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# Pinch Analysis for Temporally Constrained Carbon Trading

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Trading of carbon credits will become prevalent in response to global decarbonization efforts. There will be companies specializing in the sale of credits generated internally (e.g., using negative emissions technologies) or purchased from external sources (e.g., generated from energy conservation projects). Process Integration methodology can be adapted to provide vital decision support for such activities. In this work, an extension of Pinch Analysis (PA) is developed for planning the sale of carbon credits under temporal constraints. Projects and facilities that generate carbon credits are treated as sources, while buyers of the credits are treated as demands. It is assumed that carbon credits need to be generated before they are sold, and time is used in a manner analogous to temperature in conventional PA to impose directionality constraints when transferring credits from sources to sinks. The flow of carbon credits from each source and into each demand is assumed to occur at a fixed rate between the well-defined start and end times. Targeting viable sales is done using the standard graphical Composite Curve approach. The methodology is demonstrated with a series of illustrative case studies.

## 1. Introduction

Decarbonization of human activities will be needed to keep climate change within tolerable limits (IPCC, 2022). Deep cuts in Greenhouse Gas (GHG) emissions can be achieved through concerted measures such as energy conservation, renewable energy generation, and Carbon Dioxide Removal (CDR). Economic instruments like carbon trading will also be needed to provide the impetus for the large-scale use of industrial decarbonization measures (Hashim et al., 2022). Carbon markets should also allow the trading of CDR credits from Negative Emissions Technologies (NETs), without which the goals of the Paris Agreement cannot be achieved (Daggash and MacDowell, 2019). There is now an emerging market for CDR credits which is stimulating the commercialization of NETs despite high initial prices (Hickey et al., 2023). Alternative temporally-weighted pricing mechanisms have been proposed to deal with variations in CDR permanence (Wenger et al., 2023). There has also been recent work on models to optimize the procurement of carbon credits based on approaches such as Mathematical Programming (MP) (Magenthirarajah et al., 2022), Pinch Analysis (PA) approaches (Tan et al., 2022), and Game Theory (Babonneau et al., 2021).

Both MP and PA are used as complementary techniques within the Process Integration (PI) framework (Klemeš and Kravanja, 2013). PA was originally developed to aid in the optimal design of Heat Exchanger Networks (HENs) using thermodynamic principles (Hohmann, 1971). It has been established as a two-stage methodology consisting of targeting (i.e., identification of the optimal energy utility budget for any given process plant) and design (i.e., synthesis of HEN to meet the previously determined target) (Linnhoff and Hindmarsh, 1983). PA is now a mainstream tool found in a classic guidebook (Linnhoff et al., 1982), design textbooks (e.g., Smith, 2016), and a specialized handbook (Klemeš, 2023). This general “target before design” approach is a powerful principle that can be extended to other engineering problems. For example, the extension of PI to the synthesis of Mass Exchange Networks (MENs) was the direct result of the analogy between heat and mass transfer phenomena (El-Halwagi and Manousiothakis, 1989). Other extensions emerged from the 1990s onward. The historical

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evolution of PA and its diversification to applications beyond heat recovery are discussed in a review by Klemeš et al. (2018). PI principles have also been adapted to emerging challenges, such as stimulating the development of the Circular Economy or responding to the COVID-19 pandemic (Klemeš et al., 2022). Graphical techniques are also useful for decision support by providing insights into important aspects of engineering problems (Wang et al., 2022). Alternatives to PA have also been developed within the broad PI framework. MP models can be used for targeting (Yee et al., 1990a) and HEN synthesis (Yee et al., 1990b). Graph theoretic approaches have also been proposed and are useful for generating and evaluating alternative optimal and near-optimal HEN topologies (Orosz et al., 2022).

The potential emissions reduction benefits resulting from energy conservation due to PA were first described by Dhole and Linnhoff (1993). Carbon Emissions Pinch Analysis (CEPA) was then proposed as a systematic methodology for matching energy sources with energy demands subject to emissions constraints (Tan and Foo, 2007). The term Carbon Management Network (CMN) was also introduced to describe systems where flows of energy or carbon credits are allocated based on PI principles (Foo and Tan, 2020). Different CEPA variants, extensions, and selected country case studies are documented in the book by Foo and Tan (2020). A CEPA variant was recently developed for optimizing peer-to-peer carbon trading (Tan et al., 2022), where the problem dealt with matching vendors and buyers of carbon credits, given data on both the quantity and price of these credits. However, this methodology does not consider temporal aspects and is limited to static allocation problems. The absence of an established CEPA tool for dynamic carbon trading problems is a clear gap in the literature.

This research gap is addressed here through the development of a new CEPA variant for temporally constrained carbon trading. The methodology uses time-tested PA principles to deal with an emerging need and is directly analogous to the classic heat integration problem. The rest of the paper is organized as follows. The formal problem statement is stated in Section 2, and the steps of the graphical technique are described in Section 3. Three illustrative case studies are then solved in Sections 4–6. Finally, the conclusions are given in Section 7.

## 2. Formal problem statement

The temporally constrained CMN synthesis problem is stated as follows:

- Given a set of sources (vendors of CDR credits), each with a fixed annual output of CDR credits generated between the fixed start and end times;
- Given a set of demands (buyers of CDR credits), each with a fixed annual demand for CDR credits between the fixed start and end times;
- Given the condition that CDR credits can only be sold after they are generated;

The main problem is to determine the system target, which is either (a) the maximum quantity or load of CDR credits that are traded between sources and demands or (b) the minimum quantity of CDR credits that needs to be sourced from outside the system to meet any deficit. The corollary problem is to determine the optimal CMN that satisfies these targets.

## 3. Graphical PA technique

In this section, the classic graphical PA technique for HEN synthesis based on Composite Curves (CC) (Linnhoff et al., 1982) is adapted to the temporally constrained CMN planning problem. The quantity of CDR credits and time are used as analogues for enthalpy and temperature.

The steps of the methodology are as follows:

(S1) Generate the Source Composite Curve (SCC) by plotting the sources in rectangular coordinates, with cumulative CDR credit load as the horizontal axis and time as the vertical axis; the slope of each segment of the resulting SCC gives the total available flow of CDR credits during the corresponding time interval.

(S2) Generate the Demand Composite Curve (DCC) by plotting the demands in the same manner as in (S1).

(S3) Superimpose the SCC and DCC and inspect their resulting positions. The SCC must be completely below the DCC for the solution to be feasible.

(S4) If the initial positions of the SCC and DCC indicate an infeasible solution, shift the SCC horizontally to the right until a feasible solution results from the new position.

(S5) The positions of the SCC and DCC in (S4) indicate two key features of the optimal solution. The distance of the horizontal shift gives the target, which is the demand for CDR credits that cannot be met by the system sources. These credits have to be purchased from an external source to meet this deficit. The SCC and DCC are tangent to each other at the pinch point, which subdivides the system into regions below (before) and above (after) the pinch. The “Golden Rule” of PA can be interpreted as a condition that requires the use of externally sourced CDR credits to satisfy only demands that occur before the pinch. There can also be surplus CDR credits after the Pinch Point that can be exported from the system.

(S6) The optimal CMN matching the sources and demands can be determined by inspection or using procedures originally developed for HEN synthesis (Linnhoff et al., 1982).

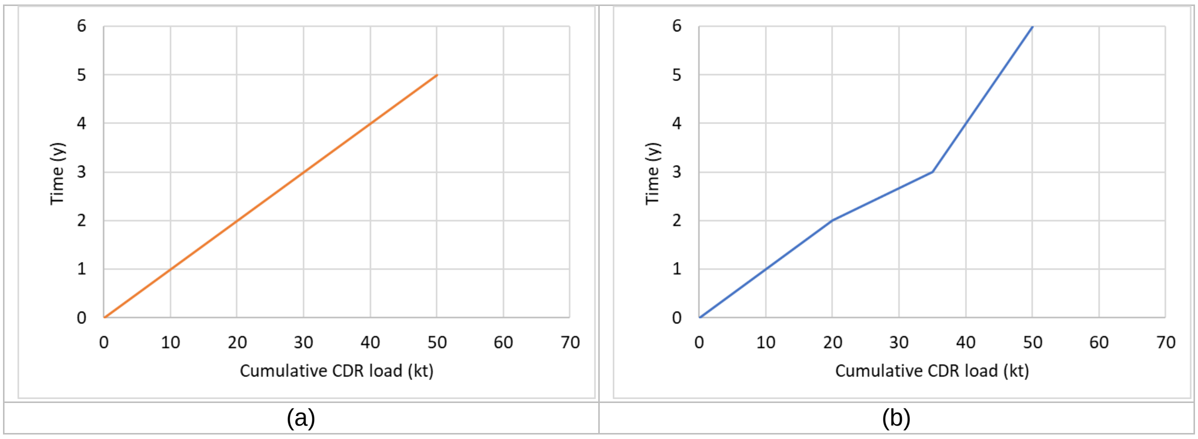
This methodology is illustrated with three case studies in the succeeding sections.

## 4. Case study 1

This case study has one source and two demands whose process data are given in Table 1. Without temporal constraints, the available CDR credits from the source are sufficient to meet the combined requirements of the two demands. The SCC and DCC can be generated using steps (S1) and (S2), as shown in Figure 1. Superimposing these two CCs based on step (S3) gives the infeasible solution in Figure 2a. The SCC can be shifted following step (S4) to provide the feasible and optimal solution in Figure 2b. It can be seen that the system requires 5 kt of supplementary CDR credits from an external source at t = 0 to satisfy the deficit that occurs early in the planning horizon before the pinch point. The pinch occurs at t = 3, after which there is 5 kt of surplus CDR credits available for export. Only 90 % (45 kt) of the internally available CDR credits can be used within the system. The resulting CMN is shown in Table 2. The externally sourced CDR credits are used to meet the part of the demand of D2 that occurs before the pinch.

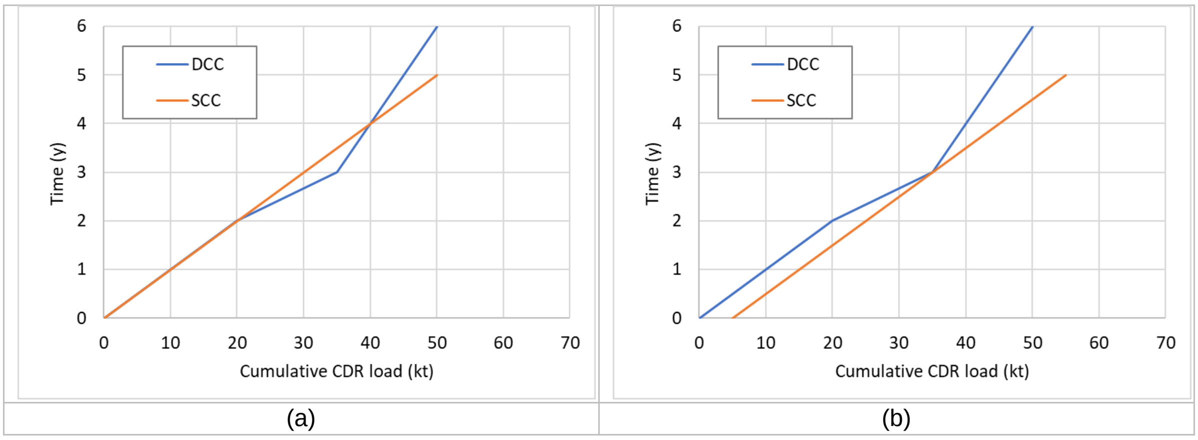
*Table 1: Process data for Case Study 1*

| Source/Demand | Start time (y) | End time (y) | CDR flowrate (kt/y) | CDR load (kt) |
|---|---|---|---|---|
| S1 | 0 | 5 | 10 | 50 |
| D1 | 0 | 3 | 10 | 30 |
| D2 | 2 | 6 | 5 | 20 |



(a) (b)

*Figure 1: Plotting the (a) SCC and (b) DCC for Case Study 1*



(a) (b)

*Figure 2: Pinch diagram showing (a) infeasible and (b) feasible and optimal solution for Case Study 1*

Table 2: Optimal CMN for Case Study 1 (values in kt)

| | D1 | D2 | Surplus |
|---|---|---|---|
| External source | 0 | 5 | 0 |
| S1 | 30 | 15 | 5 |

## 5. Case study 2

This case study has two sources and two demands with process data, as given in Table 3. The internally available CDR credits are sufficient to meet the combined demands in the absence of temporal constraints. The initial steps of generating the CCs are omitted here due to space constraints. The initial infeasible solution is shown in Figure 3a. Shifting the SCC gives the feasible and optimal solution in Figure 3b, where it can be seen that the system requires 10 kt of supplementary CDR credits from an external source at t = 0 to satisfy the deficit before the pinch point at t = 2. Only 80 % (40 kt) of the internally available CDR credits can be used within the system, with 10 kt of surplus being available for export after the Pinch. The resulting CMN is shown in Table 4. The externally sourced CDR credits are allocated entirely to D1.

Table 3: Process data for Case Study 2

| Source/Demand | Start time (y) | End time (y) | CDR flowrate (kt/y) | CDR load (kt) |
|---|---|---|---|---|
| S1 | 0 | 4 | 5 | 20 |
| S2 | 2 | 4 | 5 | 30 |
| D1 | 0 | 3 | 10 | 30 |
| D2 | 2 | 6 | 5 | 20 |

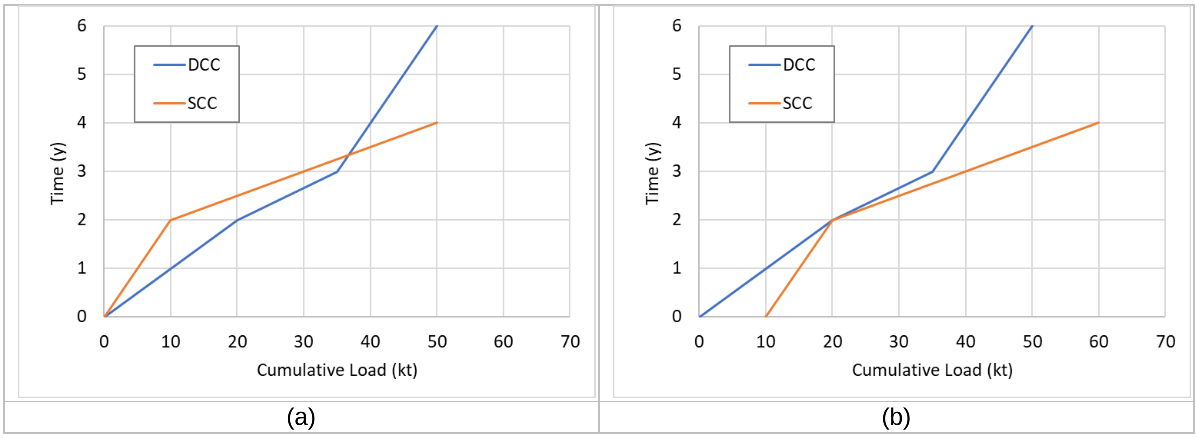


Figure 3: Pinch diagram showing (a) infeasible and (b) feasible and optimal solution for Case Study 2

Table 4: Optimal CMN for Case Study 2 (values in kt)

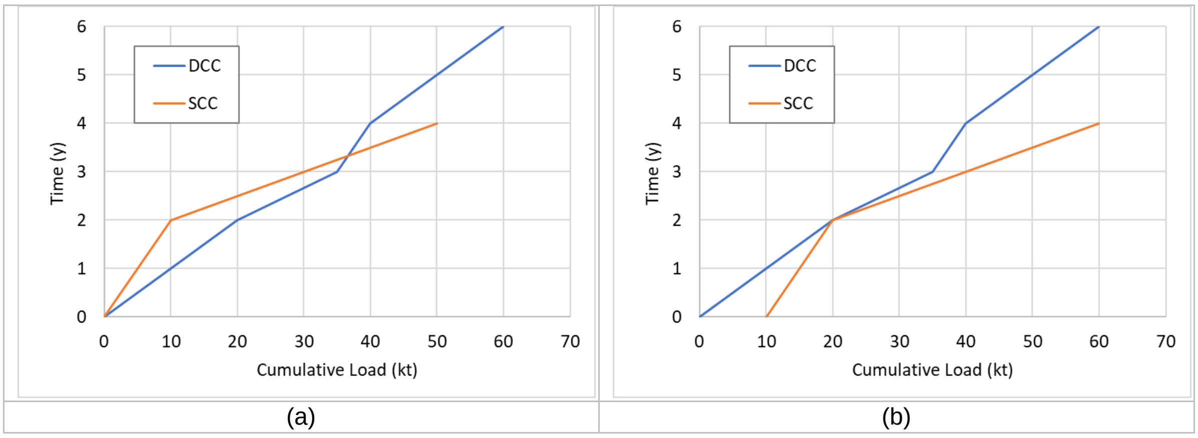
| | D1 | D2 | Surplus |
|---|---|---|---|
| External source | 10 | 0 | 0 |
| S1 | 15 | 5 | 0 |
| S2 | 5 | 15 | 10 |

## 6. Case study 3

This case study uses the same data as Case Study 2 but with an additional demand, as shown in Table 5. The available CDR credits from the two sources are not sufficient to meet the combined requirements of the three demands. The initial infeasible solution is shown in Figure 4a, while the feasible and optimal solution is shown in Figure 4b. The system still requires 10 kt of supplementary CDR credits from an external source, and the pinch point occurs at t = 2. All of the internally available CDR credits are used within the system. The resulting CMN is shown in Table 6, and is similar to that of Case Study 2 except for the additional demand.

*Table 5: Process data for Case Study 2*

| Source/Demand | Start time (y) | End time (y) | CDR flowrate (kt/y) | CDR load (kt) |
|---|---|---|---|---|
| S1 | 0 | 4 | 5 | 20 |
| S2 | 2 | 4 | 5 | 30 |
| D1 | 0 | 3 | 10 | 30 |
| D2 | 2 | 6 | 5 | 20 |
| D3 | 4 | 6 | 5 | 10 |



(a)

(b)

*Figure 4: Pinch diagram showing (a) infeasible and (b) feasible and optimal solution for Case Study 3*

*Table 6: Optimal CMN for Case Study 2 (values in kt)*

| | D1 | D2 | D3 | Surplus |
|---|---|---|---|---|
| External source | 10 | 0 | 0 | 0 |
| S1 | 15 | 5 | 0 | 0 |
| S2 | 5 | 15 | 10 | 0 |

## 7. Conclusions

A PA-based methodology has been developed for temporally constrained peer-to-peer carbon trading. This methodology considers a given set of CDR credit vendors (sources) and a set of buyers (demands). Each firm in the system is assumed to produce or buy a fixed annual quantity of CDR credits within a defined time interval. It is also assumed that the CDR credits should be generated before they are sold. The system target is determined by the direct application of the classic graphical CC approach; then, the “Golden Rule” facilitates the synthesis of the optimal CMN. The methodology was demonstrated via three illustrative case studies, which clearly show how the “target before design” PI approach applies to the problem of temporally constrained carbon trading. This PA methodology is an additional contribution of the PI framework to the global challenge of climate change mitigation.

The methodology described in this paper uses simplifying assumptions (e.g., fixed prices and fixed flowrates) that limit its general applicability. These assumptions can be relaxed in future work to address additional issues, such as: non-linear CC segments due to variations in annual CDR credit flows, carbon discounting, and pricing mechanisms to account for uncertainties in CDR permanence. There is also the prospect of adapting other PI techniques originally developed for HEN synthesis (such as the Problem Table Algorithm) to planning temporally constrained CMNs. Allocation of emissions caps among corporations or countries is another important problem of current interest that can potentially be solved using PI.

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