carbon Capture and Utilization, CCU), through its chemical conversion (Aresta, 2010). The ensemble of technologies for CO2 management is referred to CCUS (i.e., CCS + CCU), spanning from storage to physical, chemical and biochemical utilization (e.g., Enhanced Oil Recovery – EOR, methanol production). It is worth noting that a few chemical syntheses employ CO2 as feedstock at a commercial scale (e.g., urea) (Aresta, 2010), where most alternatives are at the earlier stages of technology readiness level (most of them are still at laboratory or bench scale). Conversion of CO2 to methanol (MeOH) outstands as a promising alternative, accordingly to technical and economic studies evaluating capital and operational expenditures, and environmental performance. Kourkoumpas et al. (2016) investigated the methanol production based on CO2 capture from lignite power plants, estimating MeOH production cost of 421€/t in case of a power plant owner investment. Pérez-Fortes et al. (2016) investigated the direct CO2
hydrogenation, estimating CO2 avoidance of 2t per ton of MeOH produced. Gong et al. (2016) analyzed a superior use of the usually emitted coke oven gas, claiming higher techno-economic performance when compared to other carbon to methanol routes.

In fact, EOR and CCS are presently the only CO2 management chains that include steps ready to be put into operation at high scales: some separation technologies for CO2 post-combustion capture, CO2 compression and CO2 transportation via pipelines (Araújo et al., 2014). Except for EOR, lack of large commercial scale application is mainly due to technological gaps. Technology changes in energy and transportation systems play a central role in response to climate changes, and most of these routes face technological challenges and economic barriers, requiring support to widespread use (Kypreos and Turton, 2011).

Based on a review of life cycle analyses, Cuéllar-Franca and Azapagic (2015) observed that the environmental benefit of CO2 removal with CCS is accompanied by the increase of other environmental impacts (e.g., acidification and human toxicity), and recommend consideration of a wider range of impacts from CCS and CCU, rather than focusing exclusively on the GWP (Global Warming Potential).

Economic aspects are rarely present in the literature as comparison ground between CCS and CCU, and the relevance of the missing approach is magnified within the scenario of carbon taxation. There is a growing convergence of policy-makers and economists that stabilizing a carbon price is the most effective way to reduce carbon footprint (Kypreos and Turton, 2011). Despite the purpose of increasing the marginal cost of greenhouse gas emissions (Pereira et al., 2016), most studies on carbon taxation conclude for recessive impact on households due to the increase in the prices of energy and energy-intensive goods (Dissou and Siddiqui, 2004).

However, from an engineering standpoint, carbon taxes have the potential of catalyzing the progress to technological maturity, when faced as a production cost to be avoided (or reduced) by abatement and destination route. Üçtug et al. (2014) evaluates installing a CCUS unit as a non-linear optimization problem where the objective is to maximize the net returns from pursuing an optimal mix of CCUS (with MeOH synthesis as example of utilization) and carbon trading, concluding for the dominance of carbon price and discount rate on the results. Carbon taxation was not considered by Üçtug et al. (2014) despite a conditioning scenario for investigating the potential of CCUS technologies being expansion of CO2 taxes worldwide (Eberhard, 2014) (with Sweden having presently the highest tax - US$150/t emitted CO2).

In this context, carbon taxes parallel environmental taxes (Chiu et al., 2015) and can be approached as an operational cost (OPEX). Hence, reducing emissions (e.g., via CO2 management technologies) decreases OPEX due to the incurred reduction of carbon taxes. This is especially relevant with growth in proven natural gas reserves accompanied by the increase in fossil fuels (Zhang et al., 2017), which leads to coexistence of fossil based energy generation and carbon taxes, constituting a relevant driver for CCUS technologies.

In its early stage of technological readiness, microalgae have received intense research, due mainly to its high growth rates — microalgae have the capacity to fix carbon dioxide with efficiency 10 times higher than terrestrial plants — and superior lipid content (Skjanes et al., 2007). For instance, Chlorella pyrenoidosa has total lipid content in dry biomass of up to 51% (Liu et al., 2011). Goli et al. (2016) reviewed the literature for biological CO2 fixation, with emphasis on microalgae, and recognize superiority of photobioreactors (PBR) facing raceways, although improvements in scale-up criteria are needed. Comparatively to raceways, PBR require higher capital expenditure, but can achieve much higher biomass and lipid productivities (Moheimani, 2016). If successfully developed, biofixation of CO2 by microalgae and utilization of the grown biomass in biorefineries may generate revenues that ultimately reduce the cost of mitigating CO2 emissions from fossil fired power plants.

In this direction, the use of thermochemical processes (e.g., gasification) in biorefinery designs are attractive due to the flexibility to process a variety of biomass feedstock (Garcia et al., 2016), and yielding products with a wide range of large scale applications, e.g., synthesis gas, which is a common raw material to several mature technologies (e.g., MeOH and ammonia) replacing their original fossil source, as syngas is conventionally derived from natural gas reforming. It is noteworthy that the scale of emissions associated to a fossil fired power plant requires chemical commodities (e.g., ammonia) and energy products (e.g. MeOH) for leveling large scale production and CO2 supply. Production of high added value functional biomolecules, although important for revenues, does not impact CO2 inventory due to their limited demand, and an excess of supply would drastically reduce its sale price. In fact, the portfolio of energy products and the processing scale are the most important variables that must be considered to improve the profitability of biorefineries (Garcia et al., 2016). Hence, for a biorefinery focusing at CO2 utilization, a single or few products, with long-term forecast of large demand, are recommended. High-added value biomolecules should be produced at small scale to increase revenue.

Cheah et al. (2016) reviewed current advances in biological CO2 capture and valorization, and concluded that the economic aspects must be considered to make the biofuel-driven biomass refinery more sustainable. Although the view of microalgae-based technology for CCU is not new, the literature is rare in analyses comparing CAPEX, OPEX and the resulting cost of CO2 avoided with respect to CCS. Equally impacting to the context of the present work is the inclusion of CO2 taxation into a process engineering analysis, a relevant and often neglected aspect. CO2 captured as revenue (carbon credits) is rather the dominant approach in the literature (e.g., Üçtug et al., 2014) while policy-makers are moving to CO2 as cost (taxation).

Although technological bottlenecks still prevent operation of microalgae mediated abatement of CO2 emissions on a commercial scale, this work contributes with a process engineering approach to identify potential barriers, under carbon tax incidence, and quantitatively compares the biorefinery alternative to CCS. Specifically, the study presents economic feasibility and environmental analyses of the performance of capturing CO2 by Chlorella pyrenoidosa and its chemical utilization to produce MeOH through biomass gasification, with co-production of microalgae oil to provide additional revenue (biorefinery as a CCU technology). The results from the microalgae-based biorefinery are compared with the CCS option, under carbon tax incidence. Both analyses are performed considering that the evaluated alternatives are in Brazil, where carbon taxation, although foreseen, is not yet enforced. Moreover, process design decisions are defined to benefit the economic return of the operation (Davis et al., 2014), and to propose further improvements and optimization.

2. Methods

Two alternatives are proposed to abate CO2 emission from a coal-fired power plant: a microalgae-based biorefinery (BRY) route and the CCS route. The BRY route consists of biomass production (microalgae cultivation and harvesting), oil extraction, biomass gasification and conversion to MeOH. The CCS route combines CO2 capture by chemical absorption with amine and CO2 compression for transportation and storage. To evaluate the feasibility of BRY and CCS, the process configuration for each route is defined and
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