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Integration of Geological Sequestration and Microalgae Biofixation Supply Chains for Better Greenhouse Gas Emission Abatement

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This paper studies the integration of geological sequestration and microalgae biofixation options for greenhouse gas (GHG) abatement using a supply chain optimisation approach. We propose a multi-scale multi-period mixed-integer nonlinear programming (MINLP) model, which accounts for CO_2 transportation pipeline network design, algae processing route and product selection, as well as the seasonality in CO_2 source availability and algal biomass productivity. The model considers pipeline transportation of both supercritical CO_2 and feed gas. The economic and environmental performances are simultaneously optimized using the Life Cycle Optimisation framework. Improved branch-and-refine algorithm is employed to effectively solve the resulting non-convex MINLP problems. A case study is presented to demonstrate the optimal design of potential CO_2 capture, utilization, and storage infrastructures in Texas.

1. Introduction

Carbon dioxide (CO_2), the primary anthropogenic greenhouse gas (GHG), is the leading culprit in global warming and climate change. Carbon capture and storage (CCS) through geological sequestration (Cormos et al., 2013) has been regarded as a major means of GHG abatement (Zhou et al., 2014), and it is not until recently that carbon utilization (CU) (Mataa et al., 2014) through microalgae biofixation was proposed as a new alternative for GHG abatement (Benemann and Pedroni, 2008). While most existing works investigated geological sequestration and microalgae biofixation as separate options for GHG abatement, we investigate how these two options can be integrated and synergized to form a complete carbon capture, utilization and storage (CCUS) infrastructure. From the perspective of supply chain optimisation, we employ mathematical programming tools to investigate the underlying economic and environmental potentials (Garcia and You, 2015). As shown in Figure 1, in a CCS supply chain, the CO_2 emitted from power plants is captured and separated on-site and then transported by supercritical CO_2 pipeline to geological sinks for permanent storage; In a CU supply chain, the CO_2 as a component of the power plant flue gas is pre-processed and transported by feed gas pipeline to algal biorefineries to serve as primary nutrition for algae cultivation (Gong and You, 2014a). CO_2 would be converted into lipids in algal biomass through photosynthesis. The lipids can then be extracted and upgraded into biofuels. We summarize the major novelties of this work and the new features of the proposed model below.

- Investigation on the integration of CCS and CU supply chains;
- Multi-scale modelling and optimisation that integrates the scale of supply chain network design and the scale of process design and operations for algal biorefineries;
- Multi-period modelling to capture seasonality in CO_2 emissions at power plants due to changes in demand and in lipid productivity at algal biorefineries due to variability of solar irradiation;
- Real-world case study in the state of Texas that reveals the economic and environmental potentials of integrating the two GHG abatement options.

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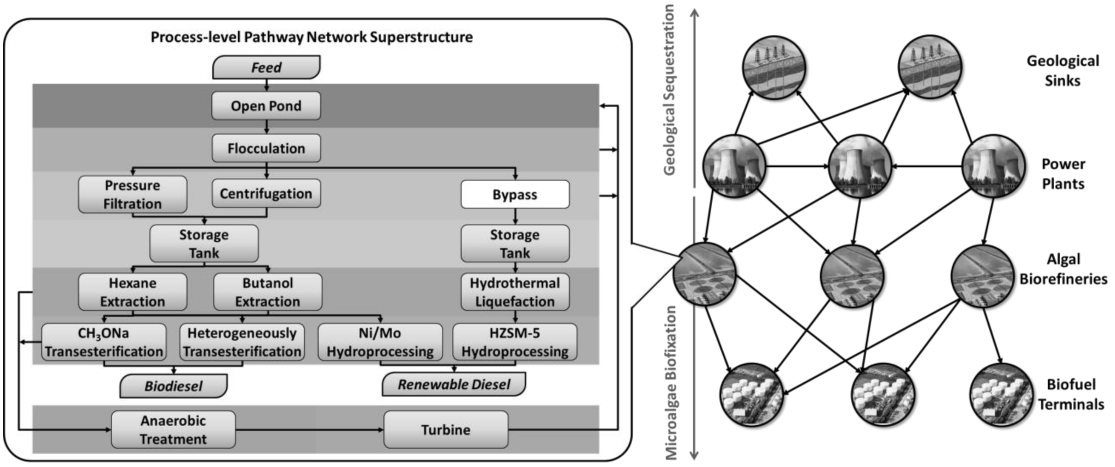

Figure 1: Superstructure of the multi-scale CCUS supply chain

The rest of this paper is organized as follows. We discuss the life cycle stages for environmental evaluation in the next section. The problem under study will be formally stated next, followed by the model formulation. Tailored global optimisation strategies to facilitate the solution process are then presented. We demonstrate the application of this work via a state-level case study at last.

2. Life cycle stages

To quantify the net GHG emissions throughout the CCUS supply chain, we summarize the major life cycle stages in Figure 2. Processes that have net positive GHG emissions are denoted with a "+" sign, and those that have net negative GHG emissions are denoted with a "–" sign. In the CCS supply chain, capture and compression of CO_2, transport of supercritical CO_2 through pipelines, and injection of CO_2 into geological formations all result in net positive GHG emissions, while GHG abatement in the geological sequestration option is achieved by permanent storage of the captured CO_2 underground. In the CU supply chain, stages that have net positive GHG emissions include clean-up and compression of feed gas, transportation of feed gas through pipelines, cultivation and conversion of algal biomass, and distribution of the produced renewable biofuels to their respective terminals. Unlike geological sequestration, microalgae biofixation reduces GHG emissions indirectly. By substituting fossil fuels in the marketplace with renewable biofuels, we can avoid the GHG emissions associated with the production, distribution, and use phases of the same amount of fossil fuels (You et al., 2011). The amount of GHGs avoided is calculated by comparing the GHG emissions of the integrated CCUS supply chain with that of a reference system, which contains the same coal-fired power plants, and includes the production and use of the same amount of conventional liquid transportation fuels.

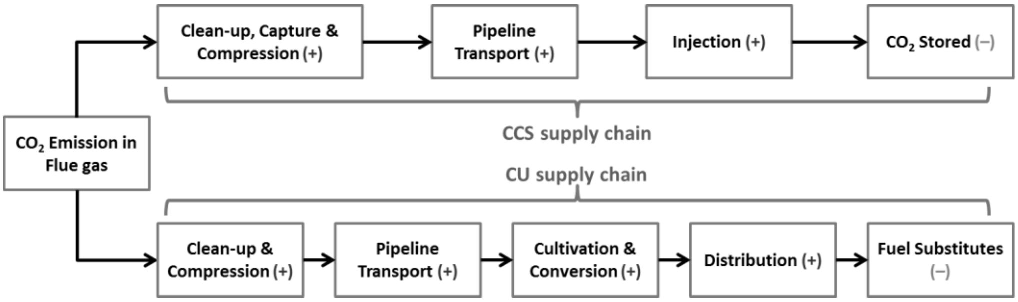

Figure 2: Life cycle stages of the CCUS supply chain

3. Problem statement

The superstructure of the integrated CCUS supply chains is shown in Figure 1. All of the facilities are denoted by a set of nodes. The nodes in the supply chain network include a set of power plants, a set of geological sinks, a set of algal biorefinery candidate sites, and a set of biofuel terminals. The power plants are sources of CO_2 emissions, where the monthly CO_2 output and corresponding unit capture costs and emissions are given. The geological sinks are permanent storage sites for CO_2, and the storage capacity and corresponding unit sequestration costs and emissions are given. The algal biorefineries convert CO_2 into lipids, which are further upgraded into renewable biofuels on-site (e.g., biodiesel, renewable diesel). A detailed process design and optimisation model is adapted from the work of Gong and You (2014b) and embedded into this supply chain superstructure. A number of promising conversion routes are included, which leads to multi-scale modelling with significantly higher fidelity. In the last stage, final algal biorefinery products are shipped to biofuel terminals that serve the customers, where the demand levels and corresponding market prices are given. Emissions related to the final products are counted as credits to the supply chain system. There are three types of arcs that link the four types of nodes. Arcs between power plants and geological sinks are linked by pipelines transporting supercritical CO_2. Arcs between power plants and algal biorefineries are linked by pipelines transporting feed gas, which typically contains 15 vol% CO_2 with the balance being nitrogen gas. A set of standard pipeline diameters are available for choice for these two types of pipelines, each with specified upper and lower bounds on the mass flow rate. The arcs between algal biorefineries and biofuel terminals are linked by road transportation, and the costs and emissions of transporting a unit weight over a unit distance are given. The distances of the arcs on earth can be estimated using great-circle distances or obtained with the help of geographic information systems (GIS). Observing that the changes in solar irradiation and length of daytime can influence the productivity of algal biomass, we employ multi-period modelling techniques to capture the seasonality in supply chain operations. In particular, we divide the planning horizon into a set of equal-length time periods and consider two different operating modes, namely daytime and night time. It is assumed that there is no production of algal biomass at night. An option of using artificial sunlight at night is not considered as it is not energy-efficient. Annual discount rate and projected lifetime are also given for the calculation of discounted cash flows. The goal is to minimize the CO_2 reduction cost and at the same time maximize the amount of CO_2 avoided from entering the atmosphere. This is achieved by optimizing the following strategic and operational decisions:

- Pipeline routing and diameter selection for the transport of supercritical CO_2 and feed gas;
- Matching of CO_2 quantities between power plant point sources and geological sinks and consumptions at algal biorefineries in different time periods and operating modes;
- Number, locations, sizes and selected technologies of the algal biorefineries;
- Production profiles at the installed algal biorefineries
- Transportation levels of the shipment of biofuels from algal biorefineries to biofuel terminals.

4. Model formulation

Considering the length of the paper, we omit detailed equations and present a general model formulation in this section.

min annualized total cost
max amount of GHGs avoided
s.t. (power plants) CO_2 mass balance, reduction target constraint (1)
(geological sinks) CO_2 mass balance, limitation on injection rate
(algal biorefineries) CO_2 mass balance, land use constraint, adapted process design model
(biofuel terminals) biofuels mass balance, bounds on demand
(supercritical CO_2 and feed gas pipelines) CO_2 mass balance, diameter selection, flow rate bounds
(monetary flows and environmental impact) calculation of cost and net GHG emissions

The economic objective is minimizing the annualized total cost of the integrated CCUS supply chain, which includes the on-site carbon capture cost, pipeline construction cost, pipeline operating and maintenance (O&M) cost, the sequestration cost, the product distribution cost and the annualized cost of algal biorefineries. The revenue from selling biofuel products is counted as credit to mitigate the total cost. The environmental objective is maximizing the amount of GHGs avoided from entering the atmosphere. The amount of CO_2 injected into the geological sinks is considered to be permanently removed from the atmosphere. The amount of CO_2 consumed at algal biorefineries is considered to be fixated in the biofuels produced. The net positive GHG emissions throughout the life cycle stages of the supply chain include emissions from carbon capture, pipeline transportation, biofuel production, and CO_2 injection at geological sinks. The GHG emissions credit from producing renewable biofuels is also accounted for. The proposed model is subject to a variety of constraints at different components of the CCUS supply chain. Instead of explaining all of the constraints, we highlight a number of critical constraints here. Reduction target constraint: we assume that an annual CO_2 emissions reduction target must be met at each power plant in line with recent EPA legislations and mandates. This constraint allows the power plants to control the quantity of CO_2 emissions to capture and utilize in each time period and operating mode, as long as the annual reduction target is met. Land use constraint: the land area available at each algal biorefinery candidate site can be different. Therefore, the capacity of the algal biorefinery could be limited by the land availability. Adapted process design model: we adapt the detailed process design model for conversion pathway selection from Gebreslassie et al. (2013) by adding indices of time periods and locations, as well as variables on process capacities. This process model accounts for mass balance and energy integration and quantifies the annualized cost and emissions associated with each conversion pathway. Note that there is no production of algal biomass at night, but production of biofuels is continuous due to the presence of storage for algal biomass. Diameter selection: only one pipeline and one diameter size can be selected on a certain arc following the single pipeline assumption by Middleton and Bielicki (2009). The above model is formulated as a bi-criterion nonconvex mixed integer nonlinear program (MINLP). The combinatorial nature is due to the presence of binary variables for selection of pipeline size, processing technology, etc. Nonlinearities stem from the process model, where the capital costs of the processes are calculated as concave power functions with respect to the capacities.

5. Solution strategies

We employ the Life Cycle Optimisation (LCO) framework that couples multi-objective solution techniques with Life Cycle Assessment (LCA) methodology (Yue et al., 2013) to simultaneously optimize the economic and environmental objectives. We adopt the standard ε-constraint method in this work and transform the environmental objective into an ε-constraint. The resulting model is a single-objective MINLP that minimizes the total annualized cost for CO_2 reduction subject to the constraint on GHG abatement for algal systems (Gong and You, 2015). Although off-the-shelf global optimizers (e.g., BARON 14, SCIP 3) can be used to solve the MINLP problem presented above, they usually require a considerable amount of computational time and resources due to the combinatorial nature and non-convexity of the model. To further facilitate the solution, we employ an improved branch-and-refine algorithm in this work (Yue and You, 2014). The algorithm takes advantage of powerful MILP solvers (e.g., CPLEX 12) and returns the global optimal solution to the nonconvex MINLP problem by solving a sequence of MILP sub-problems. These MILP problems are convex relaxations of the original MINLP, which are constructed successively as the branch-and-refine algorithm proceeds based on the piecewise linear approximations of the concave terms (You et al., 2011). We employ the SOS1 formulation to construct the piecewise linear approximations in this work, since it has been shown to be the most efficient formulation. It is apparent that the finer the grid partitioning, the smaller the approximation error. By using this improved branch-and-refine algorithm, we can automatically determine the addition of grid points and effectively converge to the global optimal solution within finite iterations.

6. Case study

We present a state-wide case study on the optimal design and planning of a CCUS supply chain network in Texas. The CCUS supply chain superstructure includes 5 existing coal-fired power plants, 1 geological sink, 5 candidate sites for building algal biorefineries, and 7 biofuel terminals. The annual CO_2 reduction target is set to 80 % for all power plants. We project the life span of the integrated CCUS infrastructure to be 20 y, and an annual discount rate of 10 % is considered. To capture seasonality of operations, we divide a year into 12 time periods (i.e., 1 month per time period). Other data are obtained or estimated from the literature, reports, databases, etc. The resulting Pareto optimal solutions are plotted in Figure 3. It can be seen that as the requirement on the amount of GHGs avoided increases from 16.688 to 21.277 Mt CO_2-equivalent/y, the annualized total cost of the project increases from 1.22 to 1.92 billion dollars. The pie charts above the Pareto curve correspond to the cost breakdowns. As can be seen, the primary costs come from the capital and O&M costs of algal biorefineries and CO_2 capture. Regarding the GHG emissions, the storage, utilization, and fossil-fuel substitution effect are considered to be (negative) credits, but the net positive GHG emissions also deserve our attention. The donut charts below the Pareto curve correspond to emissions breakdowns. As can be seen, the primary positive emissions in the supply chain come from the operations of CO_2 capture and algal biorefineries.

Point A in Figure 3 has the lowest annualized cost, so it is the most cost-effective solution. We plot in Figure 4a the amount of CO_2 emitted from the power plants (outer part), utilized by the algal biorefineries (middle part), and injected into the geological sinks (inner part) in each month as a radar chart. The sum of the amount of CO_2 utilized and stored is equal to 80 % of the total CO_2 emissions so that the 80 % CO_2

annual reduction target at the power plants is met. Analysis of the results indicates that the CO_2 emissions can be sequestrated and utilized at an average cost of \$45.52/tCO_2.

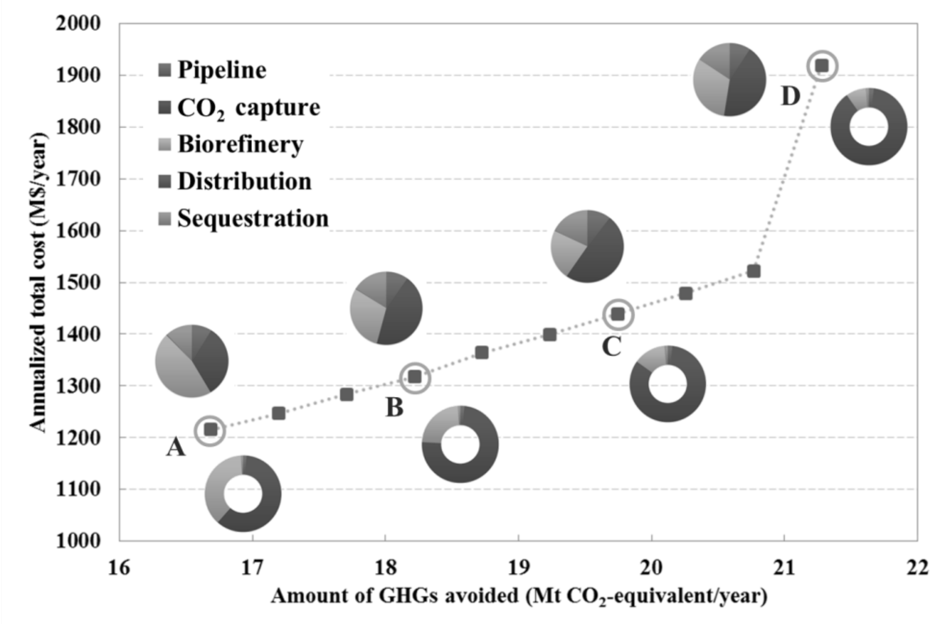

Figure 3: Pareto curve of the case study: the pie charts represent cost breakdowns; the donut charts represent emissions breakdowns

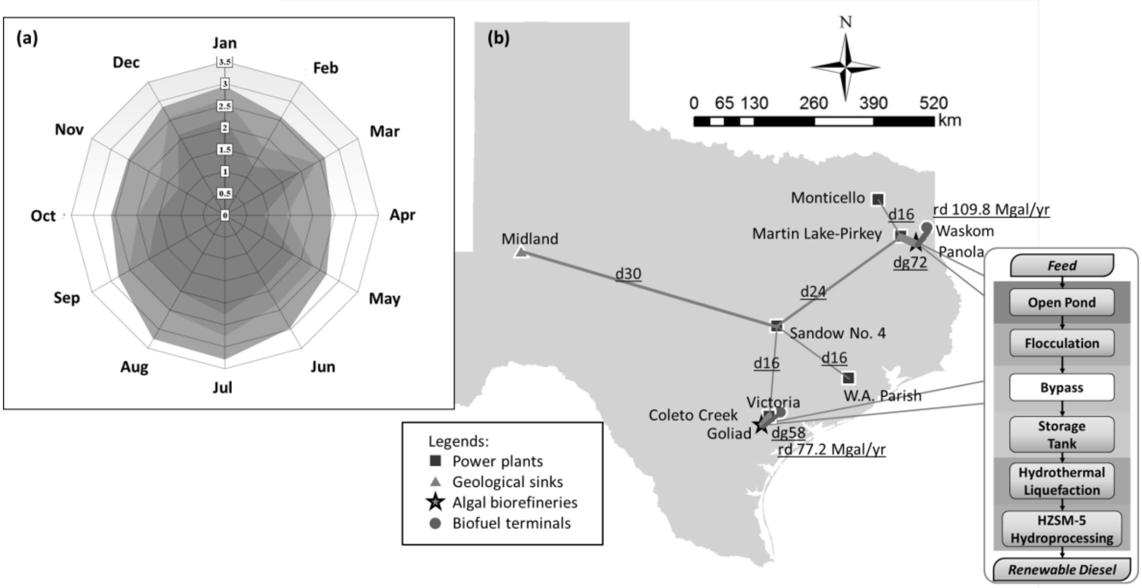

Figure 4: (a) CO_2 emissions, usage, and storage in the most cost-effective solution (unit: Mt CO_2); (b) Optimal supply chain design of the most cost-effective solution

The optimal CCUS supply chain configuration is shown in Figure 4b. We can see that both the geological sequestration and microalgae biofixation options are employed. This is because the microalgae biofixation option alone is not adequate to reach the 80 % CO_2 reduction target at the power plants since algal biorefineries cannot utilize CO_2 emissions during the night time production. On the other hand, it indicates that taking advantage of the synergies between both options leads to a lower CO_2 reduction cost compared to using the geological sequestration option alone. A total of 187 M gal of renewable diesel are produced every year at the two installed algal biorefineries through the conversion route shown on the right of Figure 4b.

7. Conclusions

We proposed a novel MINLP model for the optimal design and operations of integrated CCUS supply chains. We simultaneously considered two options for GHG abatement, namely geological sequestration and microalgae biofixation. In the former option, CO_2 is captured and separated at power plants, then transported to geological sinks via supercritical CO_2 pipelines for underground injection. In the latter option, CO_2 is pre-processed at power plants, then transported as a component of feed gas via pipelines to nearby algal biorefineries to serve as the primary nutrition for algae growth. A detailed process model was employed for the design of algal biorefineries, which involved 13 potential routes for converting algal biomass into biofuels. The seasonalities in CO_2 availability at power plants and algae productivity at algal biorefineries were modeled by a multi-period optimisation formulation, which enabled us to capture the operational variations at different times of a year. To reveal the trade-off between different supply chain design options under economic and environmental criteria, we applied the LCO framework by optimizing two objectives simultaneously. The application of this model was illustrated by a state-wide case study in Texas. Results showed that CCS through the geological sequestration option is necessary for reaching the 80 % CO_2 reduction target. Producing and selling biofuels through the microalgae biofixation option in concert with CCS can help reduce the CO_2 reduction cost and improve the GHG abatement effect.

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