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# Systematic Multi-Period Carbon Integration in an Industrial City

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Global awareness of the effects of anthropogenic carbon footprint has resulted in proposals for ambitious reduction targets. Commonly, proposals for carbon footprint reduction solutions fall into one of the three areas: improvements in energy efficiency, the use of renewables and less carbon intensive fuels, and Carbon Capture and Sequestration (CSS). On an industrial city scale, additional opportunities for utilization are accessible to convert carbon dioxide into value added products in close proximity. Utilizing carbon dioxide through conversion into fuel, algae, polymers or another value added products could reduce the overall capture costs and lessen the economic burden that prevents emissions cuts. The concept of carbon integration has recently emerged and a process integration approach presented to determine cost efficient allocations of carbon dioxide sources to potential carbon dioxide sink processes to achieve footprint targets. Since carbon footprint reduction efforts typically aim at achieving cuts by a future date, this paper presents a multi-period planning approach to explore carbon integration options over a planning horizon with time-dependent carbon constraints. The approach introduced in this work enables cost optimal source-sink mapping that takes into account the improvements in carbon capture technology and expansion of the industrial city over time. A case study is presented to illustrate the approach by exploring two alternative carbon reduction target policies.

## 1. Introduction and Background

Strict carbon reduction targets present growing challenges for the energy intensive industrial sectors to manage their carbon footprints. Footprints can be reduced by the use of more energy efficient technologies applying energy integration, fuel switching and renewable energy sources and carbon storage and sequestration (CSS). In contrast, this work explores the concept of carbon integration of an industrial park. Carbon integration aims at the recovery of carbon dioxide emitted from sources into sinks with the goal of reducing the overall carbon footprint of the system at minimum cost (Al-Mohannadi and Linke, 2015).

Previous related work focused on carbon dioxide allocation in geological storage. Storage allocation was the focus of the work of Middleton and Bielicki (2009) where pipeline costs and transmission were addressed in the formulation. On the other hand Tan et al. (2012) looked into storage capacity within the source-sink matching, while Enhanced Oil Recovery (EOR) allocation was considered extensively by Hasan et al. (2014). The aspect of network changes over time was studied in terms of carbon dioxide allocation in storage (He et al., 2013). Multi-period planning problems are common in process systems engineering and include problems such as hydrogen network design (Heever and Grossman, 2003), reactor design (Rooney and Biegler, 2000), water network synthesis (Bishnu et al, 2014), and heat exchange network synthesis (Isafiade and Fraser, 2010). Carbon reduction planning over time horizons has been investigated with a focus on considering reduction in terms of energy use. Heat and power production with carbon reduction overtime was applied by Rong and Lahdelma (2007) using a stochastic optimization approach, while Siritítputtisak et al. (2009) proposed power planning using a MINLP formulaiton for a specific region expansion plan. Zhang et al. (2012) studied the impact of different policies for carbon targets on China's power sector.

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While carbon reduction by energy use minimization and fuel switching is common practice, Carbon integration planning for an industrial park over a time horizon is more complex in that it must take into account changes in industries and processes over-time and allow smooth transition across various phases of planning. In terms of opportunities for synergy, industrial parks could ideally contain carbon dioxide converting processes, referred to as sinks, or a process can be added to consume emitted carbon dioxide. This kind of symbiosis of utilizing carbon dioxide sources, i.e. carbon dioxide emitting streams from a process, in appropriate carbon dioxide sink processes can help in reducing emissions and creating value added products. Carbon dioxide can in principle be converted in many different ways, including chemical or biological conversion into fuel or another value added product (Mikkelsen et al., 2010). Carbon integration presents a systematic approach to integrate carbon dioxide within an industrial park (Al-Mohannadi and Linke, 2015). It incorporates multiple carbon emitting streams and the potential carbon utilization options that may exist including geological storage and Enhance Oil Recovery (EOR). A step-wise approach, from data acquisition to network design, is followed to determine the lowest cost carbon integration network for carbon footprint reductions in a given industrial park adopted below from Al-Mohannadi and Linke (2015). This work extends the approach to enable multi-period planning to enable the time dependency of the problem to be taken into account when performing carbon integration, which includes time-dependent carbon footprint reduction targets as well as technology improvements over time.

## 2. Multi-period Carbon Network Optimization

The approach determines the required purity of carbon dioxide and the associated cost with the treatment. Transmission is accounted for based on sink requirements and the distances between sources and sinks. Capture, compression, and pipeline costs significantly influence connection decisions and are vital to determine the most economically attractive footprint reduction solutions. The approach can be adopted to fit different aids policy makers and designers to plan carbon capture strategies, which require long term planning and the consideration of the time aspect.

The problem contains a set of carbon plants of known sources, locations, source flow and carbon composition and a number of carbon sinks with known carbon capture capacity, pressure and composition requirements. The goal is to identify cost optimal carbon source-sink allocation network with target of emission cuts being specified for each period. Carbon sources can be transferred to sinks either in treated form or without treatment as shown in Figure 1. A single pipeline connects each source to sink, where flows can be transferred as treated, untreated or a mixture between the two. The flows undergo a compression step to overcome pressure drop in the pipeline and adjust pressure difference between source and sink. Sinks can receive carbon from various sources, mixed together to satisfy the sink's required purity.

In each period, carbon footprint reduction targets are specified as a percentage of carbon emission in the first period of planning. The target cut is to be achieved by the date specified, after which the network will carry on with the pervious network until the next cut date. It is assumed that the problem data in terms of maximum amount of carbon flow from source and sink capacities together with their concentration data are known for each period. Figure 2 provides a conceptual illustration of the multi-period carbon integration planning problem.

The objective is to minimize the total cost of the network including the cost of processing carbon dioxide in sinks, the cost of treatment and costs of compression and delivery. The formulation of the optimization problem takes the general form of a Mixed Integer Nonlinear Program (MINLP) as follows:

$$\text{Min TC } f\,(\text{Cost of Treatment} + \text{Cost of Compression} + \text{Cost of Transportation} + \text{Cost of Sinks}) \qquad (1)$$

Equality and Inequality constraints include component and total mass balances around sources and sinks, non-negativity constraints for all flows as well as purity constraints and total net capture constraints. Binary constraints were used to account for connections between periods and cost elements. To incorporate technology learning curves, cost parameters can be set accordingly for each period. The optimization problem has been implemented using "What's Best 9.0" Lindo Global solver for MS-Excel 2010 and solved on a laptop with Intel Core i7 Duo processor, 8 GB RAM and a 32-bit operating System.

As most technologies, carbon capture processes have improved in the past and this trend can be expected to continue. With new carbon capture technologies such as physical adsorption, absorption solvents developments and nanotechnology, it is important to be able to explore the impact of such technology cost changes, in particular those associated with the carbon treatment and separation. This work focuses on amine solvent absorption technology as it is the most widely applied in industry. Cost reduction can be achieved through learning by doing, research and development and other methods. Estimations of cost reduction and development of learning curves have been studied by Rubin et al. (2007)

which their work included uncertainty and sensitivity studies while Rochedo and Szklo (2013) applied a unified method to compare different rates. These works among others give learning parameters that can easily be incorporated through the capture cost parameters employed in each period.

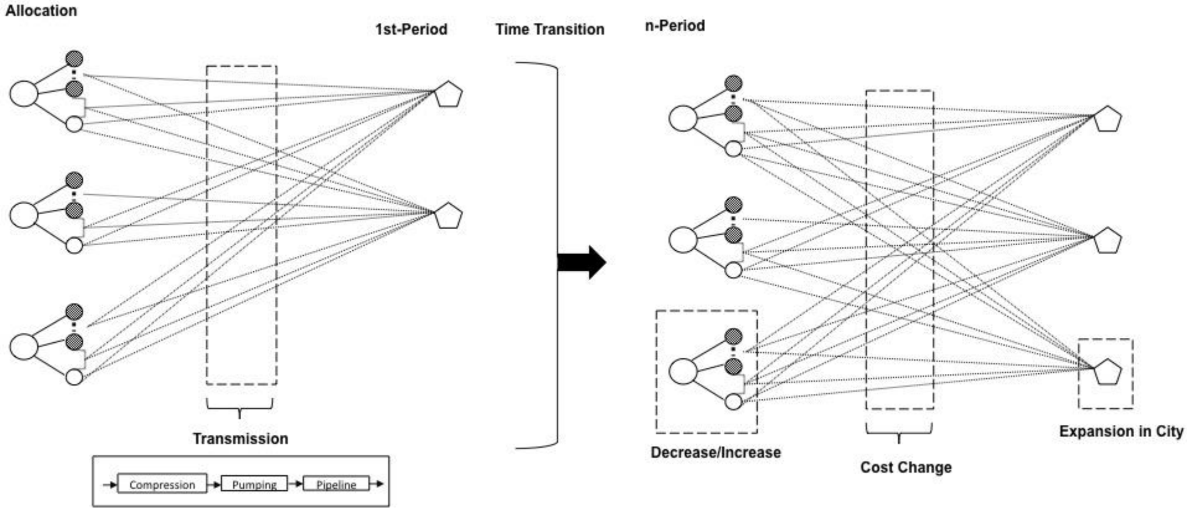

*Figure 1: Carbon Integration planning over time; filled circles represent treated sources, unfilled circles represent raw sources, and pentagons represent sinks (Al-Mohannadi and Linke, 2015)*

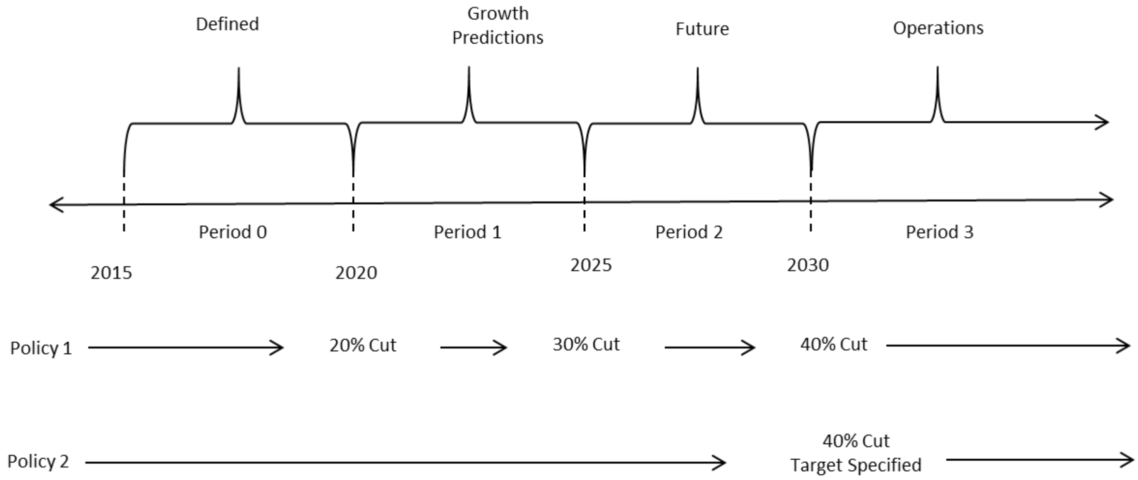

*Figure 2: Planning horizon with carbon footprint reduction policies*

## 3. Case Study

A case study was formulated and solved to illustrate the insights that can be gained from the proposed approach. The plant, source and sink, and transmission data as well as the distances between sources and sinks were taken from (Al-Mohannadi and Linke, 2015). In addition, the EOR capacity was assumed to decrease with time based on the logic explained in Dooley et al. (2010). A planning horizon of 15 y was assumed, represented by three five-year periods, with target cuts to be achieved in years 2020, 2025 and 2030. The first period is assumed to start in 2020 with the first target cut as described below. Expected technology enhancements leads to reductions in the costs of carbon removal from period to period. Costs were assumed to follow the general cost reduction due to learning, which was implemented following Rubin et al (2007). In the first period, three sources and three sinks were available, before the network expands in available sources and sinks (Figure 3). The EOR sink was considered to be technically feasible only from Period 2 onwards. Pipeline cost calculations were based on high pressure natural gas pipes.

Two alternative policies for footprint reduction were considered as illustrated in Figure 2. First, a fixed percentage cut was enforced to achieve an overall cut of 20 %, 30 % and 40 % by 2020, 2025 and 2030 (Policy 1). Second, the footprint reduction constraint was removed in the first two periods while the network had to also achieve the overall cut of 40 % by 2030 (Policy 2). Both policy options are examples of possible interpretations of carbon footprint reduction requirements.

Optimization results in the form of cost optimal networks are shown in Figures 3 (Policy 1) and 4 (Policy 2)

For Policy 1 the total cumulative cost of the carbon integration network was 305 million USD by the end of the third period. The network connections aim at minimizing total cost. Although carbon storage in aquifers is relatively costly, it was selected for its high carbon intake capacity in the first period. Enhanced Oil Recovery was the dominant sink from the second period onwards. More connections appeared in the last period to enable the target cut. Overall cost increased as more carbon dioxide was captured.

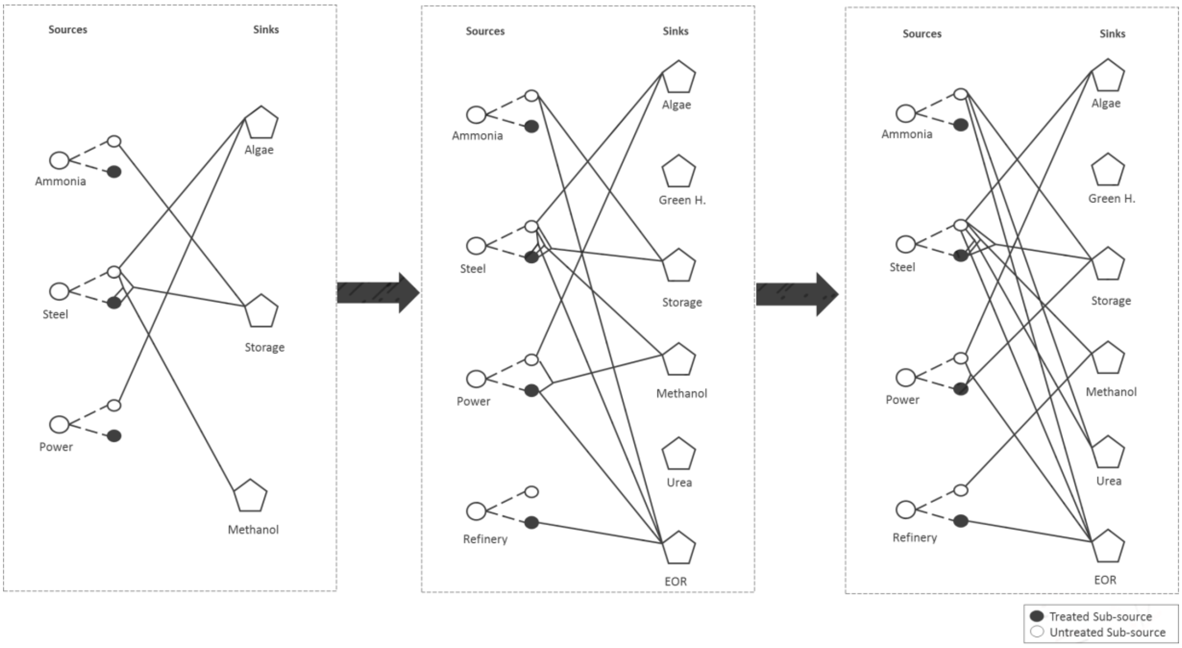

*Figure 3: Network Connections Overtime, period 1, period 2 and period 3 from left to right (Policy 1)*

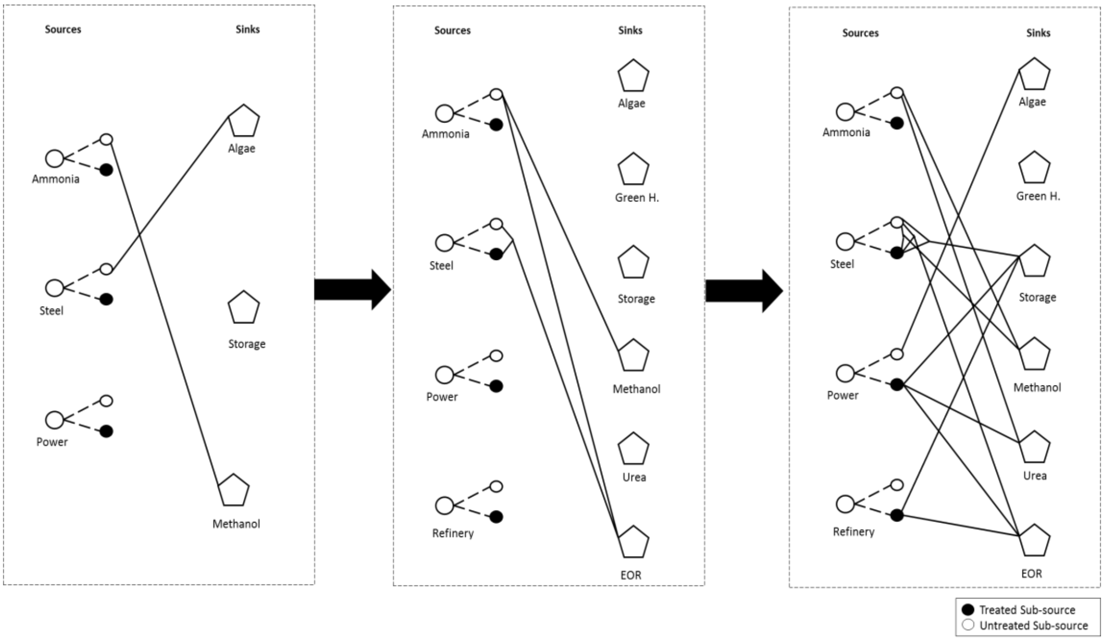

*Figure 4: Network Connections Overtime, period 1, 2 and 3 from left to right (Policy 2)*

For Policy 2, the identified cost optimal network is illustrated in Figure 4. The network remains simple in the first two periods, when the footprint reduction target is not enforced, and a complex network emerges for the last period to achieve the required footprint reduction of 40 %. The cumulative cost was 128 M USD by the end of the third period. Therefore, this one-step Policy 2 is significantly less expensive to follow than the phased reduction Policy 1. An impressive saving of approximately 60 % can be observed. This is understandable as the relaxed footprint reduction constraint gives room to generate networks that maximize profits in the first two periods without enforcing implementations of non-profitable reductions early on. The network changes in the second period aimed at pursuing the profitable EOR option. In contrast, Policy 1 enforced to reduce carbon early, eliminating the opportunity for profitability in the early periods, which resulted in clear underperformance compared to Policy 2.

By the end of the third period, the available networks from Policy 1 and Policy 2 have identical carbon footprints. Interestingly, both operating costs differ by only approximately 1 % so that the additional spent for Policy 1 will not be recovered over the useful life period of the capital investments. Interestingly, the carbon dioxide emission during the planning horizon differed by only 5 % between Policies 1 and 2.

The case study results highlight the significant impact policy making for the transition period towards carbon footprint reduction goals will have on the economics of carbon integration. Likewise, carbon footprint reduction goals might benefit from specifying cumulative emissions quotas for the transition period together with final period goals to enable the identification of policies that can achieve the minimum possible cost reductions for a given situation. Effective policies could then be derived from such solutions.

## 4. Conclusions

We have outlined a systematic approach to multi-period carbon integration. The approach allows to determine cost optimal carbon allocation networks over time to achieve desired overall footprint reductions. The optimization problem takes into account multiple sources, multiple utilization and storage options, capture processes, and compression and piping elements of the network. This allows different new technologies that can convert carbon dioxide can be incorporated to study their performance against current methods. A case study was presented to illustrate the multi-period carbon integration approach. The case study highlighted significant impact of footprint reduction policies on economics. It also illustrated the potential value of the approach to support effective policy making. Different expansion scenarios for an industrial park or a specific region can be explored using the proposed approach, giving both designers and policy makers a common tool to develop aligned future plans.

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