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On the Systematic Allocation of Natural Gas under Footprint Constraints in Industrial Clusters

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Natural gas can be monetized through a number of different paths including the sale as fuel or as different products from chemical conversions. The development of effective strategies for natural resource monetization is important for profitable resource utilization. Environmental concerns associated with natural gas monetization include carbon dioxide emissions linked to climate change, which has caused the global community to set significant carbon dioxide emission reduction targets. This presents the oil and gas sector with the challenge to contribute to emission reduction targets, whilst maintaining profitability of operations. This work integrates the recently proposed carbon integration approach for the identification of efficient carbon dioxide reduction options in industrial parks with a natural gas allocation model that takes into account alternative monetization paths. The resulting optimization-based approach can synthesize integrated natural gas and carbon dioxide networks for industrial cities that can meet carbon dioxide emissions constraints while maximizing the profitability of natural gas monetization. The application of the method is illustrated through an example of an industrial park considering typical processes associated with natural gas monetization and carbon integration.

1. Introduction

Natural gas is a key resource for global energy supply and a feedstock for the production of important basic materials. It is the fossil fuel that is associated with the lowest carbon footprint which is why it has been highlighted as an important transition fuel towards reduced global carbon emissions. Recent advances in shale gas technology have significantly boosted proven natural gas reserves and production worldwide. Natural gas monetization through various products has become an important pillar of many economies. It can be sold as fuel or converted to diverse sets of products using many alternative processing technologies. Monetization routes include production of Liquefied Natural gas (LNG), liquid fuels (GTL), methanol, ammonia, power generation, or water desalination. Each such option is associated with different profitability as well as different carbon dioxide emissions from energy inputs and carbon dioxide by-product generation. Consequently, different configurations of industrial clusters in terms of natural gas monetization processes will have different economic and emissions profiles.

In light of ambitious global carbon dioxide emissions reduction targets of 60 to 80 % (IPCC, 2014), the carbon dioxide footprint of gas monetization clusters will need to be carefully managed in future to support attainment of these goals. This will give rise to need to identify low cost carbon management strategies that exploit possibilities of carbon capture, utilization and storage (CCUS) and/or renewable energy (RE). To identify low cost CCUS strategies in industrial clusters, Al-Mohannadi and Linke (2016) have recently proposed the carbon integration approach. Carbon integration can consider capture and transportation infrastructures together with various carbon dioxide storage and utilization options, including enhanced oil recovery (EOR) and chemical and biological conversion routes. Carbon integration yields low cost carbon dioxide networks with beneficial allocations across various courses and sinks.

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The key design challenge addressed in this work is to develop profitable configurations of natural gas monetization processes while meeting overall emissions targets of the industrial cluster with the help of carbon integration to exploit CCUS options. The developed methodology takes the form of a network optimization problem that can be solved to identify effective synergies between natural gas conversion and carbon management. Given the importance of renewable power generation technologies in climate policies and their predicted rapid growth to cover a projected 50 % energy demand by mind 21st century (Prakash and Bhat, 2009), the model also considers renewable power generation options for the industrial clusters.
The remainder of the paper provides background, outlines the proposed approach and presents its application to an illustrative example. The detailed presentation of the full approach including the model formulation will be the subject of a future publication.

2. Background

Different process systems engineering approaches have been presented over the recent past to address two sub problems of carbon dioxide management and natural gas monetization. The former have a strong focus on determining carbon dioxide allocations to storage and EOR sites. For this problem, a source-sink representation for energy integration and carbon footprint targeting was proposed by Pekala et al (2010). Turk et al (1987) focused on CO2 delivery and allocation for geological storage options. Middleton and Bielicki (2009) considered infrastructure options in carbon capture and storage. Hasan et al (2014) propose an approach to optimize large-scale CO2 supply chain networks considering capture technology selection for different CO2 sources at the national level. Moving beyond carbon storage and EOR towards CCUS, Al-Mohannadi and Linke (2016) very recently proposed a systematic approach to the design of low cost carbon integration networks for industrial parks through integrated analysis of sources, utilization and storage options, as well as capture, separation, compression and transmission options. Their carbon integration approach considers capture and transmission options while evaluating different carbon dioxide converting processes. Figure 1 illustrates the carbon integration network synthesis representation. The results developed in Al-Mohannadi and Linke (2016) show how synergies between different plants creates opportunities to decrease the costs associated with carbon mitigation.

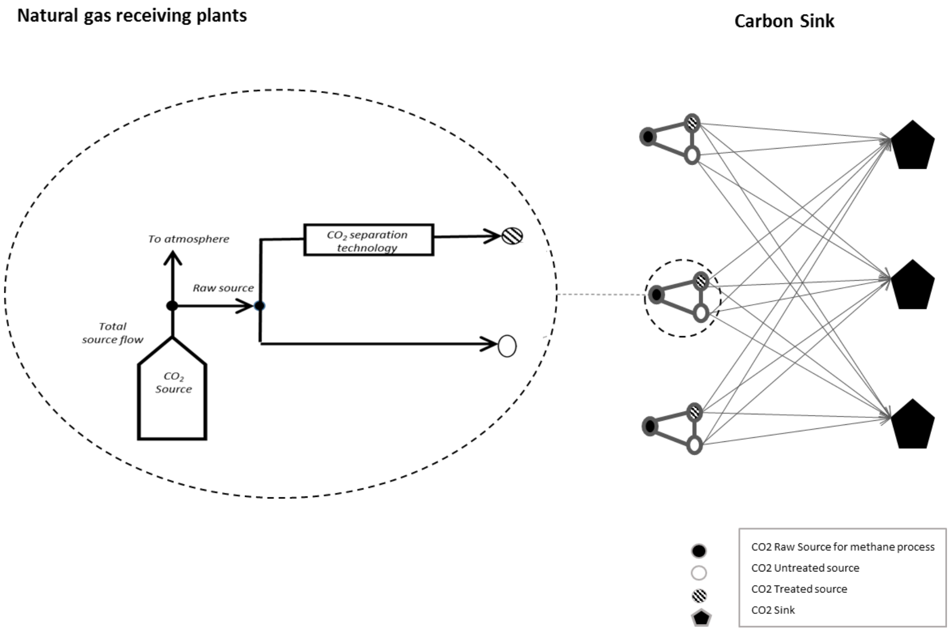

Figure 1: Carbon Integration representation (Al-Mohannadi and Linke, 2016)

Very little process systems engineering work has been published in the subject of natural gas monetization in industrial clusters. Very recently, Al-Sobhi and Elkamel (2015) propose an optimization approach to determine optimal gas allocations in an industrial cluster considering LNG, GTL, and methanol processing options.
This work is a first attempt to the development of a systematic approach that enables the simultaneous identification of economically optimal, carbon constrained natural gas monetization strategies for an industrial cluster that optimize natural gas monetization and carbon integration options simultaneously. The optimization-based approach is described in the next section.

3. Approach and Model

The overall goal is the identification of strategies for optimal natural gas monetization in an industrial cluster under an overall carbon dioxide emission constraint. In this paper, we limit our attention to clusters that utilize natural gas as the primary feedstock for its plants, the maximum supply of which is limited. Each plant receives natural gas supply from a common distribution infrastructure. In addition, each plant is connected to the existing electricity grid to facilitate power export or import. The cluster has sites available for expansion that could host additional natural gas converting plants or plants required to manage the carbon dioxide emissions of the cluster. The total carbon dioxide emission of the cluster of plants is comporised of all individual plant emissions and is constrained to an allowable total footprint.

The proposed synthesis representation is modular. A general plant unit is shown in Figure 2. It can be a sink for natural gas feedstock, a sink for carbon dioxide and a sink for imported power. In terms of outputs, a plant can produce products from conversions of natural gas and carbon dioxide or export power. It can have multiple point sources of carbon dioxide emissions. The carbon dioxide sources would normally be emitted to the athmosphere, but could be captured and reused in carbon dioxide sinks of plants in the cluster.

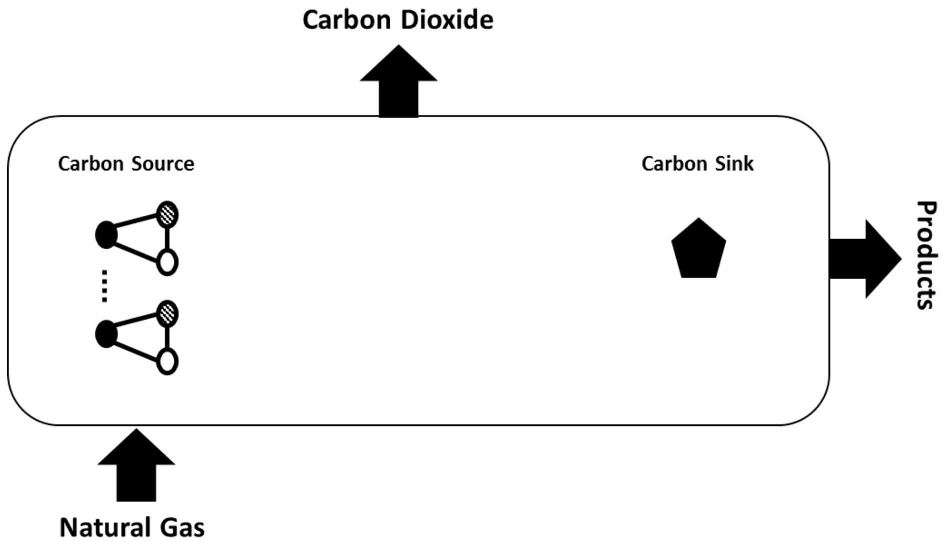

Figure 2: Plant unit

The industrial cluster consists of multiple plants and is represented as a network of interconnected resources and plants. The cluster has a source of natural gas connected to plants, a set of natural gas converting plants with known carbon dioxide sources (e.g. source flow and composition) and a number of carbon dioxide sinks with known capacity, pressure and composition requirements. The goal is to identify optimal natural gas and carbon source-sink allocation networks that maximizes the profitability of the cluster whilst not exceeding an allowable carbon dioxide emission limit. As in the carbon integration representation, carbon dioxide from plants can be allocated to carbon sinks in untreated, purified or mixed forms. Carbon sinks can receive carbon from various sources; mixed together to satisfy the sink's required purity. The representation of the cluster takes the form of a super structure that accounts for all possible connections across natural gas, plants, electricity grid, and carbon dioxide sources and sinks as shown in Figure 3. The representation further considers the introduction of renewable power generation capacity in the cluster electricity grid. A number of different renewable options can be considered that could potentially reduce carbon flow in natural gas fired power stations.

The objective is to maximize the profitability of the cluster. The formulation of the optimization problem takes the form of a Mixed Integer Nonlinear Program (MINLP). Income of the cluster may come from sales of natural gas products and carbon dioxide sinks while costs include the capital and operating costs of the added plants, treatment of carbon dioxide sources to the required sink purity, cost of compressing and transmitting carbon dioxide to the allocated sink, and capital and operating costs of renewable energy options.

Equality and Inequality constraints of the optimization problem 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 cost elements and connections between natural gas sinks and carbon source. Additional constraints on total city power balance coupled with the allowable limits on the extent of renewable energy use per technology are also part of the model.

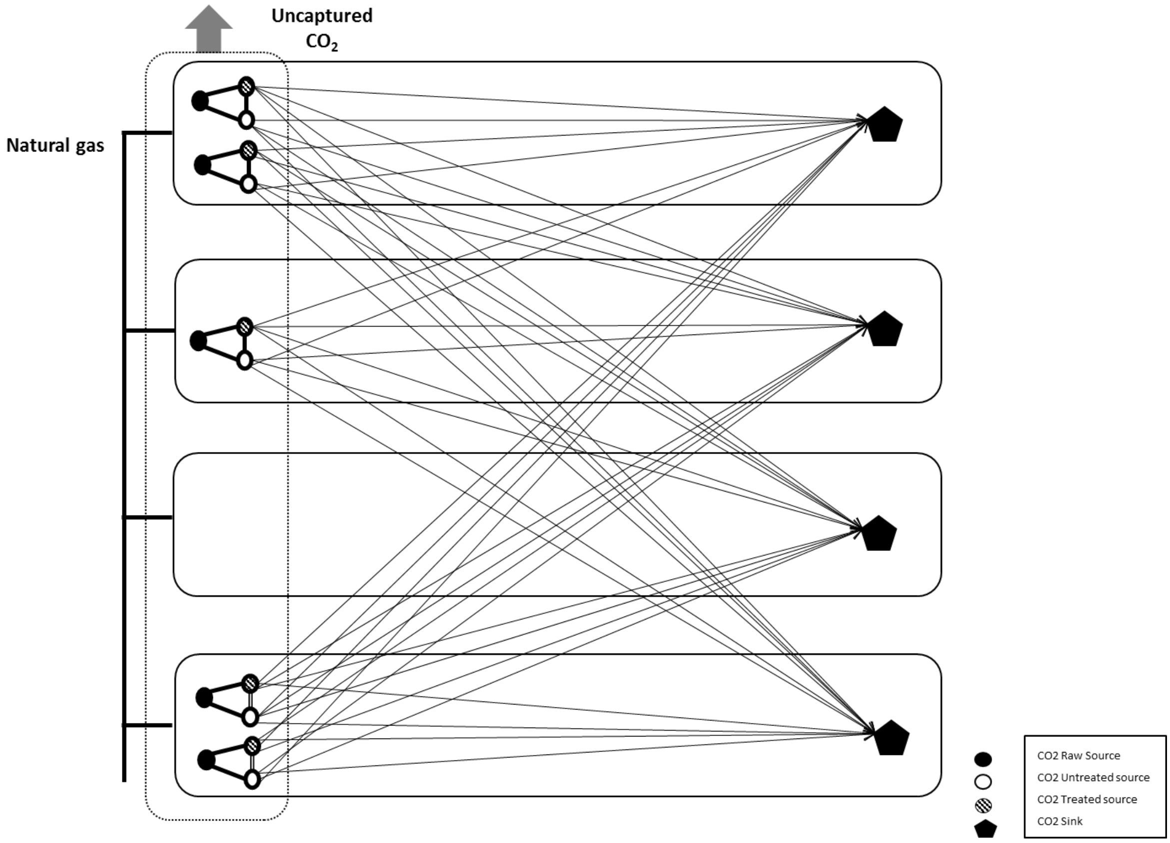

Figure 3: Superstructure representation

4. Case Study

The proposed approach is applied for an illustrative example of an industrial cluster. The cluster includes a set of existing and optional plants and processes, namely a methanol plant, an ammonia plant, an LNG plant, a power plant, a urea plant, Enhanced Oil Recovery (EOR) and geological carbon dioxide storage. Amine technology is assumed to be used to separate CO_2 from dilute carbon dioxide source streams. Natural gas receiving plants data include capital, operating costs in addition to natural gas requirement for a given capacity, power and footprints. The parameters and data needed for conventional methanol, ammonia, urea and LNG plants are based on estimations reported by Pellegrini et al, (2011), Ersayin and Ozgener, (2015), Economides, (2005), Vatani et al, (2014) and Velázquez et al, (2013). Carbon integration costs and parameters are given in Al-Mohannadi et al (2016).

A base case was first developed in which natural gas is monetized in existing processes with maximum profitability without constraints on carbon dioxide emissions. The base case yielded a solution that uses the maximum capacity of all natural gas receiving plants to maximize the overall profitability of the cluster, which was established at 2.83 billion dollars per annum. The collective footprint of the base case cluster is 15 million tons of carbon dioxide emitted per year.

Two cases are developed to illustrate the impact of reducing the base case emissions by 40 %. The results for the base case and reduced emissions Cases 1 and 2 are summarized in Tables 1.

Case 1 (conventional solution) maintains the natural gas monetization options of the base case and achieves the required carbon dioxide emissions reduction using a combination of commonly proposed options for mitigation (IPCC, 2014): geological storage, EOR and solar power generation using photovoltaics (PV) assuming location in a GCC country. The solar power generation data and cost parameters are taken from IRENA (2016). Solar power generation is set to the maximum capacity considered in the case study of 20 % of the natural gas power plant capacity. EOR is used to the maximum available capacity as a storage option due to its profitable operation. The remaining footprint reduction was achieved through geological storage (CCS).

The Case 1 solution yielded a profit of 2.21 billion USD per annum, i.e. the carbon dioxide emissions reduction requirement causes a significant drop in annual profit by USD 0.62 billion (22 %) over the unconstraint base case design.
Next, the integrated gas monetization and carbon integration model proposed in this work was solved to determine the cost optimal solution for the carbon footprint constrained gas monetization (Case 2). The resulting network has a profit of USD 2.89 billion dollars, i.e. a slight increase in profit over the base case despite the significant emissions reduction and a drastic improvement over Case 1 (conventional solution). Renewable energy (PV) is not deployed in the Case 2 solution. Natural gas is monetized in methanol, ammonia, LNG and the natural gas fired power plant. The carbon dioxide is managed as summarized in Table 2. The carbon integration network utilizes carbon dioxide from the ammonia plant in the Urea and EOR sinks to full capacity, and allocates additional carbon dioxide to storage. In addition, carbon dioxide from the LNG plant is allocated to the alternative methanol plant at maximum capacity.
The significant improvement of Case 2 over Case 1 result from the integrated assessment of options through the proposed optimization approach. Carbon dioxide is monetized into value added products and costly renewable energy options are avoided.

Table 1: Natural gas allocated in tons/day

Plants	Base Case	Case 1: Conventional Solution	Case 2: Optimized Solution
Methanol (Conventional)	6,118	6,118	6,118
Ammonia	216	216	216
LNG	10,462	10,462	10,462
Power Plant (Natural gas fired)	1,861	1,660	2,028
PV Used	0 %	20 %	0 %
Cost of Network	2.83 billion USD	2.21 billion USD	2.89 billion USD

Table 2: Carbon dioxide allocations for Case 2 (t/d)

Plants	Methanol Conventional	Ammonia	LNG	Power	Urea	EOR	Storage	Methanol Sink
Ammonia	0	0	0	0	9,004	6,317	5,679	0
LNG	0	0	0	0	0	0	0	1,893
Power	0	0	0	0	0	0	0	0
Urea	0	0	0	0	0	0	0	0
EOR	0	0	0	0	0	0	0	0
Storage	0	0	0	0	0	0	0	0
Methanol	0	0	0	0	0	0	0	0

5. Conclusions

An optimization-based approach to the development of networks that can simultaneously exploit synergies between natural gas monetization and carbon integration. The approach integrates the recently proposed carbon integration approach for the identification of efficient carbon dioxide reduction options in industrial parks with a natural gas allocation model that takes into account alternative monetization paths. The resulting optimization-based approach can synthesize integrated natural gas and carbon dioxide networks for industrial cities that can meet carbon dioxide emissions constraints while maximizing the profitability of natural gas monetization. A case study is solved illustrated the application of the approach and highlighted significant savings over ad-hoc solutions based on policy recommendations (RE and CCUS).

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