Pinch Analysis Approach to Optimal Planning Of Biochar-Based Carbon Management Networks

Raymond R. Tan, Santanu Bandyopadhyay, and Dominic C. Y. Foo

Abstract—Biochar offers a potentially scalable option for achieving negative carbon emissions. The photosynthetic fixation of atmospheric carbon into biomass, followed by carbonization of plant biomass into stable biochar which is then added to soil, results in a reversal of the normal flow of carbon from man-made systems. In addition, these systems can provide economic benefits, such as enhancement of soil quality for agriculture, or co-production of valuable goods (e.g., energy and chemicals) along with biochar. However, the amount of biochar that can be added to agricultural land without causing adverse effects is limited by impurities such as salts, heavy metals and dioxins, which can cause a decline in soil quality. Thus, allocation of biochar from different sources (i.e., pyrolysis plants) to different sinks (i.e., farms or plantations) can be framed as a source-sink optimizations problem. In process integration literature, such problems have been solved via mathematical programming, pinch analysis or allied techniques such as process graphs. In this work, a pinch analysis approach for planning biochar-based carbon management networks is proposed. This methodology provides an alternative or complementary approach that facilitates decision-making and interpretation through visually oriented graphical displays. A case study is solved to illustrate how system-wide carbon sequestration can be maximized, while still satisfying soil impurity limits.

I. INTRODUCTION

Climate change is a major environmental issue, with atmospheric carbon dioxide (CO₂) levels having now exceeded sustainable limits [1]. Negative emissions technologies (NETs) will thus be needed to reduce stabilize CO₂ concentration to a manageable level in the future. NETs can potentially achieve on a limited scale the reversal of the normal flow of carbon in human activities, and thus offset positive carbon emissions elsewhere. Examples of NETs are ocean fertilization, direct air capture (DAC), bioenergy with CO₂ capture and storage (BECCS), and biochar amendment of soil [2,3]. Biochar application, which is a well-known soil amendment strategy, is now also seen as a scalable carbon management strategy for climate change mitigation [4].

Biochar is the carbon-rich solid co-product (along with biogas and bio-oil) of the pyrolysis of biomass. The negative emissions from biochar systems result from three sequential steps of photosynthetic carbon fixation into plant biomass, thermochemical carbonization of plant biomass to form biochar, and, finally, the application of biochar into soil. As most of the carbon in biochar is unreactive (or recalcitrant), with a typical half-life of multiple centuries, adding biochar to soil results in essentially permanent carbon storage [4]; on the other hand, the reactive (or labile) carbon in biochar decomposes rapidly and returns to the natural carbon cycle. In addition to direct capture and storage of carbon, biochar systems can achieve secondary reductions in CO₂ emissions. For example, improved soil fertility can further mitigate system-wide CO₂, methane (CH₄) and nitrous oxide (N₂O) emissions by reducing the need for fertilizers [4]. Woolf et al. [5] estimate the maximum sustainable technical potential (MSTP) of biochar at 130 Gt CO₂-C equivalent until 2100. Other sources estimate the emissions reduction potential and sequestration cost of biochar at 0.9-3.0 Gt CO₂/y and US$8-300/t CO₂, respectively [3]. Furthermore, biochar is a low-technology strategy that is more readily deployable and scalable than alternative NETs such as DAC or BECCS [2]. Despite such advantages, the commercial scale use of biochar has been hampered by economic factors [6]. The website of the International Biochar Initiative contains plenty of information on current developments pertaining to biochar systems [7].

On the other hand, critics have pointed out possible disadvantages of applications of biochar based carbon sequestration systems. For example, it has been suggested that soil darkening after biochar application can lead to albedo effects that can partially offset climatic benefits of carbon sequestration. Also, biochar may introduce impurities such as dioxins, polycyclic aromatic hydrocarbons (PAHs), salts and heavy metals into soil [8]. Levels of such impurities can be determined via laboratory analysis [9]. However, determining the tolerance of the receiving soil to such impurities is not as readily determined [10]. Thus, the full-scale implementation of biochar-based carbon sequestration systems requires the use of systematic decision support tools to manage risks and benefits. Process systems engineering (PSE) and process integration (PI) are sub-disciplines of chemical engineering which can provide appropriate techniques for such purposes [11,12]. PI was originally developed for process heat recovery and energy efficiency enhancement; strong emphasis was placed on pinch analysis methodology, which uses thermodynamic principles to facilitate problem-solving [13]. Pinch analysis has since diversified to a wide range of applications [12,14]. In particular, this approach has been applied to such areas as carbon-constrained energy planning [15,16] and CO₂ capture and storage (CCS) planning [17]. Such applications may be generalized as carbon management networks (CMNs). Recent developments are described in a

R. R. Tan is with the Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines; e-mail: (phone: 632-536-4226; fax: 632-536-4226; e-mail: raymond.tan@dlsu.edu.ph).

S. Bandyopadhyay is with the Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India (e-mail: santanub@iith.ac.in).

D. C. Y. Foo is with the Department of Chemical and Environmental Engineering/Centre of Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Broga Road, 43500 Semenyih, Selangor, Malaysia (e-mail: dominic.boo@nottingham.edu.my).
review paper by Foo and Tan [18]. Quantitative PSE or PI tools for systematic planning of commercial-scale biochar systems have been reported in literature [19-21]. More recently, Tan [10] proposed to model systems consisting of multiple biochar sources and sinks as a special case of CMN, using a mixed integer linear programming (MILP) formulation. In the MILP model, different pyrolysis plants are treated as biochar sources, while different farms and plantations are treated as biochar sinks.

In this paper, a graphical pinch analysis approach to planning biochar-based CMNs is developed using assumptions as proposed previously [10], with simplifications as discussed below. The rest of this paper is organized as follows. A formal problem statement is given in the next section. Then, the pinch analysis methodology is described. A literature case study based is then solved to illustrate the methodology. Finally, conclusions and prospects for future work are given.

II. PROBLEM STATEMENT

The problem addressed by this pinch analysis methodology may be formally stated as follows:

- Given a biochar-based CMN as illustrated in Figure 1, where biochar quality is defined in terms of the concentration of one major impurity.
- Given a set of $M$ biochar sources, designated as SOURCES = \{ $i$ | $i$ = 1, 2, …, $M$ \}, each of which is a pyrolysis plant that produces a biochar stream at a carbon equivalent flowrate $SR_i$ and with an impurity concentration level of $Q_j$.
- Given a set of $N$ biochar sinks, designated as SINKS = \{ $j$ | $j$ = 1, 2, …, $N$ \}, each of which is a plantation or farm which can receive biochar at a carbon equivalent rate of $SK_j$ and at an impurity limit of up to $Q_j^{\text{MAX}}$.
- The objective is to maximize the total carbon sequestration for the system, and allocate the biochar between the sources and sinks without exceeding impurity limits of the latter.

III. PINCH ANALYSIS METHODOLOGY

The overall methodology of this approach is similar to that used for resource conservation networks (RCNs) [22]. The main steps are as follows:

- Arrange sources in order of ascending values of $Q_j$.
- Generate the source composite curve by plotting each source in sequence, using cumulative equivalent carbon flowrate as the $x$-axis and the cumulative impurity load (i.e., the product of $SR_i$ and $Q_j$) as the $y$-axis. It can be seen that, geometrically, the slope of each segment is equal to the $Q_j$ of the corresponding source.
- Likewise, arrange sinks in order of ascending values of $Q_j^{\text{MAX}}$.
- Generate the sink composite curve by plotting each sink in sequence, also using cumulative equivalent carbon flowrate as the $x$-axis and the cumulative impurity load (i.e., the product of $SK_j$ and $Q_j^{\text{MAX}}$) as the $y$-axis. Similarly, the slope of each segment is equal to the $Q_j^{\text{MAX}}$ of the corresponding sink.
- Superimpose the source and sink composite curves and note their orientation. If the source composite curve lies completely below the sink composite curve, then a feasible and optimal solution is immediately found. Otherwise, the source composite curve must be translated or shifted horizontally to the right, until it lies just below and to the right of the sink composite curve. Mathematical discussion about the optimality condition of this method is discussed elsewhere [23].
- As shown in Figure 2, the source and sink composite curves (shown in red and blue, respectively) will be tangent to each other at a pinch point [22]. The maximum horizontal overlap of the two composite curves is target of the CMN system as this signifies the maximum carbon sequestration for the system.

Figure 1. Generic CMN superstructure

Figure 2. Generic features of a pinch diagram
At the previously determined geometric orientation of the two composite curves, the following key features can be interpreted as follows. First, the overhang of the sink composite curve on the left hand side of the pinch diagram corresponds to excess biochar storage capacity which cannot be utilized due to impurities present in the system biochar streams. Secondly, the target (i.e., the overlap of the two composite curves) represents the storable carbon in the biochar system (i.e., where both carbon and impurity balances are satisfied). Thirdly, if the source composite curve extends to the right hand side of the pinch diagram beyond the sink composite curve, the horizontal length of the extension represents the excess biochar that cannot be stored in the system, due to an excess of flow rate of the biochar sources and/or exceedance of the maximum impurity levels of the biochar sinks.

The pinch point divides the pinch diagram into two zones; the left hand zone has excess storage capacity, while the right hand zone has excess biochar. This information can then be used to plan the allocation of biochar in the CMN. Firstly, a special case of the golden rule of pinch analysis applies; with the exception of the source that forms the pinch point, in an optimal solution, biochar cannot be transferred from a source to a sink that are on opposite sides of the pinch point. Secondly, the actual allocation of biochar within the CMN can be determined by inspection, or by various network synthesis techniques such as the nearest neighbor algorithm [24].

A more detailed description of the methodology can be found in the literature [15,22]. A case study is solved in the next section to illustrate these steps.

### IV. Case Study

This case study is adapted from the example used by Tan [10]. The biochar CMN has three sources and four sinks, and the impurity is PAH, which forms via undesired side reactions during pyrolysis; these persistent organic pollutants cause concerns due to potential adverse health and environmental impacts [8]. The relevant data for sources and sinks are given in Tables I and II, respectively. From these data, it is possible to generate the source composite curve (Figure 3) and sink composite curve (Figure 4) using the procedure described in the previous section. When these two composite curves are superimposed, an infeasible orientation occurs, as shown in Figure 5. The source composite curve can then be shifted horizontally to the right, until a feasible orientation is found along with a pinch point (Figure 6).

This final pinch diagram gives the optimal solution which is able to store 4,500 t/y. The pinch point occurs between Sinks 1 and 2; only 50% of the storage capacity of the former sink is used due to biochar quality limits. The excess storage capacity below the pinch point is 1,500 t/y. On the other hand, above the pinch point, all of the storage capacity of Sinks 2, 3 and 4 are utilized, while leaving an excess amount of biochar of 1,700 t/y. Since the latter quantity cannot be stored within the system, it may need to be exported to an external sink that is capable of absorbing low quality biochar.

#### TABLE I. Case Study Source Data

<table>
<thead>
<tr>
<th>Source</th>
<th>Biochar Flowrate Limit (t/y C equivalent)</th>
<th>PAH Concentration Limit (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>10</td>
</tr>
</tbody>
</table>

#### TABLE II. Case Study Sink Data

<table>
<thead>
<tr>
<th>Sink</th>
<th>Biochar Flowrate Limit (t/y C equivalent)</th>
<th>PAH Concentration Limit (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>25</td>
</tr>
</tbody>
</table>

![Figure 3. Source composite curve](image1)

![Figure 4. Sink composite curve](image2)
The corresponding biochar allocation in the CMN is given in Table III; alternative optimal networks may exist, and can be found using appropriate synthesis techniques [22, 24]. Such alternative configurations satisfy the same target values for the objective function. For example, there is a large gap between the source and sink composite curves to the right of the pinch point in Figure 5. This orientation signifies excess degrees of freedom in matching sources and sinks in this region. For example, the positions of Sources 2 and 3 can be interchanged to give the modified pinch diagram in Figure 7; the corresponding modified biochar allocation in the CMN is given in Table IV. Note that all of the biochar from Source 2 is available for export from the system, along with an excess of 500 t/y of biochar from Source 3. Such an allocation ensures that the biochar exported from the CMN is of higher quality than in the original solution, which in practice will make finding an external sink much easier. Further modification is possible by storing all of the biochar from Source 3 within the CMN, which further displaces 500 t/y of biochar from Source 1 that was originally allocated to Sink 3. Such a solution can be seen in Figure 8 and Table V. Note that the biochar available for export from the CMN system are of high quality, and originate from Sources 1 and 2.

### Table III. Optimal CMN

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink 1</th>
<th>Sink 2</th>
<th>Sink 3</th>
<th>Sink 4</th>
<th>Excess Biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>1500</td>
<td>1000</td>
<td>500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Source 2</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>Source 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>300</td>
<td>1700</td>
</tr>
<tr>
<td>Excess Storage Capacity</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table IV. Alternative Optimal CMN 1

<table>
<thead>
<tr>
<th>Source</th>
<th>Sink 1</th>
<th>Sink 2</th>
<th>Sink 3</th>
<th>Sink 4</th>
<th>Excess Biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>1500</td>
<td>1000</td>
<td>500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Source 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1200</td>
</tr>
<tr>
<td>Source 3</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>1000</td>
<td>500</td>
</tr>
<tr>
<td>Excess Storage Capacity</td>
<td>1500</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
TABLE V. ALTERNATIVE OPTIMAL CMN 2

<table>
<thead>
<tr>
<th>Source 1</th>
<th>Sink 1</th>
<th>Sink 2</th>
<th>Sink 3</th>
<th>Sink 4</th>
<th>Excess Biochar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1500</td>
<td>1000</td>
<td>0</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Source 2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1200</td>
</tr>
<tr>
<td>Source 3</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Excess</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Storage</td>
<td>1500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

VI. GENERAL IMPLICATIONS OF THE METHODOLOGY

With atmospheric CO₂ concentration continuing to rise due to the steady accumulation of emissions from human activity, large scale deployment of NETs may soon become necessary to stabilize climate and slow global warming to safe levels. Biochar is one of the scalable options available for commercial use in the medium term, since many of the component technologies are technologically mature [2,3]. What remains unproven at this stage is the use of system-wide biochar-based CMN for significant levels of CO₂ sequestration. As a CMN option, biochar proponents have pointed out significant advantages [4,5], while critics point out uncertainties about potential benefits, as well as risks associated with soil contamination [8]; thus, it has recently been proposed that systematic modeling approaches be developed to provide decision support for its large scale deployment [10]. Such techniques are needed to balance costs and benefits of biochar-based CMNs. The methodology developed in this work provides an alternative or complementary approach to the previously developed mathematical programming model. In particular, the visually oriented graphical display used in pinch analysis facilitates decision-making and solution interpretation that may have advantages over equation-based methodologies in practice [12]. Although the case study presented previously is hypothetical, it serves to illustrate how this methodology can be applied to real systems if similar data are available. In practice, biochar quality is a function of biomass feedstock characteristics and processing conditions, and can be determined using laboratory assays [9]. On the other hand, soil tolerance to impurities can be harder to judge, but may be estimated, for instance, from background levels of contaminants [8]. Any data uncertainties from the estimation process can be addressed, for instance, using sensitivity analysis [10]. Thus, given the possibility of acquiring such data about sources and sinks, the pinch analysis-based approach proposed here can be used for decision support for real applications in the future.

VI. CONCLUSION

In the present context of climate change, adopting biochar-based strategies for carbon management, along with other NETs, may prove to be an important strategy. Other than the sequestration of greenhouse gases, application of bio-char to soil can improve soil fertility and hence enhancement of crop production. However, impurities such as dioxins and polycyclic aromatic hydrocarbons (PAHs), produced during pyrolysis through undesired side reactions may lead to soil degradation. For the proper carbon management of the overall system, biochar sources should be matched properly with different biochar sinks. A graphical pinch analysis method for planning biochar-based CMNs has been developed in this work. This technique allows the allocation of biochar from different sources to different sinks, so as to maximize carbon sequestration, while ensuring that biochar does not introduce excessive impurities to the receiving soil of the different farms or plantations that are used as sinks. This pinch-based methodology can be used as a simple tool for preliminary, high-level planning of commercial-scale biochar projects. The pinch-based methodology provides physical insight to the overall problem and provides alternate solutions. Future work can focus on integration of this pinch analysis approach with other methods, such as mathematical programming models or process graphs. This methodology can also be used as the initial step of a two-stage optimization procedure, where the second stage involves maximizing the use of the impurity tolerance of the sinks. Also, multi-component, multi-objective and multi-region variants of this approach should be developed to deal with more complex problems.

REFERENCES


