SYSTEMATIC METHODS FOR THE DESIGN OF INDUSTRIAL CLUSTERS WITH CAPPED CARBON EMISSIONS

A Dissertation

by

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ABSTRACT

Hydrocarbon resource centric economies, such as Qatar, are highly vulnerable to the impact of climate policy. Climate policies could decrease demand of hydrocarbon, lowering prices and would force countries to adopt mitigation technologies. Thus, having a climate strategy is important to meet future constraints. This work develops approaches to enable policy makers to systematically explore alternative emissions reduction paths in an integrated framework. The methods introduced explore the element of time, resources management, Carbon Capture Utilization and Sequestration (CCUS) and energy integration including Renewable Energy (RE) use. The industrial city or cluster is taken as a system and modelled through balances and constraints, which were optimized applying deterministic solvers. Two approaches were developed. The first is a multi-period carbon planning approach that enables the assessment of different carbon dioxide reduction options, which may be applied to guiding transitions to a future target emission. Second is a systematic approach that enables the identification of economically optimal natural gas allocation in different conversion technologies under carbon emission targets with energy synergy. The multi-period planning approach identified allocation of carbon dioxide between sources and potential sinks in each period, compared cost elements simultaneously and resulted in a low cost network across all periods. Furthermore, the role of RE was investigated through a robust MILP. The results highlighted significant differences in economic impact of alternative footprint reduction policies. The systematic natural gas monetization approach simultaneously determined natural gas monetization and carbon dioxide management through CCUS as well as RE strategies. The method considered heat and power integration, enabling the assessment of the Natural gas (CH_4), CO_2 and Energy nexus. Several case studies were solved that indicated benefits of having optimized policies that screen all mitigation options given economic and environmental objectives out preformed adopted prescribed policies found around the globe.

DEDICATION

To my parents, thank you.

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NOMENCLATURE

Sets

C	is a set of products produced in industrial city
E	is a subset of existing plants that belong to set P
EC	is a set of combustible fuel options for power generation
ER	is a set of renewable energy options for power generation
G	is a set of steam turbine
GT	is a set of gas turbine
H	is a set of steam generation options (including renewable energy produced in plant p per level i
I	is a set of steam level
J	is a set of turbine levels
K	is a set of carbon sinks
K_p	is a set of carbon sinks in plant p
K_p	is a set of carbon sinks in plant p
M	is a set of steam sources in plant p
O	is a subset of optional plants that belong to set P
P	is a set of plants
Q	is a set of power type options in industrial city
Q	is a set of power generation options (including renewable energy produced in plant p

S	is a set of carbon sources
$S_{c,p}$	is a set of carbon sources produced in plant p associated with product c
SG	is a set of linear cost segments
T	is a set of carbon treatment technology
TP	is a set of time periods
W	is a set of steam sinks in plant p per

Subscripts

c	product
ec	combustible fuel option for power production
er	renewable energy option for power production
h	heat type
i	steam level
j	steam turbine level
k	carbon sink
k_p	carbon sinks in plant p
m	energy source
p	plants
q	power type
s	carbon source

sg	linear cost segments
t	carbon treatment technology
tp	time periods
w	energy sink

Superscripts

Compression, Capex_T	refers to a compressor unit capital cost charge/parameter for a treated allocation
Compression, Capex_U	refers to a compressor unit capital cost charge/parameter for an untreated allocation
Compression, Opex_T	refers to a compressor unit operating cost charge/parameter for a treated allocation
Compression, Opex_U	refers to a compressor unit operating cost charge/parameter for an untreated allocation
Treatment, Capex_T	refers to a treatment unit capital cost charge/parameter for a treated allocation
Treatment, Opex_T	refers to a treatment unit operating cost charge/parameter for an untreated allocation
Transmission, Capex_T	refers to a pipeline capital cost charge/parameter for a treated allocation

Transmission, Capex_U	refers to a pipeline capital cost charge/parameter for an untreated allocation
Transmission, Opex_T	refers to a pipeline operating cost charge/parameter for a treated allocation
Transmission, Opex_U	refers to a pipeline operating cost charge/parameter for an untreated allocation

Variables

$C_{k,tp}^{Sinks}$	is the total cost of processing carbon dioxide in sink k in time period tp
$C_{k,tp}^{Compression}$	is the carbon dioxide compression total cost connected to sink k in time period tp
$C_{k,tp}^{Compression,\ Capex}$	is the carbon dioxide compression capital cost connected to sink k in time period tp
$C_{k,tp}^{Treatment}$	is the carbon dioxide treatment unit total cost connected to sink k in time period tp
$C_{k,tp}^{Treatment,\ Capex}$	is the carbon dioxide treatment unit capital cost connected to sink k in time period tp
$C_{k,tp}^{Transportation}$	is the carbon dioxide transportation total cost connected to sink k in time period tp
$Cost^{Comp}$	is the cost of compressing carbon dioxide to a sink

$Cost^{Pipe}$	is the cost of transportation accounts for the pipeline overall costs of carbon dioxide flow to a carbon dioxide sink
$Cost^{Treatment}$	is the cost of treatment and separation of carbon dioxide to fit into the requirements of sink
$Cost^{CO2}$	is the cost of carbon dioxide
$Cost^{CI}$	is the cost of carbon integration network
$Cost^{EP}$	is the cost of existing plants
$Cost^{M}$	is the cost of methane
$Cost^{OP}$	is the cost of optional plants
C^{Sinks}	Sink cost
C^{LINE}	transmission line cost
$C^{Renewables}$	renewable energy cost
Elec	is the price of electricity
$F^{LINE\_T}_{s,k,t,tp,sg}$	transmission line capacity that is also used as an upper flow bound associated with the treated flow allocated from source s to sink k using treatment t in time period tp, that is costed using segment sg
$F^{LINE\_U}_{s,k,tp,sg}$	transmission line capacity that is also used as an upper flow bound associated with the untreated flow allocated from source s to sink k in time period tp, that is costed using segment sg
$F^{c}{}_{c,p}$	is the flow of product c in existing plant p

$F_{k,p}^{CO2}$	is the carbon dioxide flow into the sink
$F^{CO2}{}_{c,p}$	is the unallocated carbon dioxide from product c production in plant p
$F_{k,tp}$	is the total flow in the pipe to sink k in period tp
$F_{k,tp}^{CO2}$	is carbon dioxide flow in sink k in time period tp
$F_{Methane}^{utility}$	is the methane mass flowrate from the utility system
$F_{Methane}^{utility}$	is the CO_2 mass flowrate from the utility system
$F_{methane}$	is the total flow of methane to the industrial city
F_p	is the methane flow to a plant p
$h^{inlet,hdr}$	is the specific enthalpy of steam entering the steam header
h^{hdr}	is the specific average enthalpy of the steam header:
$\Delta h^{is}{}_{i,j,g}$	is the isentropic enthalpy across turbine g level j
Δh^{gen}	is the heat required to generate one unit of steam
$I_{s,k,tp}$	is the combined flow from treated and untreated source s to sink k in time period tp
$I_{s,k,tp}^{max}$	is the maximum combined integrated flow from treated and untreated source s to sink k in time period tp
$I^{o}{}_{p}$	is a binary variable (0,1) which defines the activation of an optional plant p
m^{stm}	is the boiler current steam load
$M_{s,c,p}$	is the available flow of carbon dioxide from source s in plant p associated with product c

$m_i^{inlet,hdr}$	is the mass flowrate of the steam into a steam header/level i.
$m_{m,h,p,i}$	is the waste heat recovered from an energy source process m of type h steam in plant p at steam level i
$m_{j,g,i}$	is the mass flowrate of steam through turbine g in turbine level j to steam header i
m_i^{LS}	is the steam mass flowrate into header i through a let-down station
m_{HRSG}	is the steam mass flowrate from the HRSG.
$m_i^{outlet,hdr}$	is the steam mass flowrate at the header outlet.
$m_{i,w,p}$	is the steam demand of steam level i to energy sink w in plant p
$m_{t,s,p,i}$	is the energy demand of treatment unit t in carbon source s in plant p
NC_{tp}	is carbon dioxide net capture target in time period tp
NCRT	is the net carbon dioxide reduction target
$P_{ec,tp}$	Power use of combustible fuel ec in time period tp
$P_{er,tp}$	Power use of renewable energy ec in time period tp
$P_{p,q}$	is the power output from plant p with type q
P^{ST}	is the power generated from steam turbines
P^{GT}	is the power generated from gas turbines
P_{export}	is the power imported from the industrial city power plant and exported to the grid
PR	is the power demand from industrial park processes.

Q^{BF}	is the energy from natural gas combustion in the boiler needed to generate steam
Q^{GT}	is the heat flow rate from the gas turbine
Q^{stm}	is the energy needed to generate steam.
$R_{s,c,p}$	is the raw carbon flow from plant p source s associated with product c
$R_{s,tp}$	is the available carbon raw source flow from source s in time period tp
REV^{c}	is the revenue from products and associate by-products
REV^{CO2}	is the revenue from carbon dioxide sinks
TC	total cost of CCUS network
$T_{s,c,p,k,p,t}$	is the treated carbon flow from sources s of product c in plant p through treatment unit t to sink k in plant p
$T_{s,k,t,tp,sg}$	treated flow allocated from source s to sink k using treatment t in time period tp, that is associated with cost segment sg
$T_{s,k,t,tp}$	is the treated carbon dioxide flow from source s to sink k out of treatment unit t in time period tp
$U_{s,c,pk,p}$	is the untreated carbon flow from sources s of product c in plant p to sink k in plant p

$U_{s,k,tp}$	is the untreated carbon dioxide flow from source s to sink k in time period tp
$U_{s,k,tp,sg}$	untreated flow allocated from source s to sink k in time period tp, that is associated with cost segment sg
$W_{j,g}$	is the power generated by steam turbine g in turbine level j
$X_{s,c,p,k,p}$	is a binary (0,1) associated with flow of treated and untreated streams for the pipeline connecting source s in plant p to sink k in plant p
$X^{Opex}_{s,k,t,tp}$	is a binary that accounts for the activation of a connection between two periods, for carbon source s to carbon sink k through treatment t in time period tp
$X^{p}{}_{p,q}$	is a variable which represent the amount of power type q used in existing plant ep and optional plant op respectively
$X_{s,k,tp}$	is a binary (0,1) associated with flow of the combined treated and untreated streams in any plant
$X_{j,g}$	is a binary (1,0) associated with steam turbine
$X^{T}_{s,k,t,tp,sg}$	binary variable associated with the treated flow allocated from source s to sink k using treatment t in time period tp, that is costed using segment sg
$X^{U}_{s,k,tp,sg}$	binary variable associated with the untreated flow allocated from source s to sink k in time period tp, that is costed using segment sg

$y^{\text{LINE\_T}}_{s,k,t,tp,sg}$	transmission line capacity from source s to sink k using treatment t in time period tp that is costed using segment sg
$y^{\text{LINE\_U}}_{s,k,tp,sg}$	transmission line capacity from source s to sink k in time period tp, that is costed using segment sg

Parameters

$A^{\text{Compression}}_{k,tp}$	Operating cost parameter for compression, associated with each active connection to sink k in time period tp
$A^{\text{Treatment}}_{k,tp}$	Operating cost parameter for treatment, associated with each active connection to sink k in time period tp
$A^{\text{Transportation}}_{k,tp}$	Operating cost parameter for pipeline, associated with each active connection to sink k in time period tp
A	in the annualization factor,
a	Slope value associated with the linear cost model, per segment
b	Intercept value associated with the linear cost model, per segment
$B^{\text{treatment capital}}$	treatment unit capital cost parameter
$C^{\text{compression, Opex A}}_{s,k,tp}$	is the carbon dioxide active operating compression cost parameter of source s to sink k in time period tp
$C^{\text{Compression, Opex I}}_{s,k,tp}$	is the carbon dioxide inactive operating compression cost parameter of source s to sink k in time period tp

$C^{\text{Sinks, Cost}}_{k,tp}$	is the carbon dioxide cost processing parameter in sink k in time period tp
$C^{\text{Treatment, Opex A}}_{s,k,tp}$	is the carbon dioxide active operating treatment cost parameter of plant source s to sink k in time period tp
$C^{\text{Treatment, Opex I}}_{s,k,tp}$	is the carbon dioxide inactive operating treatment cost parameter of plant source s to sink k in time period tp
$C^{\text{Transporation, Capex}}_{k,tp}$	is the carbon dioxide transportation capital cost connected to sink k in time period tp
$C^{\text{Transporation, Opex A}}_{s,k,tp}$	is the carbon dioxide active operating transportation cost parameter of plant source s to sink k in time period tp
$C^{\text{Transporation, Opex I}}_{s,k,tp}$	is the carbon dioxide inactive operating transportation cost parameter of plant source s to sink k in time period tp
$C^{\text{Renewable Steam}}$	is the renewable energy steam type h of level i imported to the city.
C^{c}_{c}	is the products price
$C^{\text{capex}}_{c,p}$	is the capital cost of a plant
$C^{\text{CO2}}_{k,p}$	is the price paid for carbon dioxide to produce products in sinks
C^{M}_{p}	is the methane price
$C^{\text{opex}}_{c,p}$	is the operating cost of a plant
$C^{\text{Treatment, opex}}_{c,p}$	is the carbon dioxide treatment capital cost parameter associated with product c in plant p
$C^{\text{Treatment, capex}}_{c,p}$	is the carbon dioxide treatment capital cost parameter associated with product c in plant p

$C_{c,p}^{Pipe, capex}$	is the carbon dioxide pipeline capital cost parameter associated with product c in plant p
$C_{c,p}^{Pipe, opex}$	is the carbon dioxide pipeline operating cost parameter associated with product c in plant p
$C_{c,p}^{Comp, capex}$	is the carbon dioxide compression capital cost parameter associated with product c in plant p
$C_{c,p}^{Comp, opex}$	is the carbon dioxide compression operating cost parameter associated with product c in plant p
$C^{PW}{}_{c,p,q}$	is the power price associated with product c in plant p for type q
CE	is the carbon emission
CEL	is the carbon emission limit
EF_{ec}	emission factor associated with combustible fuel ec
ER_{er}	emission factor associated with renewable energy er
$G_{er,tp}^{Renewables}$	is the renewable energy er electricity price in period tp
$G_{ec,tp}^{Fuel}$	is the fuel ec electricity price in period tp
$G_{k,tp}{}^{max}$	maximum flow requirement associated with sink k in time period tp
$G_{k,p}{}^{max}$	is the sink flow requirement
$H_{s,c,p,k,p}$	is the distance between source s and sink k
hy	number of operating hours per year

$I_{k,tp}^{Treatment}$	Operating cost parameter to maintain treatment unit, when a previously existing connection is not utilized in subsequent periods (hence becomes inactive)
$I_{k,tp}^{Compression}$	Operating cost parameter to maintain compression unit, when a previously existing connection is not utilized in subsequent periods (hence becomes inactive)
$I_{k,tp}^{Transportation}$	Operating cost parameter to maintain a pipeline, when a previously existing connection is not utilized in subsequent periods (hence becomes inactive)
$L_{s,tp}$	is the minimum carbon available flow of source s in time period tp
$L_{s,tp}$	lower flow bound for source s in time period tp
$l_{tp}^{Treatment}$	is a parameter that accounts for the capital replacement of treatment
$l_{tp}^{Compression}$	is a parameter that accounts for the capital replacement of compression
$l_{tp}^{Transportation}$	is a parameter that accounts for the capital replacement of transportation
L	is the minimum carbon dioxide flow in a pipeline
$L_{s,k,t,tp,sg}^{LINE\_T}$	lower flow bound associated with the treated flow allocated from source s to sink k using treatment t in time period tp, that is costed using segment sg

$L^{LINE\_U}_{s,k,tp,sg}$	lower flow bound associated with the untreated flow allocated from source s to sink k in time period tp, that is costed using segment sg
$L^{FUEL}_{ec,tp}$	lower limit for percentage use allowed from combustible fuel ec in time period tp
$l^{Treatment}_{tp}$	is a parameter that accounts for the capital replacement of treatment
$l^{Transportation}_{tp}$	is a parameter that accounts for the capital replacement of transportation
$l^{Compression}_{tp}$	is a parameter that accounts for the capital replacement of compression
$L_{s,c,p}$	is lower carbon flow available from source s associated with product c in plant p
$L^{c}_{c,p}$	is the lower bound for flow of product in existing plant p
$L^{p}_{p,q}$	is the specified lower allowed fractions of power type q in plant p
L^{pipe}	is the lower flow limit of source-sink connection within a pipeline
$LF_{methane}$	is the lower methane flow available to the industrial city use
LPR	is the minimum possible power output of the city
$L^{RENEWABLES}_{er,tp}$	lower limit for percentage use allowed from renewable energy er in time period tp

$M^{LINE\_T}_{s,k,t,tp,sg}$	upper flow bound associated with the transmission line capacity from source s to sink k using treatment t in time period tp, that is costed using segment sg
$M^{LINE\_U}_{s,k,tp,sg}$	upper flow bound associated with the transmission line capacity from source s to sink k in time period tp, that is costed using segment sg
$M^{FUEL}_{ec,tp}$	upper limit for percentage use allowed from combustible fuel ec in time period tp
$M^{RENEWABLES}_{er,tp}$	upper limit for percentage use allowed from renewable energy er in time period tp
$M^{c}{}_{c,p}$	is the higher bound for flow of product in existing plant p
M^{pipe}	is the upper flow limit of source-sink connection within a pipeline
$MF_{methane}$	is the maximum methane flow available to the industrial city use
MPR	is the maximum possible power output of the city
$M_{s,tp}$	is the maximum carbon available flow of source s in time period tp
M	is the maximum carbon dioxide flow in a pipeline
$N^{LINE\_T}_{s,k,t,tp,sg}$	lower flow bound associated with the transmission line capacity from source s to sink k using treatment t in time period tp, that is costed using segment sg

$N_{s,k,tp,sg}^{\text{LINE\_U}}$	lower flow bound associated with the transmission line capacity from source s to sink k in time period tp, that is costed using segment sg
$n_{j,g}$	is the efficiency of the steam turbine p in turbine level j
$P_{k,p}^{CO_2}$	is the pressure required at the carbon dioxide sink
P_{policy}^{import}	is the maximum power can be imported to the grid set by the user
P_{policy}^{export}	is the maximum power can be exported to the grid set by the user
PR_{tp}	power requirement in time period tp
$U^{p}{}_{p,q}$	is the specified upper allowed fractions of power type q in plant p.
$y_{s,p}$	is the treated carbon flow composition from sources s in plant p
$y^{u}{}_{s,p}$	is the untreated carbon flow composition from sources s in plant p
$y_{s,tp}$	composition of raw source s in time period tp
$y_{s,t,tp}$	composition of treated source s in time period tp
$y^{u}{}_{s,tp}$	is untreated source composition of source s in time period tp
$Z_{k,tp}{}^{min}$	minimum composition requirement associated with sink k in time period tp
$Z_{k,p}{}^{min}$	is the sink minimum concentration requirement, weight fraction
α	Time value factor associated with capital cost charges
β	Time value factor associated with operating cost charges

$\gamma_{t,tp}$	is amount of carbon dioxide emitted from the treatment unit t energy use in time period tp
γ_{t}	is amount of carbon dioxide emitted from the treatment unit energy use
ε_{p}^{CH4}	is the of methane required per unit of power.
ε_{p}^{p}	is the carbon dioxide mass emission per unit of power.
$\varepsilon^{t}{}_{t}$	is the treatment unit carbon removal efficiencies
ε_{tp}^{p}	accounts for the power use carbon footprint in time period tp
$\varepsilon_{t,tp}$	is the treatment unit carbon removal efficiency of treatment t in time period tp
$\varepsilon^{t}{}_{t,tp}$	treatment emission factor by treatment unit t in time period tp
η^{Blr}	is the boiler thermal efficiency
η_{k}	is the sinks efficiency
$\eta_{k,tp}$	is the sink k efficiency in time period tp
η	pump efficiency
$\Phi^{c}{}_{s,c,p}$	is a parameter associated with each defined carbon dioxide source s per product c in plant p
$\varphi^{c}{}_{c,p}$	is a parameter which represents the required methane intake per product c in plant p
$\varphi^{PW}{}_{c,p,q}$	is a parameter, which represents the required/generated power in plant p of type q

$\Phi^{CO2,\ utility}$	is a parameter associated with each defined carbon dioxide per unit of energy
$\Phi^{CH4,\ utility}$	is a parameter associated with each defined methane per unit of energy

Units

d	day
h	hours
k	kilo
kg	kilogram
km	kilometer
kWh	kilowatts per hour
MMBtu	one million British Thermal Units
MW	Megawatts
t	tons
USD	United States Dollars (currency)
wt%	weight composition
mi	miles
mol%	molar composition
y	year
$	United States Dollars (currency)

1 INTRODUCTION

At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The agreement sets out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C. Some regions such as the European Union (EU) have already committed to a 20% CO_2 reduction target by 2020, to be increased to 80% by 2050 (European Commission). Similarly, the United Kingdom adopted a proposal to reduce its carbon footprint by 80% by the year 2050 with hope to reduce it further (Harvey, 2018). For a country such as Qatar, the majority source of wealth and CO_2 emission stems from industrial cities where natural resources, natural gas and oil, are processed and converted to value added products. The ambitious carbon reduction targets pose challenges for the energy intensive industrial sectors to manage their carbon footprints. While, Qatar does not have a reduction target yet, it has ratified the COP 21 agreement. Moreover, Qatar have committed to the Qatar National Development Strategy (MDPS, 2011) that aims at balancing economic growth and environmental development, which includes carbon emission reduction efforts. Thus, there is a need to develop methods that can estimate carbon reduction policies, find the most sustainable reduction paths that can sustain growth and adhere to global reduction targets. This research will address the highlighted issues through the development of integrated systematic methods to enable the design of sustainable industrial parks under carbon dioxide limits**.**

Process system engineering optimization models, for plant level to multiple plants, could be used to create symbiosis through the exchange of materials or energy thus leading to the design of sustainable eco-industrial parks. Linnhoff and Hindmarsh (1983) introduced a targeting approach for energy recovery within a plant, pinch analysis, which paved the way to include multiple plants (Dhole and Linhoff et al, 1993). Grossmann and Papoulias. (1983) used heat integration for a process to reduce energy and raw material cost. El-Halwagi and Manousiouthakis (1989) introduced mass exchange networks that targets and optimizes materials exchange. Wang and Smith (1994) used a graphical technique to target and design for minimum wastewater generation and fresh water use via re-use. Lovelady and El-Halwagi (2009) introduced mass-integration network for water use using source-sink representation with common interception for the whole industrial city. Alnouri et al (2014, 2015) developed approaches for interplant water use and waste management in an industrial cluster. Lee and Hashim (2014) formulated a MILP to determine the cost optimal power generation mix including fuel switching, the use of renewable energy and Carbon Capture and Storage (CCS). Interplant energy integration in Eco Industrial Parks (EIPs) was studied by Chae et al. (2010) and systematic approaches have been proposed to target and design for waste heat integration (e.g. Stijepovic and Linke, 2011, Stijepovic et al., 2012). Optimized carbon dioxide from multiple sources in an industrial city to a common carbon capture with variation in the concentration and volume captured (Norstebo et al, 2012). Carbon Integration (CI), developed by Al-Mohannadi and Linke (2016), allows integrated analysis of the many possible utilization options together with the capture, separation, compression and transmission of carbon dioxide from multiple carbon dioxide sources of varying flow and quality is required to identify the most economically attractive footprint reduction solutions in an industrial park.

In this research a multi-period approach was developed that incorporates the time dimension of the carbon reduction problem, which is crucial in developing a plan from a regulatory point of view and aids industrial parks designers to screen potential technologies of CCUS and RE. More importantly, the effect of carbon reduction on the resource allocation and monetization decisions by introducing a method that explores gas monetization options under emission targets.

The industrial city or cluster is taken as a system and modelled through balances and constraints, which were optimized applying deterministic solvers. Therefore, in an attempt to design a sustainable system industrial city, the proposed work aims to evaluate and optimize carbon reduction policies and strategies, through systematic mutli-period carbon integration approach in chapter 2 and to develop an integrated approach to allocate natural gas under carbon emission targets with energy integration including renewable energy use in chapter 3. In each chapter a literature review, model and examples were solved to illustrate the applicability of the methods

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2 EVALUATING POLICIES AND CARBON REDUCTION STRATEGIES[*]

The threat of dangerous climate change has led to calls for drastic carbon dioxide emission reductions (IPCC, 2014). This would require significant emissions cuts across most industry sectors. Many policy-making entities have proposed ambitious carbon dioxide emission reduction targets as a means of mitigating global warming effects. Since the industrial sector is substantially responsible for most carbon emissions, industries are constantly being challenged to implement effective emission reduction measures. A number of conventional methods may be applied to reduce carbon dioxide emissions, such as: (1) the utilization of energy efficient technologies, (2) energy integration (3) fuel switching to less carbon intensive options, (4) the use of renewable energy sources, and (5) carbon capture, utilization and storage (CCUS). This chapter extends the carbon integration approach presented in Al-Mohannadi and Linke (2016) to enable multi-period planning. The ability to consider a planning horizon is important, because carbon dioxide emission reduction policies and strategies advocate cuts (or sequences of cuts depending on the reduction strategy) over a time horizon so as to have achieved a certain emissions reduction at a future date, which is typically many years into the future. Therefore, besides identifying a network that can achieve a certain emissions cut at low cost, it is equally important to consider the network transitions of the original carbon integration network into the future network with a reduced footprint that corresponds to the target.

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2.1 Multi-period Carbon Integration

2.1.1 Literature review

Multi-period planning problems are common in process systems engineering and include problems such as reactor design (Rooney and Biegler, 2000), hydrogen network design (Heever and Grossman, 2003), heat exchange network synthesis (Isafiade and Fraser, 2010) and water network synthesis (Bishnu et al, 2014). Multiperiod heat and mass exchange networks was investigated by Papalexandri and Pistikopolous (1994) to minimize the total cost. Heat and power production with carbon reduction over a time horizon was analyzed by Rong and Lahdelma (2007) using a stochastic optimization approach, while Mirzaesmaeeli et al (2010) proposed power planning for a specific regional expansion plan Koltsaklis et al (2014) developed a multiperiod MILP to design an energy mix to meet the expected electricity demand, while satisfying environmental constraints in terms of CO_2 emissions.Carbon reduction planning over time horizons have previously been investigated, with a focus on reducing energy use and designing Carbon Capture and Storage (CCS) networks. Zhang et al (2012) studied the impact of different policies for carbon targets on China’s power sector. Kemp and Kasim (2010) studied the optimization of carbon dioxide allocation network in storage sites on a specific region. Spatial multi-period optimization of carbon networks was also explored by Johnson et al (2011).

Multi-period planning also has useful applications in carbon dioxide storage allocation studies (He et al, 2013). Elhai et al (2014) explored multi-period CCS network optimization with simultaneous consideration of transportation and source sink matching. Graphically, Diamante et al (2014) applied a pinch approach for CCS targeting while considering multiple time periods and regions. While, Pourhashema et al (2016) studied the time effect of mitigation strategies have on biofuels production. However, this work is the first work that considers multi-period carbon integration in industrial parks.

The next section presents the problem statement and representation for multi-period Carbon integration planning for an industrial cluster, followed by the formulation of the optimization problem. The optimization problem is then solved for an illustrative case study.

2.1.2 Problem Statement

This work builds upon the problem statement and representation for carbon integration in a single period presented in Al-Mohannadi and Linke (2016). Figure 2-1 summarizes the network representation. A stationary carbon source can be captured and processed in its original composition (untreated source), or processed through a carbon dioxide separator to obtain an enriched carbon dioxide stream (treated source). Each untreated and treated source can be allocated to any of the carbon dioxide sinks that may exist or may be added to the industrial cluster. Carbon dioxide transmissions from source to sink involve compression and pipeline placement.

Figure 2-2 illustrates the multi-period carbon integration planning problem. A given industrial cluster (at time period tp=0) needs to be carbon integrated to meet a given carbon emissions constraint at the end of the planning horizon (final time period tp=TP). Additional, intermediate carbon emissions constraints may be applied in each intermediate time period tp=1, …, TP-1.

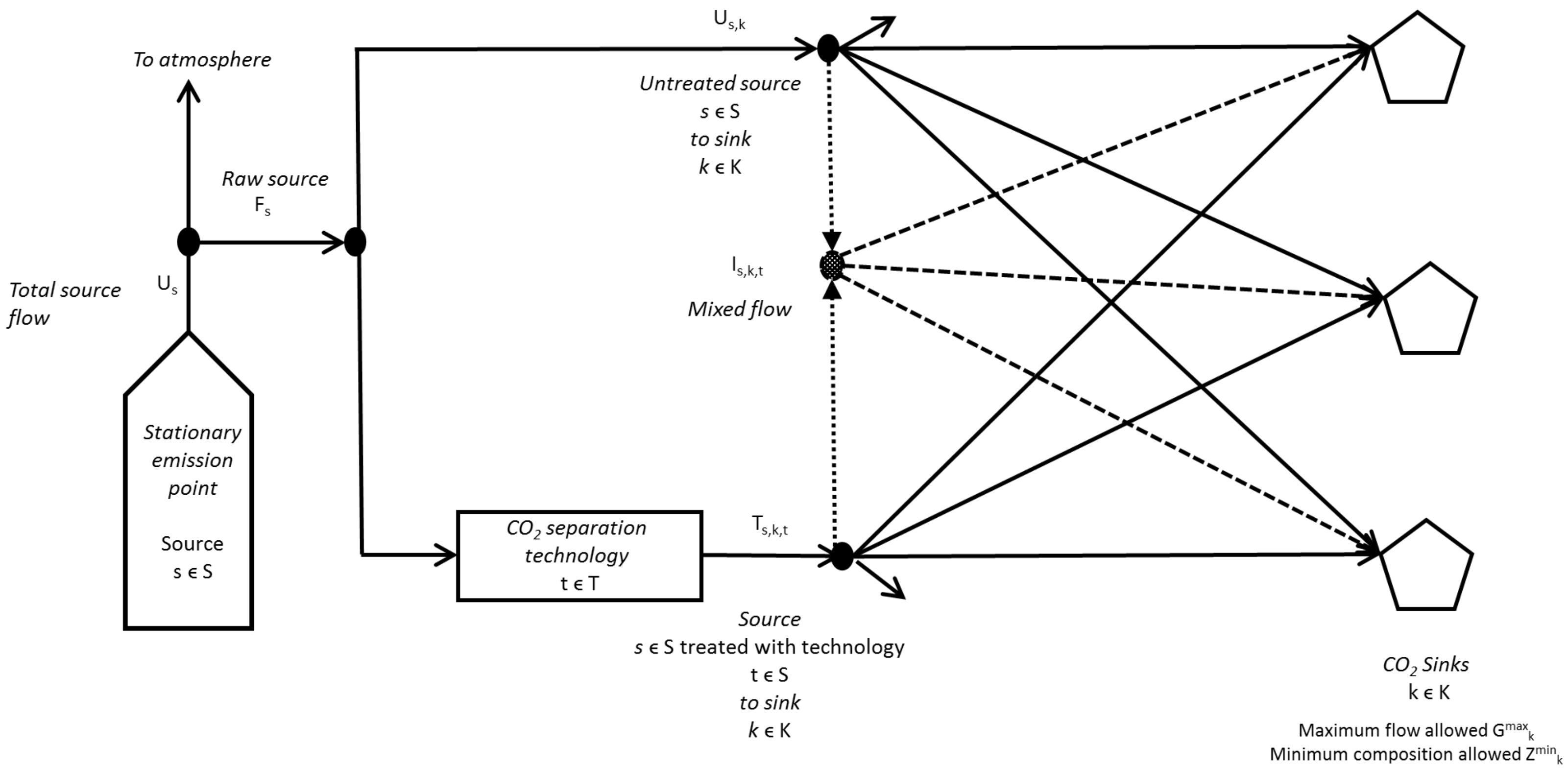


Figure 2-1: Carbon integration representation reprinted with kind permission from Al-Mohannadi et al (2016)

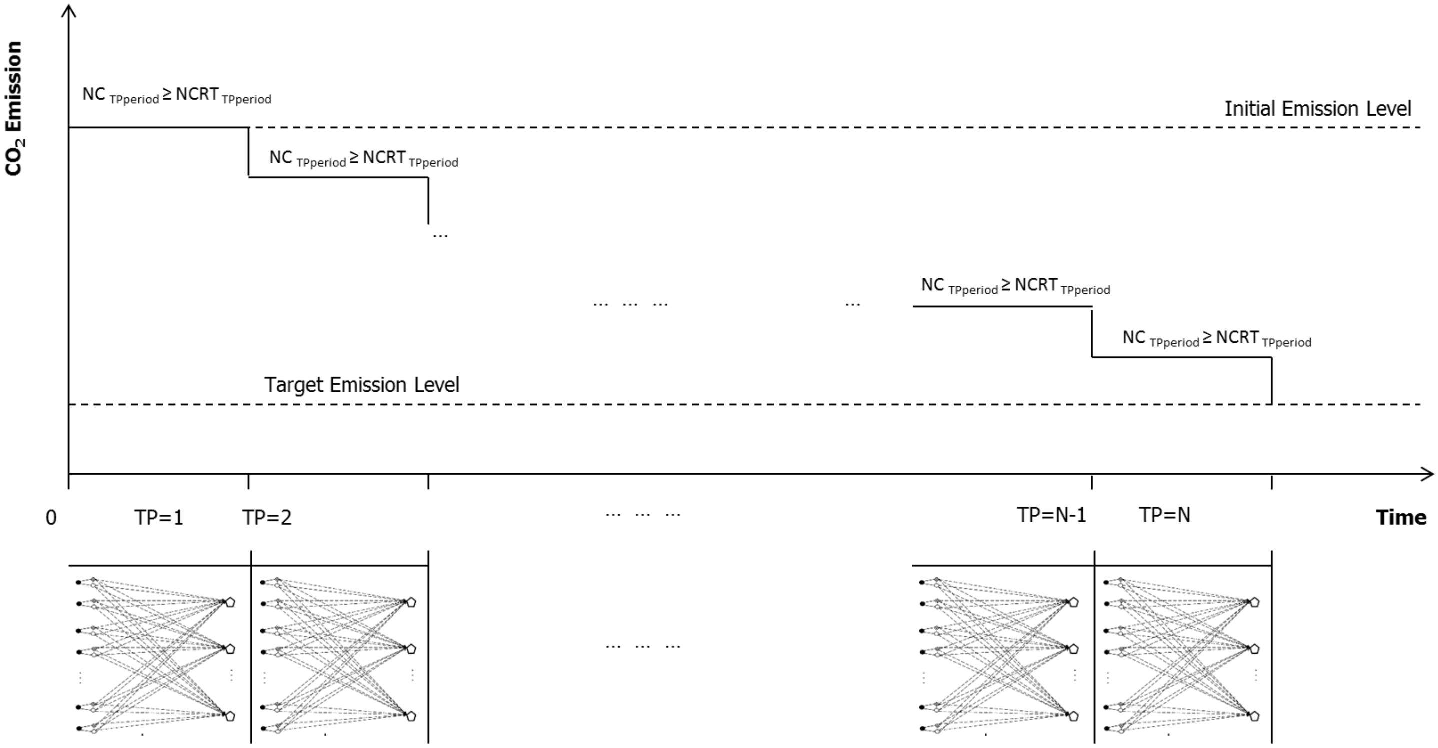


Figure 2-2: Carbon dioxide emission reduction planning over time (multi-period planning) illustrated (NCRT tp: Net Carbon Dioxide Reduction Target) reprinted with kind permission from Al-Mohannadi et al (2016)

The goal of the proposed approach will be to determine the lowest cost carbon source-sink allocation network transition in compliance with emissions reduction requirements in each time period, given the following information:

- A set of carbon emitting plants and power plants with known locations and point source emissions in each time period
- The planning horizon together with a number of defined time periods
- Carbon emissions limits for the industrial cluster in each time period or over a time planning horizon
- All carbon dioxide source flows, pressure and composition in each time period
- A number of carbon sinks with known carbon dioxide capture capacity, fixation efficiency, pressure and composition requirements in each time period
- Plants and associated sources and sinks and alterations in existing plants of the corresponding sources and sinks in each time period
- Distances of the shortest connections between all sources and sinks in the industrial cluster
- Data on the considered carbon treatment technology in terms of capture efficiency, energy use footprint, capital and operating cost
- Capital and operating costs of compression, pumping and pipelines
- Carbon dioxide emissions from electricity and heating required in carbon dioxide compression and transportation

2.1.3 Model Formulation

Let there be the following sets:

$S\ \{s|s=1,2,3,\ldots,N_{sources|}$ S is a set of carbon sources $\}$

K {k|k=1,2,3,…,N_{sinks}| K is a set of carbon sinks}

T {t|t=1,2,3,…,T_{max}| T is a set of carbon treatment technology }

TP {tp|tp=1,2,3,…,N_{period}| TP is a set of time periods }

The multiperiod problem formulation consist of a number of equality and inequality constraints, including total flow and component balances, raw carbon dioxide source flow limits (both upper and a lower bounds), minimum requirements for carbon dioxide sink flows and concentrations, total city power requirements and total balances for carbon dioxide point source availability from power production, as well as specifications associated with a net carbon reduction target. The details corresponding to the proposed model are described in this section below.

2.1.3.1 Total and Component Balances

It is assumed that the problem data in terms of maximum amount of carbon dioxide flow from source and sink capacities together with their concentration data are known for each period. A raw source *s* is located in a given plant in period *tp* and has a flow $R_{s,tp}$ with a composition $y_{s,tp}$, similarly. Flow can be allocated from a plant to a sink *k* in the same period *tp* as either treated source flow $T_{s,k,t,tp}$ or untreated source $U_{s,k,tp}$ flow. The treated plant source flow is obtained with composition $y_{s,t,tp}$ from processing any type of raw source flow in a carbon dioxide separation (carbon dioxide removal) unit *t* at a given carbon dioxide removal efficiency $\varepsilon_{t,tp}$ in period *tp.* An untreated source is a split stream with the same composition as the raw plant source as $y_{s,tp}$. Raw sources flow can be allocated between an upper and a lower limit:

$$L_{s,tp} \leq R_{s,tp} \leq M_{s,tp} \qquad \forall\ s \in S\ tp \in TP \qquad (1)$$

Where $M_{s,tp}$ is the maximum flow available from the raw source in period tp and a lower bound $L_{s,tp}$ can be set based on user requirements. The mass balances around raw sources s are given as:

$$R_{s,tp} = \sum_{k\epsilon K}\sum_{t\epsilon T} \varepsilon^{t}{}_{tp}\, T_{s,k,t,tp} + \sum_{k\epsilon K} U_{s,k,tp} \ ; \qquad \forall\ s\epsilon S\ {}_{tp}\epsilon TP \tag{2}$$

$$R_{s,tp}\, y_{s,tp} = \sum_{k\epsilon K}\sum_{t\epsilon T} \varepsilon^{t}{}_{tp} T_{s,k,t,tp}\, y_{s,t,tp} + \sum_{k\epsilon K} U_{s,k,tp}\ \ y^{u}{}_{s,tp}; \qquad \forall\ s\epsilon S\ {}_{tp}\epsilon TP \tag{3}$$

Where $\varepsilon^{t}{}_{tp}$ is the treatment technology carbon dioxide efficiency factor. The total and component balance around sinks k in period tp are given as:

$$F_{k,tp} = \sum_{s\epsilon S} \sum_{t\epsilon T} T_{s,k,t,tp}\, \varepsilon^{t}{}_{tp} + \sum_{s\epsilon S} U_{s,k,tp} \qquad \forall\ k\epsilon K\ {}_{tp}\epsilon TP \tag{4}$$

$$F_{k,tp}\, Z_{k,tp}{}^{min} \le \sum_{s\epsilon S} \sum_{t\epsilon T} T_{s,k,t,tp}\, y_{s,t,tp}\, \varepsilon^{t}{}_{tp} + \sum_{s\epsilon S} U_{s,k,tp}\, y^{u}{}_{s,tp} \qquad \forall\ k\epsilon K\ {}_{tp}\epsilon TP \tag{5}$$

Mixing is allowed at source when both treated and untreated streams are connected to the same sink in the same period. This ensures that each source is connected to each sink by only one pipeline in a given period.

$$I_{s,k,tp} = \sum_{t\in T} T_{s,k,t,tp}\, \varepsilon^{t}{}_{tp} + U_{s,k,tp} \qquad \forall\ t\epsilon T \tag{6}$$

All untreated sources are of the same carbon dioxide concentration as the raw source:

$$y^{u}{}_{s,tp} = y_{s,tp} \qquad \forall\ s\epsilon S \tag{7}$$

Any source can be connected to any sink subject to the minimum concentration requirement of the sink $Z_{k,tp}{}^{min}$ and the sink flow requirement $G_{k,tp}{}^{max}$ in period tp :

$$F_{k,tp} \leq G_{k,tp}{}^{max}; \qquad \forall\, k\epsilon K \qquad (8)$$

$$L\, X_{s,k,tp} \leq I_{s,k,tp} \leq M\, X_{s,k,tp} \qquad \forall\, s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP \qquad (9)$$

Where L is the lower flow limit and M is the upper flow limit of source-sink connection within a pipeline set by the use. $X_{s,k,tp}$ is a binary (0,1) associated with flow of the combined treated and untreated streams in any plant.

2.1.3.2 Reduction Target

The target reduction could be achieved in a number of ways. As most policies define carbon emission as a percentage reduction citing a base line to account for carbon dioxide emitted throughout the planning and implementation period as discussed by Flues et al (2014). The assessment of different policies requires a constraint on net carbon reduction requirements in each period:

$$NC_{TPperiod} \geq NCRT_{TPperiod} \qquad (10)$$

The carbon integration network needs to meet the Net Carbon Dioxide Reduction Target ($NCRT_{tp}$) for the industrial park in period tp. Figure 2-2 illustrates the reduction requirements. The $NCRT_{tp}$ is specified by the user in period tp whereas the net capture NC_{tp} is calculated as total carbon dioxide emitted subtracted from the total carbon dioxide allocated follows:

$$NC_{tp} = \sum_{k\epsilon K} F_{k,tp}{}^{CO2}(1-\eta_{k,tp}) - \sum_{s\epsilon S}\sum_{t\epsilon T} T_{s,k,t,tp}\, y_{s,t,tp}\, \gamma_{t,tp} - \sum_{k\epsilon K} F_{k,tp}{}^{CO2}\varepsilon^{p}_{tp}$$

$$\forall\ tp \in TP \qquad (11)$$

Where in period tp, $\gamma_{t,tp}$ is amount of carbon dioxide emitted from the treatment unit energy use, ${F_{k,tp}}^{CO2}$ is the carbon dioxide flow into the sink, while $\eta_{k,tp}$ is the sinks efficiency and ε_{tp}^{p} accounts for the power use carbon dioxide footprint. The following non-negativity constraints apply:

$T_{s,k,t,tp} \geq 0$ $\quad \forall$ s∈S k∈K t∈T tp∈TP (12)

$U_{s,k,tp} \geq 0$ $\quad \forall$ s∈S k∈K tp∈TP (13)

$y_{s,k,t,tp} \geq 0$ $\quad \forall$ s∈S k∈K t∈T tp∈TP (14)

$y_{s,k,tp} \geq 0$ $\quad \forall$ s∈S k∈K tp∈TP (15)

The specification of the time horizon is case study specific and depends upon the anticipated target date for the final emissions reduction target to be achieved. A typical horizon is expected in the range of one to three decades. Likewise, the number of time periods to consider within the planning horizon depends on case study specific factors such as intermediate emissions reduction target points, time lines prescribed in an industrial cluster development master plan, plant construction and commissioning schedules or other relevant issues. The time horizon and the number of time periods are user specified parameters in the approach.

2.1.3.3 Objective function

The goal for carbon integration is to minimize the total network cost (TC) whilst meeting a given net carbon dioxide reduction target for the industrial park. The objective function is given as:

$$TC= \sum_{tp \in TP} \sum_{k \epsilon K} [C_{k,tp}^{Sinks} + C_{k,tp}^{Treatment} + C_{k,tp}^{Compression} + C_{k,tp}^{Transportation}] \quad (16)$$

Where $C_{k,tp}^{Treatment}$ is the cost of treatment and separation of carbon dioxide, $C_{k,tp}^{Compression}$ is the cost of compression, $C_{k,tp}^{Transportation}$ is the cost of transportation and accounts for the pipeline overall costs, and $C_{k,tp}^{Sinks}$ is the cost of processing carbon dioxide in a given sink.

Sinks can receive carbon dioxide from various sources, mixed together to satisfy the sink purity requirements. Options of processing carbon dioxide can exist within the city, out of the city as geological utilization or can be an added process within the city. Hence, sink processing costs for each time period are calculated based on the carbon dioxide flow from sources ${F^{CO2}}_{s,k,tp}$into the sink multiplied by the cost of processing $C_{k,tp}^{Sinks,\ Cost}$in period tp:

$$C_{k,tp}^{Sinks} = C_{k,tp}^{Sinks,\ Cost} ({F^{CO2}}_{s,k,tp}) \quad (17)$$

Carbon dioxide sources can be transferred to sinks either in treated form or without treatment as shown in Figure 2-1. A single pipeline connects each source to sink, where flows can be transferred as treated, untreated or as a mixture of treated and untreated source. The flows undergo a compression step to overcome pressure drop in the pipeline and adjust pressure difference between source and sink. Therefore, treatment costs consist of three elements, capital cost $C_{k,tp}^{Treatment,\ Capex}$, active operating cost $C_{s,k,tp}^{Treatment,\ Opex\ A}$ and inactive operating cost $C_{s,k,tp}^{Treatment,\ Opex\ I}$ for source s :

$$C_{k,tp}^{Treatment} = C_{k,tp}^{Treatment,\ Capex} + \sum_{s \in S} [(C_{s,k,tp}^{Treatment,\ Opex\ A} + C_{s,k,tp}^{Treatment,\ Opex\ I}) \quad (18)$$

Similarly, compression costs consist of three elements, capital cost $C_{k,tp}^{\text{Compression, Capex}}$, active operating cost $C_{s,k,tp}^{\text{Compression, Opex A}}$ and inactive operating cost $C_{s,k,tp}^{\text{Compression, Opex I}}$, for source s:

$$C_{k,tp}^{\text{compression}} = C_{k,tp}^{\text{compression, Capex}} + \left(C_{s,k,tp}^{\text{compression, Opex A}} + C_{s,k,tp}^{\text{compression, Opex I}}\right) \quad \forall\ tp \in TP\ k \in K \qquad (19)$$

Likewise, transportation costs consist of three elements, capital cost $C_{k,tp}^{\text{Transportation, Capex}}$, active operating cost $C_{s,k,tp}^{\text{Transportation, Opex A}}$ and inactive operating cost $C_{s,k,tp}^{\text{Transportation, Opex I}}$, for source s.

$$C_{k,tp}^{\text{Transportation}} = C_{k,tp}^{\text{Transportation, Capex}} + \sum_{s \in S} \left(C_{s,k,tp}^{\text{Transportation, Opex I}} \right) \quad \forall\ tp \in TP\ k \in K \qquad (20)$$

The calculation of the capital cost of treatment, compression and transportation are presented in Table 2-1. Flow rates across connection may vary through different periods. Three types of cost have been defined to describe possible scenarios, (1) capital cost, (2) active operating cost and (3) inactive operating cost. If a connection appears or its capacity increases, the corresponding capital cost is accounted for in the period the change is implemented. In addition, for the total installed infrastructure in a period, a capital replacement charge required for renewing equipment at the end of its useful life is applied.

Table 2-1: Logic derived for each of the following cost elements, per time period reprinted with kind permission from Al-Mohannadi et al (2016)

Equation	#
$C^{\text{Treatment, Capex}}_{k,tp} = \text{if} \begin{cases} C^{\text{Treatment, Capex}}_{k,tp} \geq C^{\text{Treatment, Capex}}_{k,tp-1} & C^{\text{Treatment, Capex}}_{k,tp-1} - C^{\text{Treatment, Capex}}_{k,tp} + l_{tp}^{\text{Treatment}} C^{\text{Treatment, Capex}}_{k,tp} \\ C^{\text{Treatment, Capex}}_{k,tp} < C^{\text{Treatment, Capex}}_{k,tp-1} & l_{tp}^{\text{Treatment}} C^{\text{Treatment, Capex}}_{k,tp-1} \end{cases}$	(21)
$C^{\text{Treatment, Opex A}}_{s,k,tp} = A^{\text{Treatment}}_{k,tp} \sum_{t \in T} T_{s,k,t,tp} X^{\text{Opex}}_{s,k,t,tp}$ $\forall\ tp \in TP\ k \in K$	(22)
$C^{\text{Treatment, Opex I}}_{s,k,tp} = I^{\text{Treatment}}_{k,tp} \sum_{t \in T} T_{s,k,t,tp} (1 - X^{\text{Opex}}_{s,k,t,tp})$ $\forall\ tp \in TP\ k \in K$	(23)
$C^{\text{Compression, Capex}}_{k,tp}$ $= \text{if} \begin{cases} C^{\text{Compression, Capex}}_{k,tp} \geq C^{\text{Compression, Capex}}_{k,tp-1} & C^{\text{Compression, Capex}}_{k,tp-1} - C^{\text{Compression, Capex}}_{k,tp} + l_{tp}^{\text{Compression}} C^{\text{Compression}}_{k,tp} \\ C^{\text{Compression, Capex}}_{k,tp} < C^{\text{Compression, Capex}}_{k,tp-1} & l_{tp}^{\text{Compression}} C^{\text{Compression}}_{k,tp-1} \end{cases}$	(24)
$C^{\text{Compression, Opex A}}_{s,k,tp} = (X^{\text{Opex}}_{s,k,t,tp}) A^{\text{Compression}}_{k,tp}$ $\forall\ tp \in TP\ k \in K$	(25)
$C^{\text{Compression, Opex I}}_{s,k,tp} = (1 - X^{\text{Opex}}_{s,k,t,tp}) I^{\text{Compression}}_{k,tp}$ $\forall\ tp \in TP\ k \in K$	(26)
$C^{\text{Transportation, Capex}}_{k,tp} = \text{if}$ $\begin{cases} C^{\text{Transportation, Capex}}_{k,tp} \geq C^{\text{Transportation, Capex}}_{k,tp-1} & C^{\text{Transportation, Capex}}_{k,tp-1} - C^{\text{Transportation, Capex}}_{k,tp} + l_{tp}^{\text{Transportation}} C^{\text{Transportation}}_{k,tp} \\ C^{\text{Transportation, Capex}}_{k,tp} < C^{\text{Transportation, Capex}}_{k,tp-1} & l_{tp}^{\text{Transportation}} C^{\text{Transportation}}_{k,tp-1} \end{cases}$	(27)
$C^{\text{Transportation, Opex I}}_{s,k,tp} = (1 - X^{\text{Opex}}_{s,k,t,tp}) I^{\text{Transportation}}_{k,tp}$ $\forall\ tp \in TP\ k \in K$	(28)

In terms of operating cost of an established connection, which is active in a time period, its (active) operating costs are determined based on flow rate of the connection and corresponding heat and power requirements. If a connection does not receive flow in a time period, it is classified as inactive and an (inactive) costs associated with maintenance is applied. Additional cost details that are associated with compression, pumping, transmission, sinks processing costs and efficiency parameters are all outlined below and highlighted in Table 2-2. The proposed multi-period problem has been carried out by minimizing Equation (16), subject to Equations (1)-(28).

Table 2-2: Cost Expression details based on (Al-Mohannadi and Linke, 2016) reprinted with kind permission from Al-Mohannadi et al (2016)

Cost Element	**Correlation**
Capital cost of Treatment	$C_{k,tp}^{\text{Treatment, Capex}} = B^{\text{treatment capital}}{}_{s,t,k,q} T_{s,k,t,tp}$
Active Operating cost of Treatment	$C_{s,k,q}{}^{\text{Pipe, A}} = A^{\text{treatment}}{}_{s,t,k,q}\ T_{s,k,t,tp}$
Inactive cost of treatment	$C_{s,k,tp}{}^{\text{Pipe, A}} = I^{\text{treatment}}{}_{s,t,k,q} T_{s,k,t,tp}$
Capital cost of compressor,	$CC_{k,tp}{}^{\text{capital}} = 158{,}902\ \left(\frac{P^{\text{comp}}.I_{s,k,tp}}{224}\right)^{0.84}$
Active Operating cost of compressor	$CC_{sp,k,tp}{}^{\text{operating, A}} = P^{\text{comp}}.(I_{s,k,tp}{}^{\text{max}})\ \text{Elec}\ \ \text{hy}$
Inactive cost of compressor	$C_{k,tp}^{\text{Compessor,I}} = 31{,}800 \quad I_{s,k,tp}$
Capital cost of pump	$PC^{\text{capital}}{}_{k,tp} = [(\ 1.11*10^6 \frac{P^{\text{pump}}.(I_{s,k,tp}{}^{\text{max}})}{1000} + 0.07*10^6)\ ]$
Active Operating cost of pump	$PC_{s,k,tp}{}^{\text{operating,A}} = \eta\ P^{\text{pump}}.(I_{s,k,tp})\ \text{Elec}\ \ \text{hy}$
Inactive cost of pump	$C_{k,tp}^{\text{pump,I}} = 22{,}200\ I_{s,k,tp}$
CAPEX Compression, h(I)	$h_{k,tp} = CC_{s,k,tp}{}^{\text{capital}} + PC^{\text{capital}}{}_{k,tp}$
OPEX Active Compression	$C_{s,k,tp}^{\text{Compression, Opex A}} = CC_{s,k,t,tp}{}^{\text{operating, A}} + PC_{k,tp}{}^{\text{operating,A}}$
OPEX Inactive Compression	$C_{s,k,tp}^{\text{Compression, Opex I}} = C_{s,k}^{\text{Compessor,I}} + C_{s,k}^{\text{pump,I}}$
Capital Cost of piping, g(I)	$g_{k,tp}{}^{\text{Pipe}} \left(\frac{\text{USD}}{\text{mi}}\right) = H_{s,k}\ \left[95{,}230\ \left(D^{c}{}_{s,k,tp}\right) + 96{,}904\right]$
Inactive Operating Cost of pipe	$C_{s,k,tp}{}^{\text{Pipe,I}} = 7{,}752\ H_{s,k}\ I_{s,k,tp}$

2.1.4 Illustrative Example

Consider an industrial park with five plants, namely a fertilizer plant producing both ammonia and urea, an iron and steel production facility, a fuel additive facility producing methanol, a refinery and a natural gas fired power plant, which can be carbon dioxide sources or sinks. The problem data and information in terms of cost correlations, source and sink parameters are given in Table 2-3 and Table 2-4, are based on Al-Mohannadi and Linke (2016) and recommendations from Anderson (2009). Amine technology is assumed to be used to separate CO_2 in this example. The capital expenditure replacement parameter for treatment and piping was taken to be 0.1, based on a 20 year lifetime, while the capital expenditure replacement parameter for compression was taken to be 0.2, based on a 10 year lifetime.

Table 2-3:Sinks Requirements and Parameters reprinted with kind permission from Al-Mohannadi et al (2016)

Sinks	**CO_2 Composition (wt%)**	**CO_2 Flow (t/d)**	**Sink fixation ($tCO_{2\ emitted}/tCO_{2\ captured}$)**	**CO_2 Cost (USD/t CO_2)**
EOR	0.94	6317	0	-30
Methanol	0.99	1710	0.09	-21
Urea	0.99	1126	0.39	-15
GH	0.94	1030	0.50	-5
Algae	0.06	283	0.42	0
Storage	0.94	8317	0	8.6

Table 2-4: Treatment Cost Parameter Breakdown in USD/tCO$_2$. Reprinted with kind permission from Al-Mohannadi et al (2016)

Source Plant	$\mathbf{B^{treatment\ capital}_{s,t,k,q}}$	$\mathbf{A^{treatment}_{s,t,k,q}}$	$\mathbf{I^{treatment}_{s,t,k,q}}$
Fertilizer Plant	0	0	0
Steel Production	23.2	5.8	2.3
Refinery	27.8	6.7	2.8
Power Plant	34.5	8.6	3.4

The initial collective footprint of the industrial park is 10 million tons of carbon dioxide emitted per year. The goal set for the example is to reduce these emissions by 50% by the beginning of the last period of a 10 year time horizon represented by five time periods. The multi-period carbon integration optimization was performed for two alternative policies as summarized in Table 2-5:

- *Case 1:* A phased emissions reduction over time, and
- *Case 2:* No specific reduction requirements in any but the last time period.

Table 2-5:Case 1 and Case 2 emissions reductions over the initial emission. . reprinted with kind permission from Al-Mohannadi et al (2016)

	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**
Case 1	10%	20%	30%	40%	50%
Case 2	0%	0%	0%	0%	50%

The optimization model has been implemented for this example using Lindo “What'sBest 9.0” (2006) Global solver for MS-Excel 2010 via a desktop PC with Intel Core i7 Duo processor, 8 GB RAM and a 32-bit operating System. The MINLP has 3594 variables and 650 constraints. The solution time was 1,056 seconds

The example problem was first solved for the case of a phase emissions reduction (Case 1). The resulting network is shown in Figure 2-3 with the corresponding allocation flows summarized in Table 2-6. The minimum cost of the solution across all periods was identified at -247 million USD, i.e. the revenues generated in the sink processes exceed the capital and operating expenditures of the carbon integration network. The capital expenditure in Case 1 was of 580 million USD while the revenue was - 827 million USD.

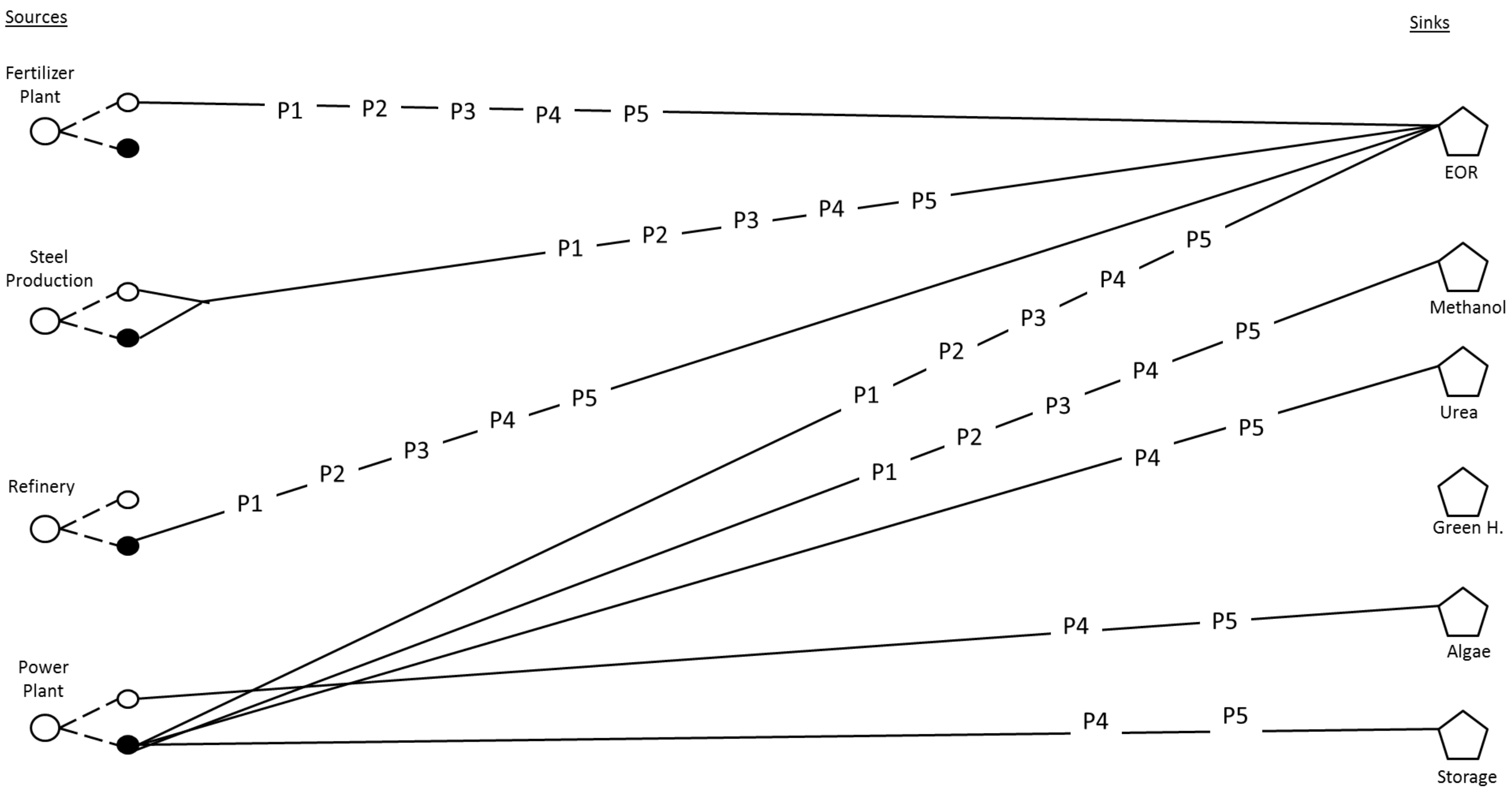


Figure 2-3: Case 1 Multi-period network design obtained, filled circles refer to treated sources and unfilled to untreated. Reprinted with kind permission from Al-Mohannadi et al (2016)

Table 2-6: Case 1 - Combined Carbon dioxide flow tCO_2/d. reprinted with kind permission from Al-Mohannadi et al (2016)

Source	Period/Sink	EOR	Methanol	Urea	Greenhouse	Algae	Storage
Fertilizer Complex	P1	977	0	0	0	0	0
	P2	977	0	0	0	0	0
	P3	977	0	0	0	0	0
	P4	977	0	0	0	0	0
	P5	977	0	0	0	0	0
Iron and Steel Production	P1	3138	0	0	0	0	0
	P2	3138	0	0	0	0	0
	P3	3138	0	0	0	0	0
	P4	3138	0	0	0	0	0
	P5	3138	0	0	0	0	0
Refinery	P1	983	0	0	0	0	0
	P2	983	0	0	0	0	0
	P3	983	0	0	0	0	0
	P4	983	0	0	0	0	0
	P5	983	0	0	0	0	0
Power Plant	P1	1220	1710	0	0	0	0
	P2	1220	1710	0	0	0	0
	P3	1220	1710	0	0	0	0
	P4	1220	1710	1126	0	283	401
	P5	1220	1710	1126	0	283	2667

The carbon integration network shows connections to the Enhanced Oil Recovery (EOR) sink from all sources from period 1 onwards with flows corresponding to the maximum capacities of the ammonia, steel and refinery sources, balanced with partial flow from the power station source to reach maximum EOR capacity. Likewise, a connection is present across all period from the treated power station source to the methanol sink, which is supplied at its maximum capacity. The network exceeds the capture targets in the first three periods and capitalizes on the profitability of source to EOR and methanol connections. The high purity source from the ammonia plant meets the EOR sink purity requirement and is allocated in its untreated from. The steel plant supplies a mixture of treated and untreated source flows to EOR, while the refinery and the power station each supply a treated source stream.

When the cumulative net capture target was increased to 40% in the fourth period, three additional sinks enter the network. Both the urea plant sink as well as the algae production sink are supplied at their maximum capacity, with the balance of the net capture target being met by employing the storage sink. All additional sinks in Period 4 are supplied by treated source streams from the power plant. A further increase of the cumulative net capture target to 50% resulted in an increase in the flow from the treated power plant source to the storage sink.

The example problem was next solved for the case of no specific emissions reduction requirement in any but the last time period (Case 2). The resulting network is summarized in Table 2-7. The minimum cost of the solution across all periods was identified at -258 million USD, i.e. the carbon integration network is associated with an additional profit of 11 million USD as compared to Case 1, in which a more prescriptive carbon reduction scheme was followed.

Table 2-7: Case 2 - Combined Carbon dioxide flow tCO_2/d. Reprinted with kind permission from Al-Mohannadi et al (2016)

Source	Period/Sink	EOR	Methanol	Urea	Greenhouse	Algae	Storage
Fertilizer Complex	P1	977	0	0	0	0	0
	P2	977	0	0	0	0	0
	P3	977	0	0	0	0	0
	P4	977	0	0	0	0	0
	P5	977	0	0	0	0	0
Iron and Steel Production	P1	3138	0	0	0	0	0
	P2	3138	0	0	0	0	0
	P3	3138	0	0	0	0	0
	P4	3138	0	0	0	0	0
	P5	3138	0	0	0	0	0
Refinery	P1	983	0	0	0	0	0
	P2	983	0	0	0	0	0
	P3	983	0	0	0	0	0
	P4	983	0	0	0	0	0
	P5	983	0	0	0	0	0
Power Plant	P1	1220	1710	0	0	0	0
	P2	1220	1710	0	0	0	0
	P3	1220	1710	0	0	0	0
	P4	1220	1710	0	0	0	0
	P5	1220	1710	1126	0	283	2667

In the network identified for Case 2, the EOR and methanol sinks are supplied with carbon dioxide from all four sources in all time periods, identical to the solution identified for Case 1. This is due to the overall profitability associated with the EOR process and methanol sinks. In the last period, the urea, algae and storage sinks are supplied by treated power plant source to achieve the net carbon reduction target capture of 50% in the last period.

Both Case 1 and Case 2 networks achieve the required emissions reduction by the end of the planning horizon. Case 2 gave the best solution as it achieved the same reduction target with less cost than Case 1. The case study illustrates how the proposed approach can support the testing and analysis of different carbon reduction scenarios.

2.1.5 Conclusion

The work presented a systematic approach to multi-period carbon integration. The approach allows to determine cost optimal carbon dioxide allocation networks over time to achieve desired overall footprint reductions over a planning horizon. Carbon dioxide reduction targets can be set for each time period to allow the assessment of alternative policies towards achieving the desired reduction by the target date. The optimization problem determines minimum cost solutions and takes into account multiple sources, multiple utilization and storage options (sinks), capture processes, and compression and piping elements of the network. An example was presented to illustrate the multi-period carbon integration approach and presented results highlight differences in solutions for alternative footprint reduction policies. The proposed approach enables policy makers to systematically explore alternative emissions reduction paths in an integrated framework. While the current work aims at exploring long-term planning options for carbon integration, the optimization of networks taking into account short-term operational issues would make an interesting area for future extensions.

2.2 Optimizing Policies and Carbon Reduction Strategies

The goal of this chapter is the identification of optimal transitions towards climate footprint reduction targets using a linear multi-period carbon integration approach. Policy-making entities have proposed ambitious carbon dioxide emission reduction targets as a means of mitigating global warming effects. Since the industrial sector is substantially responsible for most carbon emissions, industries are constantly being challenged to implement effective emission reduction measures. A number of conventional methods may be applied to reduce carbon dioxide emissions, such as: (1) the utilization of energy efficient technologies, (2) energy integration (3) fuel switching to less carbon intensive options, (4) the use of Renewable Energy (RE), and (5) carbon capture, utilization and storage (CCUS). Recently, Carbon Integration has been proposed as a novel technique that identifies minimum cost CCUS options to be utilized for carbon dioxide management in industrial clusters (Al-Mohannadi and Linke, 2016). Carbon Integration allows optimal carbon dioxide capture options to be determined at source, the optimal selection of processing options (sinks), as well as the optimal allocation of carbon dioxide to sinks, for a specific carbon dioxide emission reduction target.

Generally speaking, carbon dioxide emission targets are often proposed for a point in time in the (distant) future. The same target may be achieved in various ways, depending on how the carbon reduction policy is being implemented over time. To assess policies of phasing out CO_2 emissions over time until the future target is met, a multi-period carbon integration approach was proposed to develop cost optimal CCUS networks over time following a prescribed CO_2 reduction policy, described in the previous chapter. The proposed multi-period approach takes the form of a mixed integer nonlinear program (MINLP) and requires policies to be known a priori. It does not allow for reduction policies to be identified. In addition, while the multi-period Carbon Integration approach considers a rich set of CO_2 capture, storage and utilization options in network optimization, renewable energy options have not been considered alongside the CCUS network synthesis. Given their importance for cost effective attainment of climate targets results from multi-period carbon integration alone do not provide a complete picture for cost effective climate policy development. To overcome the shortcomings of the existing multi-period carbon integration approach, this work will introduce an approach that can simultaneously determine optimal climate reduction policies together with CCUS network and renewable energy selections in a multi-period approach. Moreover, the proposed approach will take the form of a mixed integer linear program (MILP) and be significantly faster and more robust to solve.

2.2.1 Background

Many policies are drafted yearly, in an attempt to successfully reduce carbon dioxide emissions. Most of the policies are outlined for regulatory reasons, by prescribing a required target, over a specified time horizon. Different carbon dioxide emission reduction strategies that are often dictated by over time GHG emission targets, (Huisingh et al. 2015). While other policies define individual emission reduction targets across different industrial sectors, especially ones associated with carbon dioxide point sources that result in considerable emissions (Pinho and Madaleno, 2011). Several studies compare and contrast the implementation of different of carbon dioxide emission reduction policies whenever applicable, by prescribing appropriate target emission goals. Clarke et al. (2009) studied how total carbon dioxide emission targets may be achieved, by comparing countries that begin mitigation immediately, to countries that start their mitigation process at a delayed phase. Other efforts have focused more specifically on industrial emissions, such as Blanford et al. (2014) and Kriegler et al (2014). On the other hand, other contributions such as the work by Hauch (2003) study carbon dioxide emissions trading in the energy sector from a policy-making standpoint.

Luderer et al (2014) assess near term mitigation targets, and goals by considering targets up to 2020. The importance of implementing near term mitigation efforts is crucial for achieving low-concentration goals. This aspect was also highlighted in IPCC Fifth Assessment Report (2014) report, which in turn emphasizes the benefit of methods that assess the deployment of low carbon emission technologies for achieving future emission targets. Hence, a roadmap that includes the most promising technologies to be adopted, may be used to draft a successful policy. However, carbon capture technology selection often leaves an ambiguous area that is open for different interpretations. Thus, the assessment of various carbon dioxide capture, utilization and storage schemes that achieve a specific emission reduction target, the application of such methods may greatly assist in policy drafting. Moreover, it should be noted that many policies are updated as a result of market-driven factors, such as knowledge expansion as a result of research and development initiatives, as pointed out by Flues et al (2014). More specifically, multi-period planning of carbon integration networks may often incorporate carbon capture technologies that are the focus of significant research and development efforts. Many carbon capture technologies have been reported to improve in the past, and this trend is expected to continue (Rubin et al, 2007, Rochedo and Szklo, 2013). Expected improvements are typically forecasted through learning curves, which may also be considered from a multi-period planning perspective. Significant technology cost reduction may be achieved through research and development (Rubin et al, 2004). For instance, Riahi et al. (2014) exploit the multi-period nature of the problem by investigating the effect of transitioning targets and fluctuating prices onto emission reduction strategies.

In addition to the deployment of carbon capture technologies, renewable energy may also be assessed as alternative carbon dioxide emission reduction outlets. This may be achieved either by prescribing a renewable energy set target to be integrated into the overall energy mix, or by more specifically assigning a particular renewable energy selection (such as solar, wind, geothermal or bio-fuels) as a possible emission reduction alternative. Most strategies include energy efficiency regulation, electricity supply or pricing regulation or setting technology standards to be implemented by a target date (Productivity Commission, 2011). Moreover, renewable costs are expected to decline with time and deployments. The short-term cost reductions are highly uncertain as they depend on unpredictable investment decisions, which could accelerate or slow the deployment growth (IRENA, 2013, Trappey et al, 2016). Therefore, investigations of renewable energy alternatives in multi-period carbon integration problems are highly sensitive to time factors. Thus, this work will incorporate RE with mutliperiod carbon integration approach to enable policy assessment.

2.2.2 Problem statement and approach

The problem addressed in this work is the synthesis over planning time horizon of cost optimal networks of carbon sources, carbon capture and utilization and storage sinks (CCUS) in a cluster with multiple processing and fossil fuel power plants, together with the selection of renewable energy options to generate electricity without fossil fuel. The main objective is to reduce carbon dioxide emitted from the cluster to achieve a future emissions target while not exceeding allowable emissions limits during the transition time frame.

As explained in the introduction, the multi-period carbon integration approach addresses the above problem partially: it allows the synthesis of cost optimal multi-period CCUS networks for prescribed CO_2 emissions reduction policy. The MINLP model did not account for the role of renewable energy use, and used nonlinear yet simplified cost expressions for compression, pumping, and transmission. The work applied heuristics and parameters for the pipeline pressure drop, the compressor power consumption and assumed number of compression stages. These assumptions in the model omitted the potential to search for cost optimal combinations of compression stages and pipe diameters. Despite these simplifying assumptions, the MINLP problem is difficult and time consuming to solve. Thus, in this work we aim to develop a linear model to achieve an easy to solve formulation. At the same time as removing the nonlinearities, which are associated with the transportation options (compression, pressure drop, pipe sizing), we aim to consider cost optimal decisions with respect to pipe sizes and compression stages. This will be achieved through a two-step approach. Prior to CCUS-RE network synthesis, we determine the cost optimal transportation for possible source to sink connections in terms of pipe sizes and compression states, which we then process in the simple MILP CCUS-RE optimization model. The decomposition approach we adopt in our work was first proposed by Kwak (2016) to achieve linear carbon integration models while at the same time increasing the richness and model accuracy of the transportation options considered as compared to the MINLP carbon integration model.

The decomposition approach of Kwak (2016) is illustrated in Figure 2-4 and Figure 2-5. The work expanded the assumptions used in Al-Mohannadi and Linke (2016) to optimize the pressure drop and compression stages using an exhaustive search technique that resulted in linear cost-optimum models. The method consists of three stages, in the first stage, the transportation process of the source-sink connection is decomposed into its process units to decide the direction of the process integration. In the second stage, the exhaustive search is conducted to collect the minimum transportation cost data of the possible source-sink connections. Then, the optimum transportation cost for every source-sink connection is established as a linear function of the flow rate. The linear cost functions produced embed complex calculations and reduces complexity without compromising on the details needed for the find the cost-optimum connection for a given source-sink connection. As shown in Figure 2-4, the exhaustive search for every available source-sink connection and its process units is carried out to collect the minimum total transportation cost information by applying the different possible design variable of the each process unit iteratively. For every possible case, the minimum cost information is established on the accurate process calculation and this information assures the feasibility of the derived cost models in the next stage. In the final stage, the collected minimum cost data for every source-sink connection was plotted and expressed as a function of the carbon dioxide flow rate. And if necessary, piecewise linearization work is conducted to increase the accuracy of the cost function.

In addition to the linear CCUS models, the proposed approach considers renewable power generation options in equality and inequality constraints to enable the selection of RE in the context of cost optimal CCUS network selections. In addition, the approach allows cost optimal reductions to be determined over time while considering final and transition CO2 emission reduction targets and limits.

The resulting approach enables regulatory authorities to systematically assess the impact of implementing different policies in the form of carbon dioxide emission reduction schemes, onto carbon capture, utilization and storage schemes that are attainable by industrial clusters. In addition, the proposed methodology also accounts for the integration of renewable energy options for power generation over time, as an alternative emission mitigation strategy. The remainder of the manuscript presents the optimization model, followed compares and contrasts the case of a given industrial cluster that aims to achieve the same carbon dioxide emission target, through CCUS and RE policies.

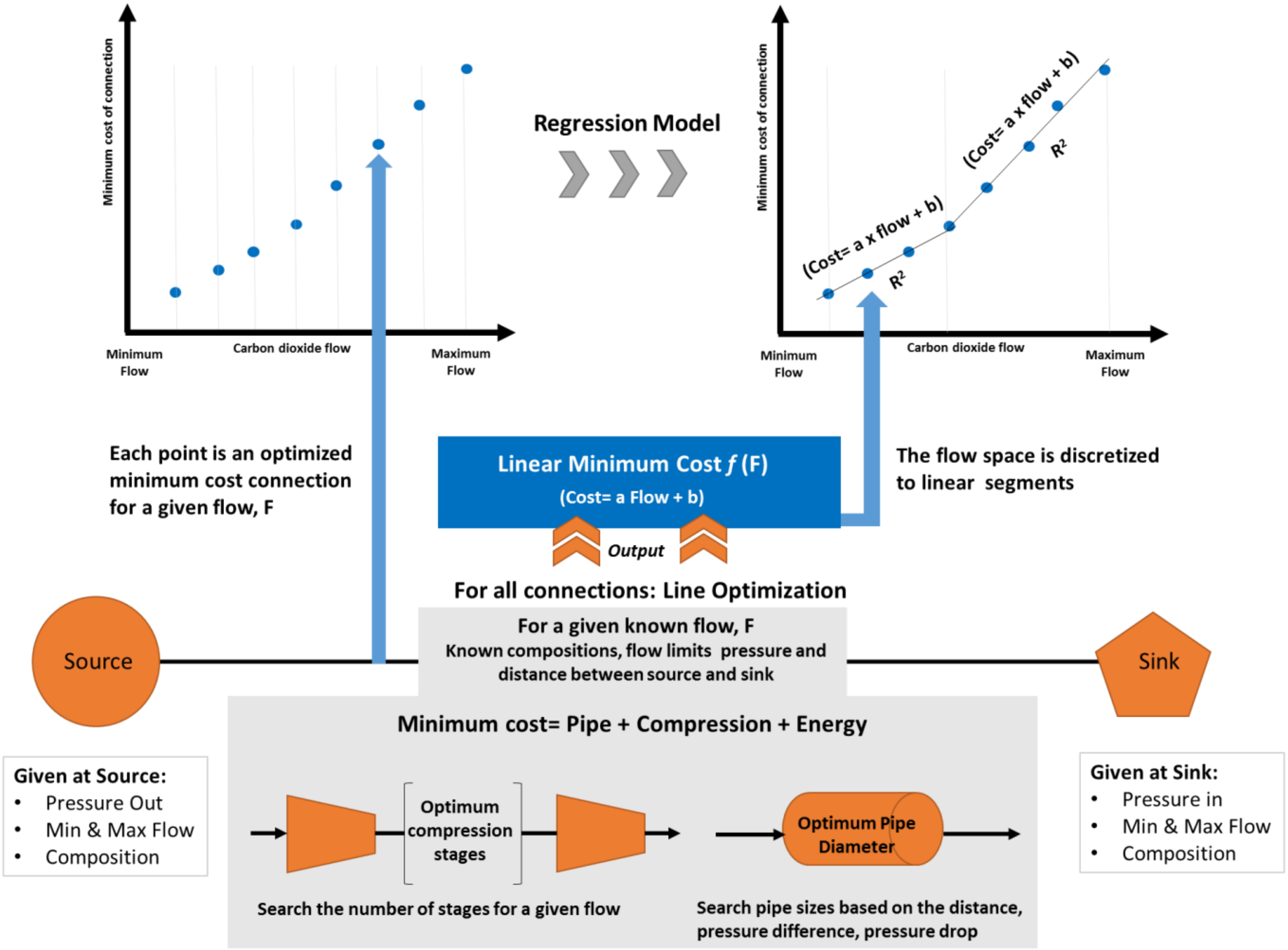
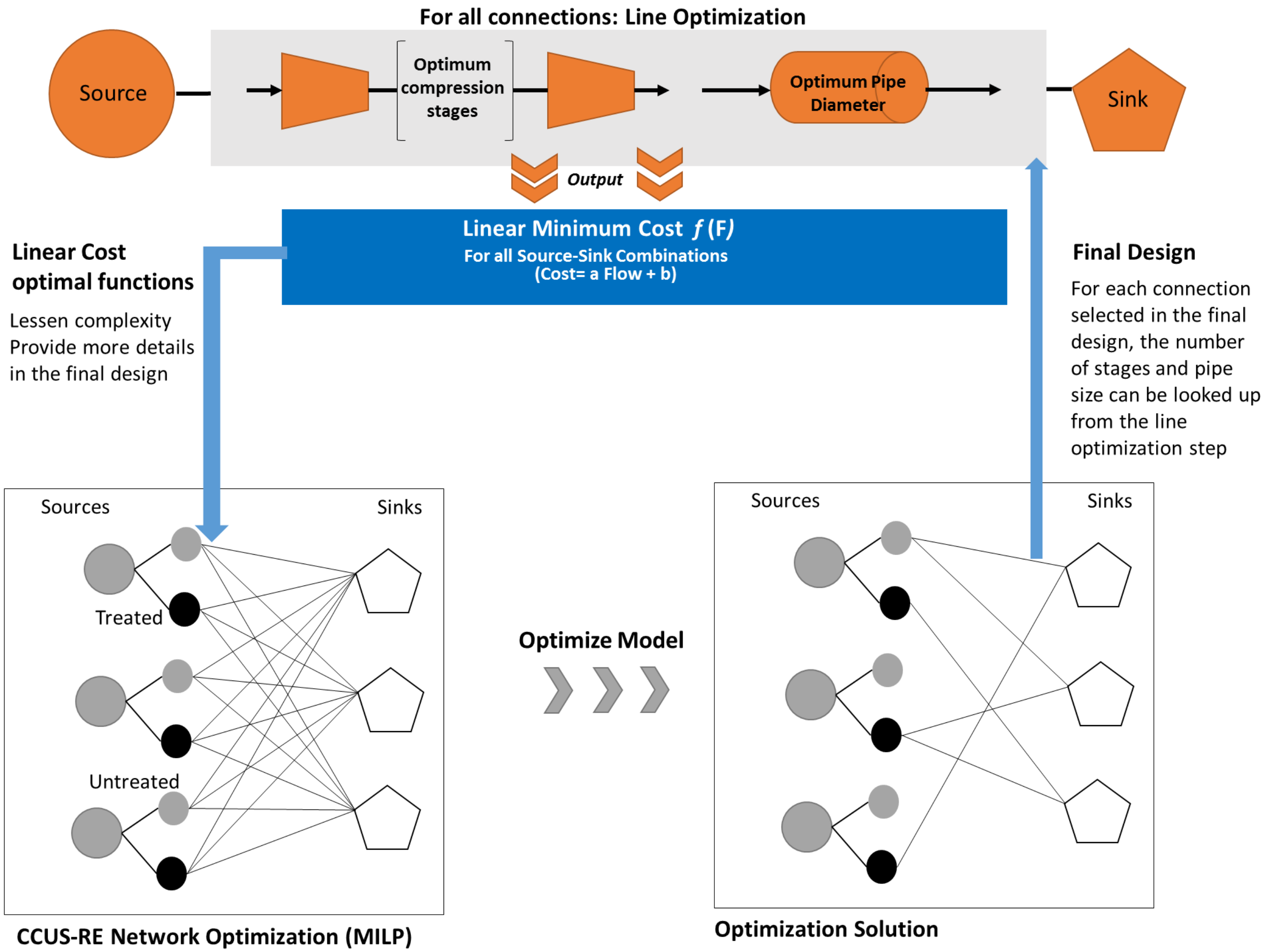


Figure 2-4: Linear Cost Modeling Approach: Source-Sink transportation and compression optimization based on Kwak (2016)



Linear Cost optimal functions

Lessen complexity
Provide more details in the final design

Final Design

For each connection selected in the final design, the number of stages and pipe size can be looked up from the line optimization step

Figure 2-5: Two Optimizations: Line Connection and CCUS-RE Networks

2.2.3 Linear Policy Instigative Model

An optimization model is formulated to explore the superstructure representation described above. The following sets were used:

S {s|s=1,2,3,…,$N_{sources|}$ S is a set of carbon sources }

K {k|k=1,2,3,…,N_{sinks}| K is a set of carbon sinks}

T {t|t=1,2,3,…,T_{max}| T is a set of carbon treatment technology }

TP {tp|tp=1,2,3,…,N_{period}| TP is a set of time periods }

SG {sg|sg =1,2,3,…,N_{sg}| SG is a set of linear cost segments }

EC {ec|ec=1,2,3, ,…,N_{EC}| EC is a set of combustible fuel options for power generation}

ER {er|er=1,2,3, ,…,N_{ER}| ER is a set of renewable energy options for power generation }

Total and component mass balances of the flow around sources and sinks along with constraints are described below.

2.2.3.1 Total and Component Balances

The mass balances around raw sources s are given as:

$$R_{s,tp}=\sum_{k\in K}\sum_{t\in T}\varepsilon_{tp}^{t}T_{s,k,t,tp}+\sum_{k\in K}U_{s,k,tp} \qquad \forall\ s\in S,\ tp\in TP \qquad (29)$$

Carbon sources can be transferred to sinks either in treated form or without treatment

$$T_{s,k,t,tp}=\sum_{sg\in SG}T_{s,k,t,tp,sg} \qquad \forall\ s\in S,\ k\in K,\ t\in T,\ tp\in TP \quad (30)$$

$$U_{s,k,tp}=\sum_{sg\in SG}U_{s,k,tp,sg} \qquad \forall\ s\in S,\ k\in K,\ tp\in TP \qquad (31)$$

Component balance around raw sources s is given as:

$$R_{s,tp}y_{s,tp}=\sum_{k\in K}\sum_{t\in T}\varepsilon^{t}_{t,tp}T_{s,k,t,tp}y_{s,t,tp}+\sum_{k\in K}U_{s,k,tp}y_{s,tp} \qquad \forall\ s\epsilon S,\ tp\epsilon TP \qquad (32)$$

The total and component balance around sinks k in period tp are given as:

$$F_{k,tp}=\sum_{s\in S}\sum_{t\in T}T_{s,k,t,tp}\varepsilon^{t}_{tp}+\sum_{s\epsilon S}U_{s,k,tp} \qquad \forall\ k\epsilon K,\ tp\epsilon TP \qquad (33)$$

$$F_{k,tp}Z^{min}_{k,tp}\leq\sum_{s\in S}\sum_{t\in T}T_{s,k,t,tp}y_{s,t,tp}\varepsilon^{t}_{tp}+\sum_{s\epsilon S}U_{s,k,tp}\,y_{s,tp} \qquad \forall\ k\epsilon K,\ tp\epsilon TP \qquad (34)$$

Any source can be connected to any sink subject to the minimum concentration requirement of the sink $Z^{min}_{k,tp}$ and the sink flow requirement $G^{max}_{k,tp}$ in period tp

$$F_{k,tp}\leq G^{max}_{k,tp} \qquad \forall\ k\epsilon K,\ tp\epsilon TP \qquad (35)$$

Raw sources flow can be allocated between an upper and a lower limit:

$$L_{s,tp}\leq R_{s,tp}\leq M_{s,tp} \qquad \forall\ s\epsilon S\ tp\epsilon TP \qquad (36)$$

Equations (9) and (10) ensure only one piecewise segment is used to cost each treated and untreated connection.

$$\sum_{t\in T}\sum_{sg\in SG}X^{T}_{s,k,t,tp,sg}\leq 1 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP \qquad (37)$$

$$\sum_{sg\in SG}X^{U}_{s,k,tp,sg}\leq 1 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP \qquad (38)$$

The flows undergo a compression step to overcome pressure drop in the pipeline and adjust pressure difference between source and sink. Therefore, a connection from source to sink requires compression, pumping and a pipeline, which is considered a line. $L^{LINE\_T}_{s,k,t,tp,sg}$ and $L^{LINE\_T}_{s,k,tp,sg}$ account for lower maximum flow, $F^{LINE\_T}_{s,k,t,tp,sg}$ and $F^{LINE\_U}_{s,k,tp,sg}$ account for the upper maximum flow limit that for each treated and untreated carbon dioxide allocation respectively between source s to sink k in time period tp and cost segment sg. When describing those upper limits, $F^{LINE\_T}_{s,k,t,tp,sg}$ and $F^{LINE\_U}_{s,k,tp,sg}$ may be referred to as the treated and untreated transmission line capacity between source s to sink k in time period tp. cost segment sg, respect $N^{LINE\_T}_{s,k,t,tp,sg}$ and $N^{LINE\_U}_{s,k,tp,sg}$ account for the lower flow limit associated with the capacity of each treated and untreated transmission line respectively between source s to sink k in time period tp and cost segment sg. Similarly, $M^{LINE\_T}_{s,k,t,tp,sg}$ and $M^{LINE\_U}_{s,k,tp,sg}$ account for the upper flow limit associated with the capacity of each treated and untreated transmission line, respectively between source s to sink k in time period tp and cost segment sg While, the binaries $X^{T}_{s,k,t,tp,sg}$ and $X^{U}_{s,k,tp,sg}$ ensure the limits activated when the allocation is activated following equations:

$$y^{LINE\_T}_{s,k,t,tp,sg} = F^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg}) \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP,\ sg\epsilon SG \qquad (39)$$

$$y^{LINE\_U}_{s,k,tp,sg} = F^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg}) \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP,\ sg\epsilon SG \qquad (40)$$

$$y^{LINE\_T}_{s,k,t,tp,sg} - M^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg}) \leq 0 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP \qquad (41)$$

$$y^{LINE\_U}_{s,k,tp,sg} - M^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg}) \leq 0 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP \qquad (42)$$

$$-F^{LINE\_T}_{s,k,t,tp,sg} + y^{LINE\_T}_{s,k,t,tp,sg} \leq 0 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP \qquad (44)$$

$$-F^{LINE\_U}_{s,k,tp,sg} + y^{LINE\_U}_{s,k,tp,sg} \leq 0 \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP \qquad (45)$$

$$F^{LINE\_T}_{s,k,t,tp,sg} - y^{LINE\_T}_{s,k,t,tp,sg} + M^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg}) \leq M^{LINE\_T}_{s,k,t,tp,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP \qquad (46)$$

$$F^{LINE\_U}_{s,k,tp,sg} - y^{LINE\_U}_{s,k,tp,sg} + M^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg}) \leq M^{LINE\_U}_{s,k,tp,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP \qquad (47)$$

$$L^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg})\leq T_{s,k,t,tp,sg}\leq y^{LINE\_T}_{s,k,t,tp,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP,\ sg\epsilon SG \quad (48)$$

$$L^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg})\leq U_{s,k,tp,sg}\leq y^{LINE\_U}_{s,k,tp,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP,\ sg\epsilon SG \quad (49)$$

$$N^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg})\leq F^{LINE\_T}_{s,k,t,tp,sg}\leq M^{LINE\_T}_{s,k,t,tp,sg}(X^{T}_{s,k,t,tp,sg}) \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP,\ sg\epsilon SG \quad (50)$$

$$N^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg})\leq F^{LINE\_U}_{s,k,tp,sg}\leq M^{LINE\_U}_{s,k,tp,sg}(X^{U}_{s,k,tp,sg}) \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP,\ sg\epsilon SG \quad (51)$$

$$N^{LINE\_T}_{s,k,t,tp,sg} = F^{LINE\_T}_{s,k,t,tp+1,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ t\epsilon T,\ tp\epsilon TP,\ sg\epsilon SG \quad (52)$$

$$N^{LINE\_U}_{s,k,tp,sg} = F^{LINE\_U}_{s,k,tp+1,sg} \qquad \forall\ s\epsilon S,\ k\epsilon K,\ tp\epsilon TP,\ sg\epsilon SG \quad (53)$$

Where $L^{LINE\_T}_{s,k,t,tp,sg}$, $L^{LINE\_U}_{s,k,tp,sg}$ represent lower flow limits for treated and untreated flow, while $M^{LINE\_T}_{s,k,t,tp,sg}$, $M^{LINE\_U}_{s,k,tp,sg}$ represent upper flow limits for source-sink connection within a pipeline. Each allocation is assumed to consist of two different flows that are set by the range of use (a lower end, and a higher end). Only one of the flow ends must be active, for which the corresponding set of correlations are activated accordingly through the appropriate use of binary variables. $X^{T}_{s,k,t,tp,sg}$ and $X^{U}_{s,k,tp,sg}$ are the respective binary variables (0,1) that are associated with each treated and untreated stream individually. $F^{LINE\_T}_{s,k,t,tp,sg}$ and $F^{LINE\_U}_{s,k,tp,sg}$ represent both the lower and higher end flows at which each carbon allocation (or line) consisting of a pipeline, a compressor, a pump (only for allocations that require supercritical conditions), as well as any treatment required for the entire allocation arrangement. $M^{LINE\_T}_{s,k,t,tp,sg}$ and $N^{LINE\_T}_{s,k,t,tp,sg}$ are the corresponding upper and lower bounds associated with each treated stream of CO_2 allocated, $M^{LINE\_U}_{s,k,tp,sg}$ and $N^{LINE\_U}_{s,k,tp,sg}$ are the corresponding upper and lower bounds associated with each untreated stream of CO_2 allocated.

The net capture NC_{tp} is calculated as total carbon dioxide emitted subtracted from the total carbon dioxide allocated follows:

$$NC_{tp}=\sum_{k\in K} F_{k,tp}^{CO_2}\left(1-\eta_{k,tp}\right)-\sum_{s\epsilon S}\sum_{t\epsilon T} T_{s,k,t,tp}y_{s,k,t,tp}\gamma_{t,tp}-\sum_{k\epsilon K} F_{k,tp}^{CO_2}\varepsilon_{tp}^{p}+\sum_{s\epsilon S}\left(R_{s,tp}-M_{s,tp}\right) \quad \forall\ tp\in TP \qquad (54)$$

$$T_{s,k,t,tp,sg}\geq 0 \quad \forall\ s\epsilon S\ k\epsilon K\ t\epsilon T\ tp\epsilon TPsg\epsilon SG \qquad (55)$$

$$U_{s,k,tp,sg}\geq 0 \quad \forall\ s\epsilon S\ k\epsilon K\ tp\epsilon TP\ sg\epsilon SG \qquad (56)$$

$$y_{s,t,tp}\geq 0 \quad \forall\ s\epsilon S\ k\epsilon K\ t\epsilon T\ tp\epsilon TP \qquad (57)$$

$$y_{s,k,tp}\geq 0 \quad \forall\ s\epsilon S\ k\epsilon K\ tp\epsilon TP \qquad (58)$$

2.2.3.2 Carbon dioxide point source flow availability (from power generation)

The total power output is assumed to be constant in each period to meet the power requirement of the carbon integration network and the supply/grid export demand. Power is generated in power plants through the use of a mix of fuels and renewable energy. Each type of fuel and energy option has a CO_2 footprint, allowed usage limits and an associated cost. The emission from the power plant is given as

$$\sum_{s\in S} M_{s,tp}=\sum_{ec\in EC} EF_{ec}P_{ec,tp}+\sum_{er\in ER} EF_{er}P_{er,tp} \quad \forall\ tp\epsilon TP \qquad (59)$$

The total power is ensured by the equations below

$$PR_{tp}= P_{ec,tp}+P_{er,tp} \quad \forall\ tp\epsilon TP \qquad (60)$$

$$L_{ec,tp}^{FUEL}\leq P_{ec,tp}\leq M_{ec,tp}^{FUEL} \quad \forall\ ec\epsilon EC\ tp\epsilon TP \qquad (61)$$

$$L_{er,tp-1}^{RENEWABLES} \leq P_{er,tp} \leq M_{er,tp}^{RENEWABLES} \qquad \forall\ er \epsilon ER\ tp \epsilon TP \qquad (62)$$

$$P_{er,tp} - P_{er,tp-1} \geq 0 \qquad \forall\ er \epsilon ER\ tp \epsilon TP \qquad (63)$$

PR_{tp} is the power station output specification in the city in period tp, fixed in each period. Each type of combustible fuel is associated with an emission factor, $EF_{ec,}$ and a power limit in period tp. $P_{ec,tp}$ allowed power limits, $L_{ec,tp}^{FUEL}$ and $M_{ec,tp}^{FUEL}$ as lower and upper limits respectively. Each type of renewable energy is associated with an emission factor, $EF_{er,}$ and a power limit in period tp $P_{er,tp}$ allowed limits, $L_{er,tp-1}^{RENEWABLES}$ and $M_{er,tp}^{RENEWABLES}$ as lower and upper limits respectively. Renewable power once installed will continue being used and that is ensuring using the lower limit by equation (62) and (63)

2.2.3.3 *Objective Function*

The goal for carbon integration is to minimize the total network cost (TC) whilst meeting a given net carbon dioxide reduction target for the industrial park. The objective function is given as:

$$TC = \sum_{tp \in TP} \sum_{k \epsilon K} [C_{k,tp}^{Sinks}] + \sum_{tp \in TP} \sum_{s \epsilon S} \sum_{k \epsilon K} [C_{s,k,tp}^{LINE}] + \sum_{er \epsilon ER} [\Delta C_{er,tp}^{Renewables}] \qquad (64)$$

$$C_{k,tp}^{Sinks} = C_{k,tp}^{Sinks,\ Cost} \sum_{s \in S} F^{CO2}{}_{s,k,tp} \qquad \forall\ k \epsilon K\ tp \epsilon TP \quad (65)$$

$$C_{s,k,tp}^{LINE} = C_{s,k,tp}^{Treatment,Capex,F} + C_{s,k,tp}^{Compression,Capex,F} + C_{s,k,tp}^{Transportation,CapexF} \qquad \forall\ k \epsilon K\ tp \epsilon TP \quad (66)$$

$$\Delta C_{er,tp}^{Power,\ Renewable} = (G_{ec,tp}^{Fuel} - G_{er,tp}^{Renewables})\ P_{er,tp} \qquad \forall\ er \epsilon ER tp \epsilon TP \qquad (67)$$

Through time, a plant capacity might increase, decrease, sinks would reach maximum capacity or a plant may cease to exist either by contract with the cluster operator, policy, end of life or change in market demand. These factors result in dynamic connections between plants that can exist then disappear, the flow might change; it might switch for one period and appear in the second period. The cost of a connection would have to account to for these different associated costs for all elements of treatment, compression and transmission. Such transition factors are controlled using equations below, which ensure that any capital costs associated with the presence of a transmission line consisting of a pipeline, a compressor, (and a pump in case of supercritical conditions), utilize the line capacity for capex charges only once, across all time periods.

$$C_{s,k,tp}^{\text{Treatment,Capex,F}} = C_{s,k,tp}^{\text{Treatment Capex}} - C_{s,k,tp-1}^{\text{Treatment Capex}} \qquad \forall\, s\epsilon S \;\; k\epsilon K \;\; tp\epsilon TP \qquad (68)$$

$$C_{s,k,tp}^{\text{Treatment,Capex,F}} \geq 0 \qquad \forall\, s\epsilon S \;\; k\epsilon K \;\; tp\epsilon TP \qquad (69)$$

$$C_{s,k,tp}^{\text{Compression,Capex,F}} = C_{s,k,tp}^{\text{Compression, Capex}} - C_{s,k,tp-1}^{\text{Compression, Capex}} \qquad \forall\, s\epsilon S \; k\epsilon K \; tp\epsilon TP \qquad (70)$$

$$C_{s,k,tp}^{\text{Compression,Capex,F}} \geq 0 \qquad \forall\, s\epsilon S \;\; k\epsilon K \;\; tp\epsilon TP \qquad (71)$$

$$C_{s,k,tp}^{\text{Transportation,Capex,F}} = C_{s,k,tp}^{\text{Transprotation,Capex}} - C_{s,k,tp-1}^{\text{Transportation, Capex}} \qquad \forall\, s\epsilon S \; k\epsilon K \; tp\epsilon TP \qquad (72)$$

$$C_{s,k,tp}^{\text{Transportation,Capex,F}} \geq 0 \qquad \forall\, s\epsilon S \;\; k\epsilon K \;\; tp\epsilon TP \qquad (73)$$

Treatment cost is the summation of all segments of the cost based on the maximum flow of the line across all periods is given by equations below:

$$C_{s,k,tp}^{\text{Treatment, Capex}} = \sum_{t\in T} \alpha_{s,k,t,tp}^{\text{Treatment, Capex\_T}} \left(\sum_{sg\in SG} \left[A_{s,k,t,tp,sg}^{\text{Treatment, Capex\_T}} \, F_{s,k,t,tp,sg}^{\text{LINE\_T}} + B_{s,k,t,tp,sg}^{\text{Treatment, Capex\_T}} \, X_{s,k,t,tp,sg}^{T} \right] + \; l_{tp}^{\text{Treatment}} \, C_{s,k,tp-1}^{\text{Treatment, Capex}} \right) \qquad \forall\, s\epsilon S,\; k\epsilon K \;\; tp\epsilon TP \qquad (74)$$

$$C_{s,k,tp}^{\text{Treatment, Opex}} =$$

$$\sum\nolimits_{t\in T} \beta_{s,k,t,tp}^{\text{Treatment,Opex\_T}} \left(\sum\nolimits_{sg\in SG}\left[A_{s,k,t,tp,sg}^{\text{Treatment, Opex\_T}}\, T_{s,k,t,tp,sg}+B_{s,k,t,tp,sg}^{\text{Treatment, Opex\_T}}\, X_{s,k,t,tp,sg}^{T}\right]\right)$$

$$\forall\ s\epsilon S,\ k\epsilon K\ tp\epsilon TP \qquad (75)$$

Transportation capital cost is based on the maximum flow of the line across all periods described in equation (76)

$$C_{s,k,tp}^{\text{Transportation, Capex}} =$$

$$\sum\nolimits_{t\in T} \alpha_{s,k,t,tp}^{\text{Transportation,Capex\_T}} \left(\sum\nolimits_{sg\in SG}\left[A_{s,k,t,tp,sg}^{\text{Transportation, Capex\_T}}\, F_{s,k,t,tp,sg}^{\text{LINE\_T}}+B_{s,k,t,tp,sg}^{\text{Transportation, Capex\_T}}\, X_{s,k,t,tp,sg}^{T}\right]\right) +$$

$$\alpha_{s,k,tp}^{\text{Transportation,Capex\_U}} \sum\nolimits_{sg\in SG}\left(A_{s,k,tp,sg}^{\text{Transportation, Capex\_U}} F_{s,k,tp,sg}^{\text{LINE\_U}}+B_{s,k,tp,sg}^{\text{Transportation, Capex\_U}} X_{s,k,tp,sg}^{U}\right)+$$

$$l_{tp}^{\text{Transportation}}\ C_{s,k,tp-1}^{\text{Transportation, Capex}}$$

$$\forall\ s\epsilon S,\ k\epsilon K\ tp\epsilon TP \qquad (76)$$

Compression capital and operating costs are based on the maximum flow of the line across all periods is given by equations (77) and (78).

$$C_{s,k,tp}^{\text{Compression, Capex}} =$$

$$\sum\nolimits_{t\in T} \alpha_{s,k,t,tp}^{\text{Compression,Capex\_T}} \left(\sum\nolimits_{sg\in SG}\left[A_{s,k,t,tp,sg}^{\text{Compression, Capex\_T}}\, F_{s,k,t,tp,sg}^{\text{LINE\_T}}+B_{s,k,t,tp,sg}^{\text{Compression, Capex\_T}}\, X_{s,k,t,tp,sg}^{T}\right]\right) +$$

$$\alpha_{s,k,tp}^{\text{Compression,Capex\_U}} \sum\nolimits_{sg\in SG}\left(A_{s,k,tp,sg}^{\text{Compression, Capex\_U}} F_{s,k,tp,sg}^{\text{LINE\_U}}+B_{s,k,tp,sg}^{\text{Compression, Capex\_U}} X_{s,k,tp,sg}^{U}\right) + l_{tp}^{\text{Compression}}$$

$$C_{s,k,tp-1}^{\text{Compression, Capex}}$$

$$\forall\ s\epsilon S,\ k\epsilon K\ tp\epsilon TP \qquad (77)$$

$$C_{s,k,tp}^{\text{Compression, Opex}} =$$

$$\sum\nolimits_{t\in T} \beta_{s,k,t,tp}^{\text{Compression,Opex\_T}} \left(\sum\nolimits_{sg\in SG}\left[A_{s,k,t,tp,sg}^{\text{Compression, Opex\_T}}\, T_{s,k,t,tp,sg}+B_{s,k,t,tp,sg}^{\text{Compression, Opex\_T}}\, X_{s,k,t,tp,sg}^{T}\right]\right) +$$

$$\beta_{s,k,tp}^{\text{Compression,Opex\_U}} \sum_{sg\in SG}\left(A_{s,k,tp,sg}^{\text{Compression, Opex\_U}} U_{s,k,tp,sg} + B_{s,k,tp,sg}^{\text{Compression, Opex\_U}} X_{s,k,tp,sg}^{U}\right)$$

$$\forall\ s\epsilon S,\ k\epsilon K\ tp\epsilon TP \qquad (78)$$

The Mixed Integer Linear Program (MILP) formulation presented in the previous section has been implemented using “What'sBest 9.0” Lindo solver(2006) for MS-Excel 2010 via a desktop PC with Intel Core i7 Duo processor, 8 GB RAM and a 32-bit operating that used a branch and bound solver.

2.2.4 Policy Scenarios Application

An industrial city with processes is analyzed under different scenarios. The collective footprint is of 10 million tons of carbon dioxide emitted per year. Five plants are considered to be present in the industrial park, namely a fertilizer complex producing ammonia and urea, an iron and steel facility, fuel additive production, an oil refinery, and a power plant. Five CO_2 receiving sinks identified in or near the industrial city: algae production, an agriculture greenhouse, Enhanced Oil Recovery (EOR), saline storage in addition to the fertilizer complex and the fuel additive production. The goal is reduce emissions by 50% by the year 2030 starting from the current year. 2-year periods have been defined for 10 years horizon. Data of the sources, sinks and required parameters are shown in Table 2-8 adopted from Chapter 2.

Table 2-8: Carbon Integration Data

	Plant	CO_2 Composition. (wt%)	CO_2 Flow (t/d)	Sink fixation (t $CO_{2\ \text{emitted}}$/ t $CO_{2\ \text{captured}}$)	CO_2 Cost (USD/t CO_2)
Sinks	Enhanced Oil Recovery	0.94	6317	0	-30
	Methanol	0.99	1710	0.098	-21
	Fertilizer Complex – Urea	0.99	1126	0.39	-15
	Greenhouse	0.94	1030	0.5	-5
	Algae	0.06	283	0.42	0
	Saline Storage	0.94	8317	0	8.6
Source	Fertilizer Complex -CO_2 amine unit	1	977	0	0
	Steel-iron mill	0.44	3451	0	29
	Power Plant-gas turbine	0.07	9385	0	43
	Oil Refinery-boiler	0.27	1092	0	35

Linear cost correlations were obtained using Kwak (2016) method. The work carries an exhaustive search and develops cost correlation that was then used in a carbon integration optimization. The search explores pipeline diameters, number of stages of compressors and the possibility of adding turbines in addition to exploring pressure drop and the needed thermodynamic properties (Kwak, 2016). For this multi-period adaptation, the operating and capital costs were separated and a correlation for each was developed based on the previously mentioned method. The correlations used are shown in Table 2-9 and Table 2-10. The treatment operating cost for the treatment are described in chapter 2, with summing the active and inactive operating costs. The capital expenditure replacement parameter for treatment and piping was taken to be 0.1, based on a 20 year lifetime, while the capital expenditure replacement parameter for compression was taken to be 0.2, based on a 10 year lifetime.

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Table 2-9: Untreated Capital Cost Correlations

Sinks	Sources	Flow Range (MTPD)	Pipeline Capital Cost $C^{pipe, capex}_{c,p}$ ($a U_{s,tp} + b$)			Compression Capital Cost, $C^{comp, capex}_{c,p}$ ($a U_{s,tp} + b$)			Compression Operating Cost, $C^{comp, opex}_{,p}$ ($a U_{s,tp} + b$)		
			Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Algae	Fertilizer Complex	10~300	7,700	944,000	0.95	30	4,000	0.67	8	750	0.67
	Iron and Steel Production	10~285	1,900	2,906,000	0.94	400	121,000	1.00	280	1,470	1.00
	Refinery	10~285	2,100	3,152,000	0.94	400	123,000	1.00	280	1,780	1.00
	Power Plant	10~285	2,300	3,407,000	0.93	400	123,000	1.00	280	1,940	1.00
Greenhouse	Fertilizer Complex	10~977	32,700	13,724,000	0.93	600	65,000	0.99	340	6,120	1.00
	Iron and Steel Production	10~1030	15,600	23,889,000	0.94	500	177,000	0.99	300	15,180	1.00
	Refinery	10~1030	16,400	25,144,000	0.94	500	179,000	0.99	300	15,860	1.00
	Power Plant	10~1030	17,200	26,145,000	0.93	500	180,000	0.99	300	15,980	1.00
Methanol	Fertilizer Complex	10~977	500	209,000	0.94	1,800	177,000	1.00	1,040	5,460	1.00
	Iron and Steel Production	10~1710	400	310,000	0.92	1,700	223,000	1.00	1,060	4,400	1.00
	Refinery	10~1092	600	333,000	0.92	1,800	187,000	1.00	1,060	5,610	1.00
	Power Plant	10~1710	400	451,000	0.89	1,700	228,000	1.00	1,060	5,340	1.00
Urea	Fertilizer Complex	10~977	500	212,000	0.94	2,100	178,000	1.00	1,160	5,530	1.00
	Iron and Steel Production	10~1130	500	282,000	0.91	2,100	186,000	1.00	1,160	4,940	1.00
	Refinery	10~1092	700	242,000	0.92	2,100	174,000	1.00	1,160	3,490	1.00
	Power Plant	10~1126	500	251,000	0.92	2,100	179,000	1.00	1,160	3,820	1.00
Enhanced Oil Recovery	Fertilizer Complex	10~977	500	212,000	0.94	2,200	178,000	1.00	1,180	5,550	1.00
	Iron and Steel Production	10~3451	300	505,000	0.96	1,800	363,000	1.00	1,220	6,090	1.00
	Refinery	10~1092	600	226,000	0.92	2,100	175,000	1.00	1,180	3,650	1.00
	Power Plant	10~6316	300	673,000	0.90	1,800	485,000	1.00	2,140	2,950	1.00
Storage	Fertilizer Complex	10~977	500	209,000	0.94	2,200	177,000	1.00	1,180	5,460	1.00
	Iron and Steel Production	10~3451	300	386,000	0.93	1,900	345,000	1.00	1,180	6,290	1.00
	Refinery	10~1092	600	333,000	0.92	2,200	187,000	1.00	1,180	5,610	1.00
	Power Plant	10~8317	200	746,000	0.94	1,700	926,000	1.00	1,160	65,990	1.00

Table 2-10: Treated Capital Cost Correlations

Sinks	Sources	Flow Range (MTPD)	Pipeline Capital Cost $C^{pipe, capex}_{s,tp}$ (a $T_{s,tp}$ + b)			Compression Capital Cost, $C^{comp, capex}_{s,tp}$ (a $T_{s,tp}$ + b)			Compression Operating Cost, $C^{comp, opex}_{,s,tp}$ (a $T_{s,tp}$ + b)		
			Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Algae	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	10~285	3,400	478,000	0.96	40	4,000	0.66	20	460	0.69
	Refinery	10~285	8,700	1,085,000	0.95	40	5,000	0.66	40	980	0.65
	Power Plant	10~285	17,200	1,769,000	0.93	100	9,000	0.88	28	1,800	0.89
Greenhouse	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	10~1030	3,600	1,523,000	0.93	200	45,000	0.89	66	13,000	0.90
	Refinery	10~1030	34,300	14,695,000	0.93	200	46,000	0.89	68	13,600	0.90
	Power Plant	10~1030	34,600	14,825,000	0.93	200	46,000	0.89	70	13,600	0.90
Methanol	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	10~1710	300	267,000	0.95	1,500	242,000	1.00	1,000	5,200	1.00
	Refinery	10~1092	500	322,000	0.93	1,600	197,000	0.99	1,000	5,400	1.00
	Power Plant	10~1710	400	369,000	0.95	1,500	254,000	0.99	1,000	8,200	1.00
Urea	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	10~1130	400	254,000	0.93	1,800	195,000	1.00	1,000	4,000	1.00
	Refinery	10~1092	600	228,000	0.93	1,800	181,000	1.00	1,000	1,400	1.00
	Power Plant	10~1126	500	211,000	0.93	1,800	186,000	1.00	1,000	2,000	1.00
Enhanced Oil Recovery	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	100~3451	200	390,000	0.92	1,600	378,000	1.00	1,200	5,800	1.00
	Refinery	10~1092	500	214,000	0.93	1,900	182,000	1.00	1,200	1,600	1.00
	Power Plant	315~6317	300	683,000	0.91	1,500	610,000	1.00	1,200	1,800	1.00
Storage	Fertilizer Complex	0	-	-	-	-	-	-	-	-	-
	Iron and Steel Production	10~3451	200	363,000	0.90	1,600	359,000	1.00	1,200	5,400	1.00
	Refinery	10~1092	500	322,000	0.93	1,900	197,000	1.00	1,200	5,400	1.00
	Power Plant	100~6800	200	697,000	0.91	1,400	745,000	1.00	1,200	12,400	1.00

2.2.4.1 MINLP vs. MILP Multiperiod Model

To compare the performance between the MINLP model presented in chapter 2 and the MILP model this work presents, the same network solution of solved in chapter 2-1 shown in Figure 2-6 and Table 2-6, was compared. It should be noted that in MINLP, merged pipes one pipe was allowed from a source to sink while in MILP, treated and untreated sources had different pipes. The total cost of the MINLP network was -247 million USD. The same allocation was tested in the MILP model this work presents and resulted in a total cost of -272 million USD. The 10% improvement in the cost using the MILP model was due to the application of Kwak (2016) pre-optimization line connection as was shown in Figure 2-5 In the MINLP model the compression stages were assumed to be 4 stages in chapter 2 and a heuristic for the pressure drop in a pipeline Whereas in the MILP, the pre-optimization step was able to 1) optimize the number of compression stages, 2) estimate pressure drop using non-linear iterative functions leading to a more accurate pipe size (Kwak, 2016), both of which led to less energy use and thus reduced the cost required for compression and transportation. Analysing the connection from the fertilizer complex to the Enhanced Oil Recovery sink .The MINLP default compression stages were 4 and a pipe size of 4 inches resulting in a total cost of the connection of -84 million USD for the 10 year time horizon. Whereas, the MILP optimized number of stages were 5 and a pope size of 3 inches, resulting in a total cost of -89 million USD over the 10 year time horizon.

2.2.4.2 Carbon Reduction Policy: CCUS

First policy was explored was for phased emission reduction overtime. The policy requires 10% reduction of CO_2 emissions to reach 50% target at the end of five periods. The MILP has 9551 variables and 2577 constraints. The solution time was 9 seconds. The total cost of the network was -282 million USD. From period 1 to period 5, a total of six connections always were selected.

The enhanced oil recovery received treated CO_2 from the power plant. Untreated CO_2 from the fertilizer complex was connected to the methanol producing sink, the methanol sink also received treated CO_2 from the oil refinery thus filling the maximum capacity of the sink. The urea sink maximum intake was satisfied by treated CO_2 from the iron and steel facility and treated CO_2 from the oil refinery. In period 4 and 5, a new connection to the storage sink appeared that was supplied by treated CO_2 from the power plant, which increased from 489 in period 4 to 2,745 in period 5. The results are shown in Figure 2-7 and Table 2-11.

The phased policy was optimized, given a fixed quota of carbon dioxide equal to the phased reduction and a final design requirement to reach 50% reduction of CO_2.The MILP has 9549 variables and 2574 constraints. The solution time was 16 seconds. The total cost of the network was -285 million USD. From period 1 to period 5, a total of seven connections always were selected. The enhanced oil recovery received treated CO_2 from the power plant and treated and untreated iron and steel facility. Untreated CO_2 from the fertilizer complex was connected to the methanol producing sink, the methanol sink also received treated CO_2 from the iron and steel complex thus filling the maximum capacity of the sink. The urea sink maximum intake by treated CO_2 from the power plant and treated CO_2 from the oil refinery. While, the algae sink was supplied 183 tCO_2/d by untreated CO_2 from the oil refinery. In period 4 and 5 the Algae plant was supplied by more untreated CO_2 from the oil refinery, filling the Algae sink to 283 tCO_2/d, and a new connection appeared connecting treated CO_2 from the power plant to the storage sink 2,579 tCO_2/d. The results are shown in Figure 2-8 and Table 2-12. The prescribed cuts limits the exploration of alternative reduction methods. Limiting the overall carbon dioxide emitted throughout the period of carbon reduction to achieve 50% cut as the last design. This result is an optimized policy that could achieve higher revenue.

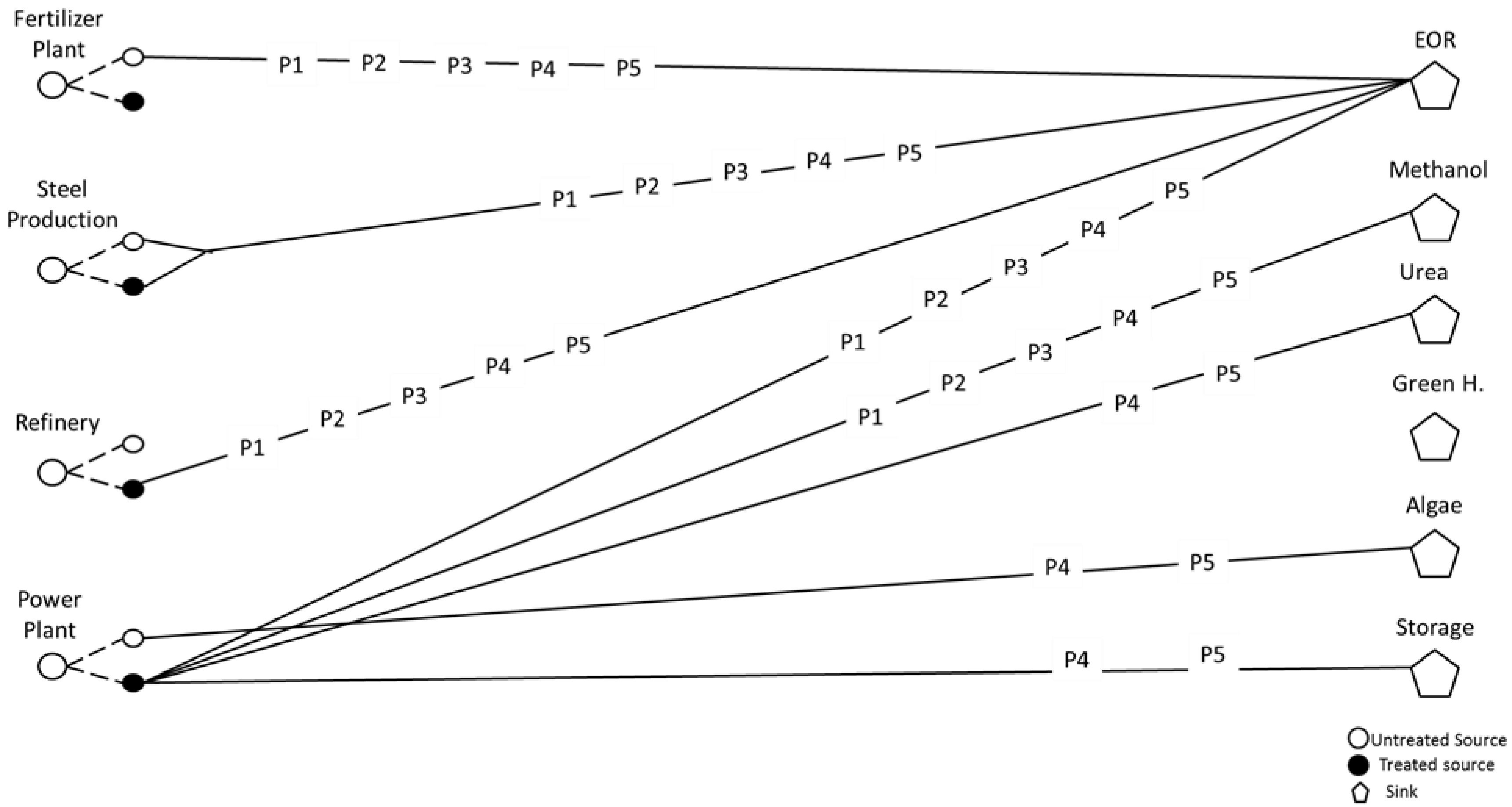

Figure 2-6: MINLP Optimized Network

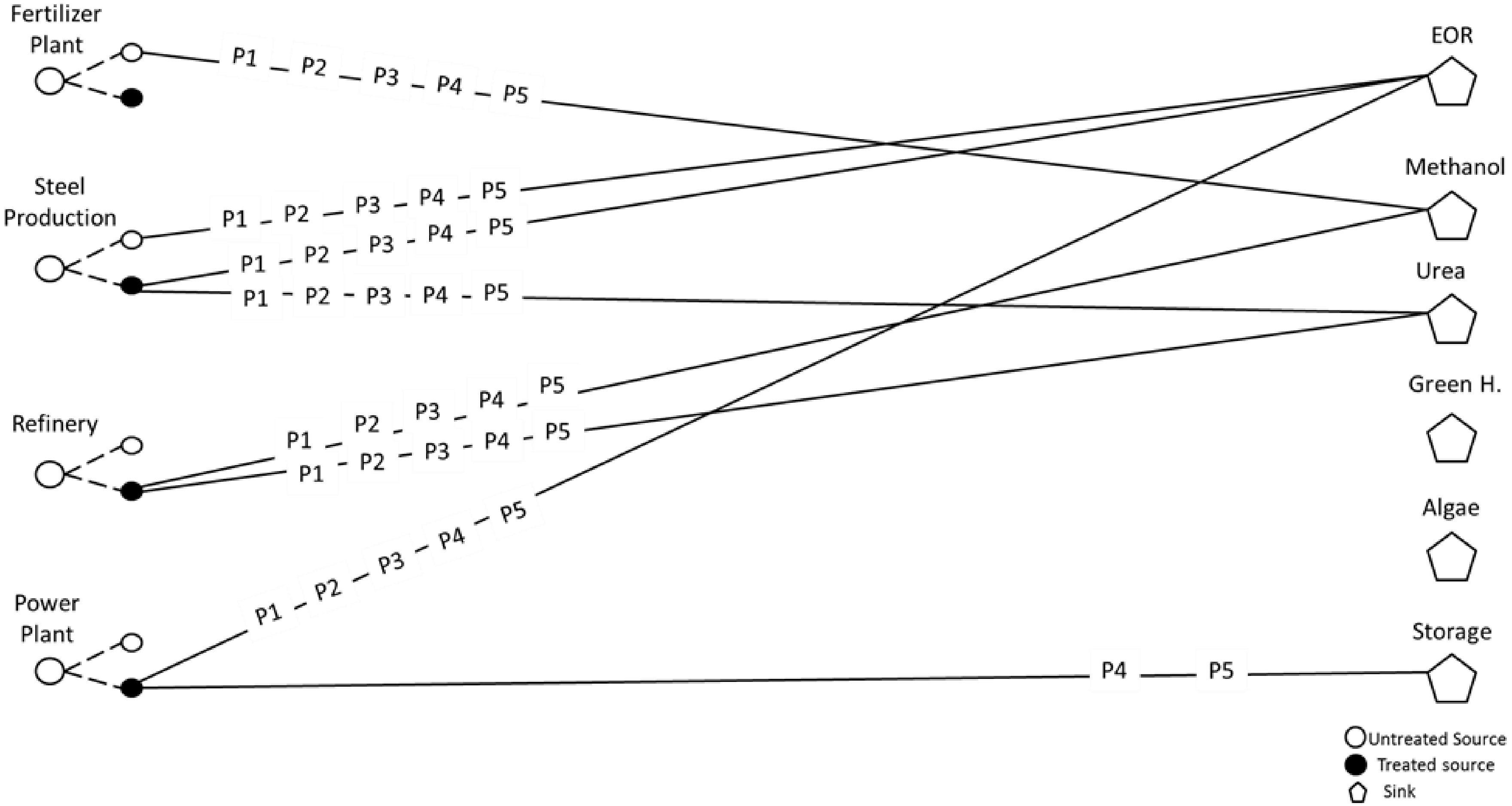

Figure 2-7:Phased CCUS Reduction Policy Allocation

Table 2-11: Phased CCUS Reduction Policy Allocation

Source	Period	Flow type	EOR	MEOH	UREA	GH	Algae	Storage
Fertilizer Complex	P1	T1	-	-	-	-	-	-
		U1	-	977	-	-	-	-
	P2	T2	-	-	-	-	-	-
		U2	-	977	-	-	-	-
	P3	T3	-	-	-	-	-	-
		U3	-	977	-	-	-	-
	P4	T4	-	-	-	-	-	-
		U4	-	977	-	-	-	-
	P5	T5	-	-	-	-	-	-
		U5	-	977	-	-	-	-
Iron and Steel Production	P1	T1	2,367	-	767	-	-	-
		U1	317	-	-	-	-	-
	P2	T2	2,367	-	767	-	-	-
		U2	317	-	-	-	-	-
	P3	T3	2,367	-	767	-	-	-
		U3	317	-	-	-	-	-
	P4	T4	2,367	-	767	-	-	-
		U4	317	-	-	-	-	-
	P5	T5	2,367	-	767	-	-	-
		U5	317	-	-	-	-	-
Oil Refinery	P1	T1	-	733	359	-	-	-
		U1	-	-	-	-	-	-
	P2	T2	-	733	359	-	-	-
		U2	-	-	-	-	-	-
	P3	T3	-	733	359	-	-	-
		U3	-	-	-	-	-	-
	P4	T4	-	733	359	-	-	-
		U4	-	-	-	-	-	-
	P5	T5	-	733	359	-	-	-
		U5	-	-	-	-	-	-
Power Plant	P1	T1	3,633	-	-	-	-	-
		U1	-	-	-	-	-	-
	P2	T2	3,633	-	-	-	-	-
		U2	-	-	-	-	-	-
	P3	T3	3,633	-	-	-	-	-
		U3	-	-	-	-	-	-
	P4	T4	3,633	-	-	-	-	489
		U4	-	-	-	-	-	-
	P5	T5	3,633	-	-	-	-	2,745
		U5	-	-	-	-	-	-

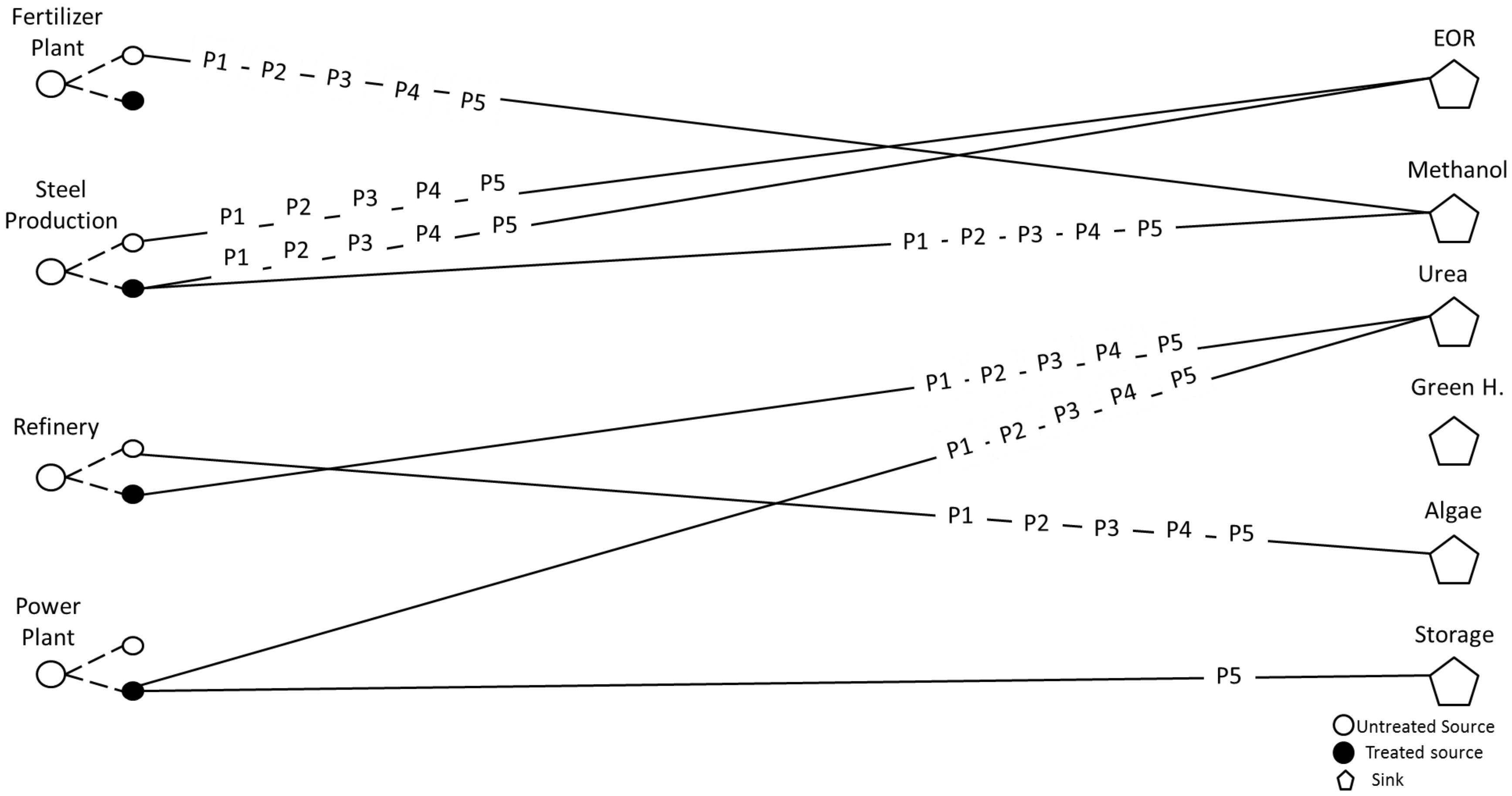

Figure 2-8: Optimized CCUS Reduction Policy Allocation

Table 2-12: Optimized CCUS Reduction Policy Allocation

Source	Period	Flow type	EOR	MEOH	UREA	GH	Algae	Storage
Fertilizer Complex	P1	T1	-	-	-	-	-	-
		U1	-	977	-	-	-	-
	P2	T2	-	-	-	-	-	-
		U2	-	977	-	-	-	-
	P3	T3	-	-	-	-	-	-
		U3	-	977	-	-	-	-
	P4	T4	-	-	-	-	-	-
		U4	-	977	-	-	-	-
	P5	T5	-	-	-	-	-	-
		U5	0	977	-	-	-	-
Iron and Steel Production	P1	T1	2,401	733	-	-	-	-
		U1	317	-	-	-	-	-
	P2	T2	2,401	733	-	-	-	-
		U2	317	-	-	-	-	-
	P3	T3	2,401	733	-	-	-	-
		U3	317	-	-	-	-	-
	P4	T4	2,401	733	-	-	-	-
		U4	317	-	-	-	-	-
	P5	T5	2,401	733	-	-	-	-
		U5	317	-	-	-	-	-
Oil Refinery	P1	T1	-	-	809	-	-	-
		U1	-	-	-	-	183	-
	P2	T2	-	-	809	-	-	-
		U2	-	-	-	-	183	-
	P3	T3	-	-	809	-	-	-
		U3	-	-	-	-	183	-
	P4	T4	-	-	809	-	-	-
		U4	-	-	-	-	283	-
	P5	T5	-	-	809	-	-	-
		U5	-	-	-	-	283	-
Power Plant	P1	T1	3,599	-	317	-	-	-
		U1	-	-	-	-	-	-
	P2	T2	3,599	-	317	-	-	-
		U2	-	-	-	-	-	-
	P3	T3	3,599	-	317	-	-	-
		U3	-	-	-	-	-	-
	P4	T4	3,599	-	317	-	-	-
		U4	-	-	-	-	-	-
	P5	T5	3,599	-	317	-	-	2,579
		U5	-	-	-	-	-	-

2.2.4.3 Carbon Reduction Policy: Renewable energy vs. CCUS

The MILP method was applied to investigate the role of renewable energy and how it compete with CCUS for carbon reduction. According to the International Renewable Energy Agency (IRENA), Qatar hopes to reach 20% capacity by 2030 (IRENA, 2016) mainly through the use of Solar Energy in power production. Taking Qatar's policy as an example, it was assumed that the power plant capacity could be replaced up to 20% by renewable energy, represented using photovoltaic. The power plant is built for a capacity of 1.034 GW with a 70% efficiency running for 8760 hours per year using natural gas as a fuel with a CO_2 emission of 0.00054 tCO_2/kWh. The power plant sells power to the grid at 0.040 USD/kWh . The electricity from Photovoltaic produced by the power plant had Levelized Cost of Electricity (LOCE) of 0.065 USD/kWh, a value within the range reported renewable power generation cost in 2017 (IRENA, 2018)

The policy investigated described a fixed 4% of solar energy replacement of the power plant in each period to reach 20% target installation by 2030 and 50% reduction target of CO_2. The MILP has 9328 variables and 2583 constraints. The solution time was 5 seconds. The total cost of the network was -169 million USD and total amount of CO_2 reduced was 164 million tons over the 10 year time horizon. The network allocation was similar to the original given CCUS policy (Figure 2-7), with the different in period 4 and 5 where storage was not supplied any CO_2 in period 4 and was only supplied 676 tCO_2/d in period 5. This was due to the cheaper savings of the reducing the tons of CO_2 through solar energy than compressing, transporting and capturing CO_2 in the storage sink.

However, when the policy was optimized for the same CO_2 emission reduction and no fixed solar energy deployment, only 17% of solar energy was activated in period 5 and the network cost was -229 million USD. The CO_2 network is shown in Figure2-9. The MILP has 9627 variables and 2584 constraints. The solution time was 63 seconds. The connection to the EOR was supplied by treated and untreated CO_2 from the steel facility and treated CO_2 from the power plant. Treated CO_2 from the steel facility was connected to storage in all periods. The optimized renewable policy resulted in a saving of 60 million USD. However, the price of the kWh of the solar energy exported affects the deployment of PV, thus different price scenarios were tested as described in Table 2-13.

Table 2-13: Effect of Changes in PV Price on CCUS-RE Networks

PV LOCE, USD/kWh		0.100	0.065	0.040	0.021
Emission reduction, million tons CO_2		164	-169	177.7	177.8
Total Cost, million USD		-225	-229	-358	-594
PV selection each period, % replaced of power plant	Period 1	0%	0%	20%	20%
	Period 2	0%	0%	20%	20%
	Period 3	0%	0%	20%	20%
	Period 4	0%	0%	20%	20%
	Period 5	0%	17%	20%	20%

At a high price of PV, 0.100 USD/kWh, PV is never selected, instead to meet the required emission reduction of 164 million tons of CO_2 over 10 years, the storage sink is activated. Similar allocation to Figure 2-7, with a new connection. From period 1 to period 3, storage demand by supplied by treated 300 tCO_2/d from the power plant which increases in period 4 and 5 to 2,579 tCO_2/d. When PV LOCE 0.040 USD/kWh, equal to power plant price, the cost of the network was -358 million USD and allocation similar to Figure 2-9. PV is selected from period 1 to period 5 at maximum capacity. The added profit comes from the cost neutral CO_2 ton reduced using PV compared to the storage sink. At the lowest price of PV, naturally PV was used from period 1 to period 5 at a maximum capacity. The allocation is the same as the optimized CCUS network, Figure 2-8 PV price can change from period to period. The cost forecasts provided through research and development produced leaning curves can be incorporated into a multi-period planning model, so as to reflect appropriate technology cost-reduction trends over time. Taking the capital cost of photovoltaic to be at 0.05 every 2 years (Kersten et al, 2011), the network results to a total cost of -256 million USD with similar allocation to Figure 2-9 and. PV selection in period 5 at maximum capacity.

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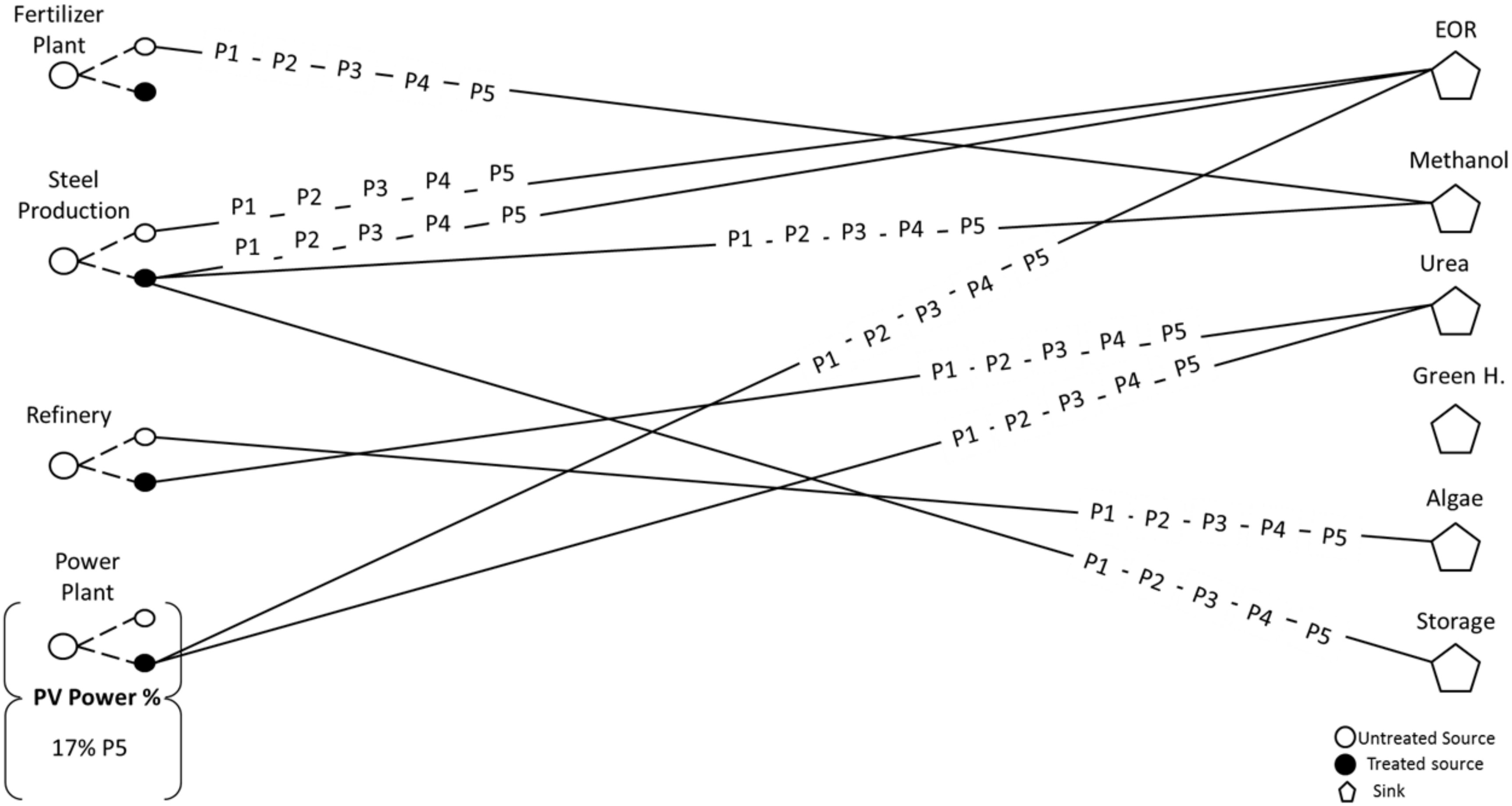

Figure 2-9: Optimized Carbon Reduction of CCUS-RE Policy

2.2.5 Conclusion

A systematic linear multi-period carbon integration approach have been proposed. The approach determines 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, and capture processes, power generation options including the use of renewable energy and compression and piping elements of the network. An example was presented to illustrate the linear approach and the different policy options including carbon capture utilization and storage and renewable energy targets. The results highlighted significant differences in economic impact of alternative footprint reduction policies. Different scenarios for an industrial park be explored using the proposed approach, giving both designers and policy makers a common tool to develop aligned future plans.

3 NATURAL GAS MONETIZATION UNDER CARBON EMISSION TARGETS[*]

3.1 Systematic Carbon Constrained Natural Gas Monetization Networks

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 associated with the lowest carbon dioxide (CO_2) footprint, enables dynamic power generation to balance intermittent renewable power generation in grid, and has repeatedly been highlighted as an important transition fuel towards low carbon futures (U.S. Energy, 2014). Recent advances in hydraulic fracking have significantly boosted proven natural gas reserves and resulted in increased natural gas processing capacities in many parts of the world (American Petrolum Institute, 2015). Besides its direct use a fuel, natural gas can be processed into a variety of products, prominent examples of which include liquid fuels, fertilizer and methanol (Al-Douri et al, 2017). Natural gas utilization through various products has become an important pillar of many economies. The State of Qatar is a prominent example as it has developed into the leading exporter of Liquefied Natural Gas (LNG), and a major producer of fertilizer and other basic materials over the past two decades (U.S. Energy, 2015).

Natural gas can be monetized through many alternative paths. It can be sold as natural gas, power, desalinated water, or converted into diverse sets of fuels and materials using many alternative processing technologies (Vora and Senetar, 2012). Each natural gas utilization option is associated with different profitability as well as certain carbon dioxide emissions either from energy inputs or as byproduct. Often, the alternative plants to process available natural gas feedstock are located in industrial clusters, cities or parks. The development of sustainable clusters

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[*] Part of this chapter was reprinted with kind permission from “On the synthesis of carbon constrained natural gas monetization networks” by Dhabia M. Al-Mohannadi, Sabla Y. Alnouri, and Patrick Linke. *Journal of Cleaner Production*. Volume 168, 735-745. Copyright 2017 by Elsevier Ltd

for the utilization of natural gas will not only aim at maximizing profits from natural gas conversions into fuels and materials. It will also be designed to meet carbon dioxide footprint constraints to align with global efforts to avoid dangerous climate change. It is therefore important to simultaneously consider carbon dioxide management options together with the assessment of natural gas utilization paths so as to devise highly profitable industrial clusters with low carbon dioxide emission.

The design challenge for such a cluster is to identify the most promising configurations from a number of possible alternatives, which may be derived by combinations of different natural gas utilization processes, and the many alternative carbon management options that could be applied in the industrial cluster, whilst exploiting synergies between natural gas conversion and carbon dioxide management. Moreover, given the combinatorial nature of this problem, there is a storng need for a systematic approach that can screen through the alternatives. This work presents a systematic apporach that could assist with the design and development of low carbon emission gas utilization strategies. The method would reduce the probability of overlooking solutions that could come from non systematic trial-and-error approaches. Research contributions on the development of systematic approaches have focused on either one of the two dimensions of the problem in isolation:

1. Reducing the carbon footprints of existing industrial complexes with process integration approaches, and
2. Identifying highly profitable natural gas utilization schemes.

3.1.1 Literature Review

In terms of process integration approaches for carbon mitigation, Tan and Foo (2007) developed a graphical method to achieve a carbon target by meeting energy demand. Similarly, graphical carbon-constrained energy planning was carried by Ooi et al (2013). Source-sink representation for energy integration and carbon footprint targeting was performed by Pekala et al (2010) for CCS. While, Turk et al (1987) used source-sink notation for CO_2 delivery and allocation focused only for geological storage sink options. Middleton and Bielicki (2009) considred infrastructure options of CCS, while Weihs and Wiley (2010) have attempted a cost-optimal CO_2 transmission network for CCS. Noureldin and El-Halwagi (2015) synthesizing carbon, hydrogen, and oxygen (C-H-O)S Networks (CHOSYNs) for the design of eco-industrial parks. Mixed Integer Non-Linear Program (MINLP) approach was used by Hasan et al (2014) to optimize large scale CO_2 supply chain networks considering capture technology selection for different CO_2 sources.

Al-Mohannadi and Linke (2016) had performed a systematic 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. The carbon integration approach considers detailed transmission and associated costs while evaluating different carbon dioxide converting processes. The synergies between different firms creates incentives to decrease the costs associated with carbon mitigation and reduces emission wastes.

Research into systematic approaches to developing gas utilization networks has only emerged very recently. Tan and Barton (2015) published a work focused on small scale shale gas production between LNG or Gas-to-Liquid (GTL) processes with a multiperiod formulation for a number of known natural gas producing wells. They followed by Tan and Barton (2016) updating the parameters using stochastic programing todealwith uncertainity in the decision making process.

However, Al-Sobhi and Elkamel (2015) have published the only work that is concerned with natural gas utilization considering industrial clusters. They determine allocation in an industrial cluster across LNG, GTL, and methanol processing options. Their proposed method establish plant performance using a commercial simulator to produce specifications, economic analysis, and environmental impact for comparison. Then, an optimization problem is formulated and solved to determine optimal gas allocations with maximum revenue. The method is specific to the three processes of utilization mentioned and does not consider carbon dioxide reduction effect on or possible carbon dioxide utilization options.

The current methods that deal with natural gas utilization do not cover the aspect of multiple processing options of natural gas and carbon diooxide simulatenously in industrial parks. Thus,, this work presents a first attempt to the development of a systematic approach that enables the identification of economically optimal, carbon constrained natural gas utilization strategies for an industrial cluster. The design problem is described in the next section, followed by the development of the proposed approach and its illustration with a case study.

3.1.2 Design Problem

This work aims to identify strategies for natural gas utilization in an industrial cluster under an overall carbon dioxide emission constraint. Therefore in this work, the attention is limited to clusters that utilize natural gas as the primary feedstock for its plants, where the maximum supply of natural gas is limited. Each plant receives natural gas supply from a common distribution infrastructure. In addition, each plant is connected to the existing electricity grid for 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 made up of all individual plant emissions and is constrained to an allowable total footprint. The total overall footprint and/or the footprints of individual plants may be limited by future policy and regulation.

At the beginning of the analysis, the cluster may already contain a variety of natural gas converting plants such as gas to fuels processes, gas to chemicals processes, power stations, and other plants that utilize gas as an energy source such as aluminum smelters, polysilicon plants or steel plants. Each plant is associated with a carbon dioxide emission and contributes to the overall carbon dioxide footprint of the cluster, which is to be reduced to attain future footprint goals. Additional plants may be introduced to the city that may perform one or more of the following functions:

a. Convert natural gas to alternative products;
b. Convert or sequestrate CO_2 through carbon capture utilization and storage (CCUS);
c. Produce power at reduced or eliminated specific natural gas requirements which feeds directly into the electricity grid, e.g. wind, solar power, etc

Taking a natural resource centric view, the gas allocation and plant selection should be optimized to achieve a maximum economic return on the gas utilized in the cluster. This is done while meeting the imposed carbon dioxide footprint limits and maintaining any minimum production requirements that may exist across different products as well as power generation from the cluster. Such minimum production requirements may stem from existing contracts to maintain operations of certain existing plants within the cluster.

This work introduces a superstructure-based optimization approach to enable the identification of the best performing gas utilization options for the cluster under carbon dioxide constraints. The approach allows to simultaneously exploit alternative natural gas and carbon dioxide conversion options in the cluster to identify configurations that stay within the allowable carbon dioxide emission for the cluster and offer gas utilization at maximum profitability. The work limits its focus on the management of the two key materials: natural gas (methane) as a feedstock and carbon dioxide as a footprint to be mitigated. In terms of energy management, it is assumed that each plant has a dedicated utility system to provide all heating and cooling for its processes. Each plant may be a net exporter or importer of power. Dedicated power stations export power into the Grid for use in the cluster and/or to meet export requirements. Power stations would typically be natural gas fired in the absence of a carbon dioxide emission constraint. Renewable power generation can be considered as options to reduce carbon dioxide footprints.

The problem addressed in this work can be formally stated as follows. The goal is to determine the optimal:

- Selection of production plants to be included in the cluster,
- Selection of natural gas fired and renewable energy power generation plants,
- Allocation of natural gas to each of the defined plants in the cluster,

- Capture, treatment and allocation of carbon dioxide sources to potential carbon dioxide sinks, storage or utilization

To yield the maximum monetary return from the cluster whilst meeting a prescribed total carbon dioxide emissions limit for the cluster and any other relevant production constraints imposed on the cluster or on individual plant. The following information is assumed to be known about the cluster, processing options and carbon dioxide emissions management options:

- The number of plants and their locations
- Set of products produced in the cluster, per plant, referred to as products.
- Known natural gas composition, flow limits, and price
- For each plant known power qualities, limits and costs, carbon dioxide conversion and fixation, known products to methane or carbon dioxide conversion, and price of each product with capacity limits
- A total power requirement associated with the cluster
- Known total carbon dioxide emission from the cluster based on original layout (existing plants)
- Known emission regulation or commitments

3.1.2.1 Design Representation

The proposed optimization-based approach will search a superstructure network representation of the cluster to explore interactions between natural gas supply, conversion options, power generation replacement options as well as carbon dioxide management options. The superstructure network is developed out of individual plant modules to capture the relevant inputs and outputs for a given plant in the cluster.

3.1.2.2 Generic plant module

The main building block of the network representation is a plant module shown in Figure 3-1. A plant is a sink for natural gas feed from the supply infrastructure, a sink for carbon dioxide and a sink for imported power. In terms of outputs, a generic plant produces products from conversions of natural gas and carbon dioxide, exports power, and has multiple point sources of carbon dioxide emissions.

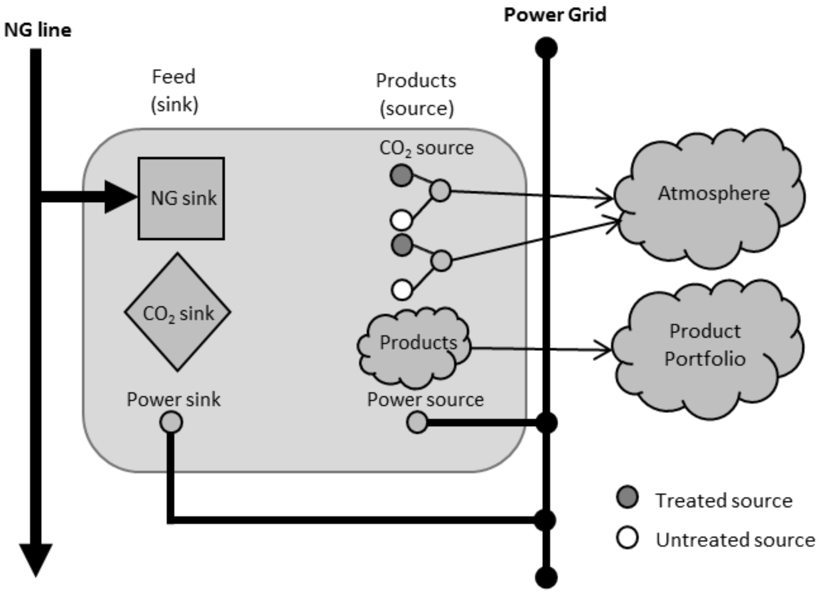

Figure 3-1: Generic plant module. Reprinted with kind permission from Al-Mohannadi et al (2017)

The carbon dioxide sources would normally be emitted to the atmosphere, but could be captured and converted to value added products in a carbon dioxide sink of a process in the same plant, other plants or used in other applications witin the industrial cluster. Carbon dioxide sources can be considered for utilization or sequestration in either its original form (untreated) or as an enriched carbon dioxide stream (treated source) (Al-Mohannadi and Linke, 2016). Products from a plant will become part of the product portfolio of the industrial cluster.

Not all sources and sinks of the generic plant module will be active in all plants. The module setup will depend upon the specific plant under consideration. A typical example of plant module for a Liquefied Natural Gas plant will have an active natural gas sink and will have multiple sources of carbon dioxide from the process which could be a by-product from natural gas processing step or from the gas turbine exhust. It will also produce LNG as its product exported from the plant and the module will have power source or sink through connections to the electricity grid depending on the plant the utility system setup. While, a plant module for a methanol plant will have a natural gas or carbon dioxide sink, depending on the technology, and produce methanol as its main product. It may be a power source and sink through connections to the electricity grid. On the other hand, a plant module such as algae production would only be a carbon dioxide sink and would produce algae products (e.g. fodder) for the product portfolio, may have a carbon dioxide source and import/export power from/to the electricity grid. Other plant modules would only sell power to the exisiting power grid such as a natural gas fired power plant. The typical plant module would have a natural gas sink, a carbon dioxide source and export power to the electricity grid. As for renewable power plant module, such as a wind park, the module would not have any sinks and export power as the only output.

The generic plant module enables representation of each individual plant to be considered for participation in the cluster. It forms the building block of the network superstructures that will be optimized in this work.

3.1.2.3 Network superstructure representation

To capture all possible configurations of the industrial cluster in terms of gas allocations, carbon dioxide source and sink integration, and power generation options as a basis for optimization, a superstructure network is generated using the generic plant modules.

In general, the superstructure will contain a number of plants, each represented by a plant module. The cluster has a natural gas supply infrastructure that is connected to all active natural gas sinks across all plant modules. Any products produced in each plant are placed in the industrial cluster product portfolio. Further, the cluster has an electricity grid to which the active power sources and sinks of all plant modules are connected. In addition, all active carbon dioxide sinks of all plant modules are connected both treated and untreated carbon dioxide sources all plant modules in the cluster. The carbon dioxide sources of each plant module are further connected to the athmosphere. The carbon dioxide source and sink connectivities follow the carbon integration approach proposed by Al-Mohannadi and Linke (2016). Figure 3-2 illustrates the superstructure connectivity for a small cluster involving two production plants, one gas fired power station and one renewable power generation plant. .

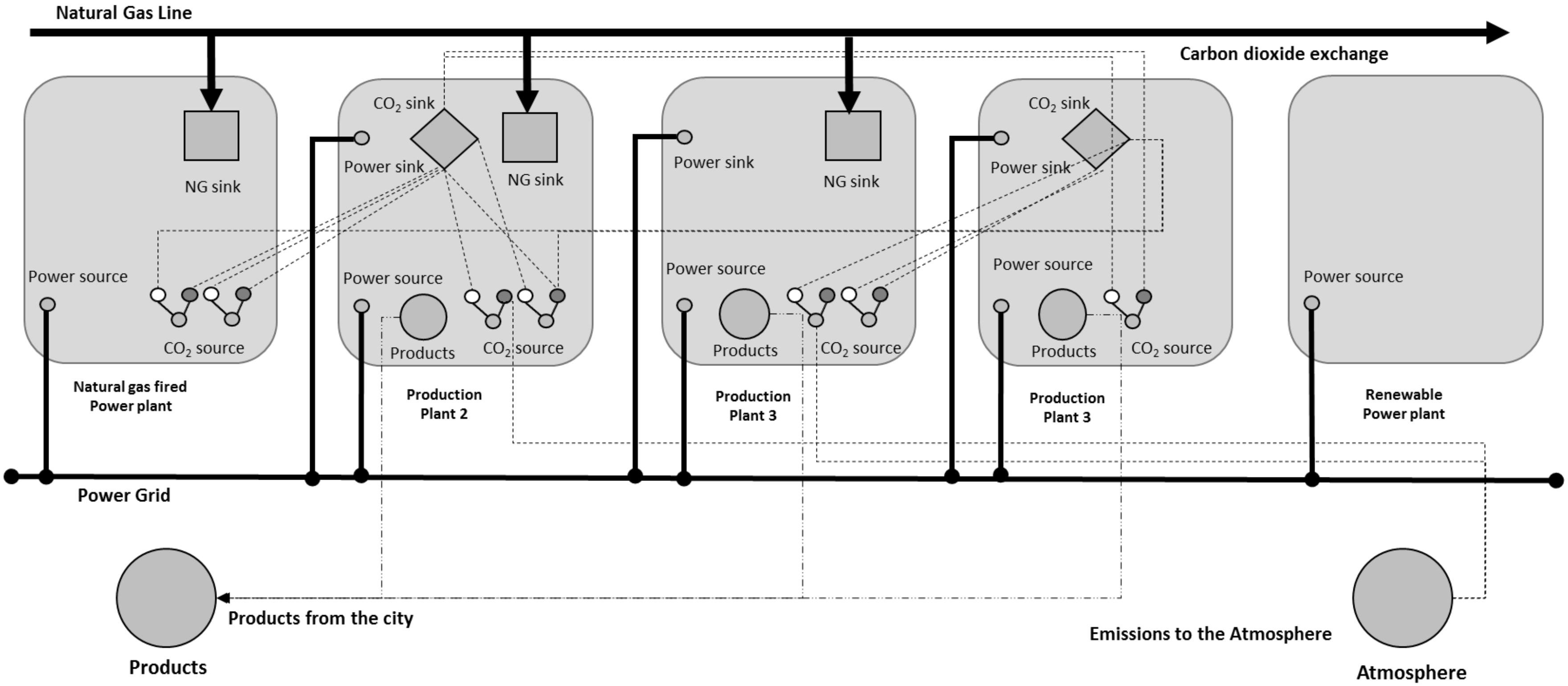

Figure 3-2: Illustration of natural gas and carbon dioxide network superstructure with 3 generic production plants, NG-fired power plant, and renewable power plant. Reprinted with kind permission from Al-Mohannadi et al (2017)

The superstructure representation embeds all possible configurations for the cluster in terms of plant existence and source and sink interconnectivities. The next section formulates the superstructure optimization problem, which can then be solved to identify the cluster design, which maximizes profitability of gas utilization within the allowable cluster carbon dioxide emission.

3.1.3 Model formulation

An optimization model is formulated to explore the superstructure representation described above. The following sets were used:

P $\{p|p=1,2,3,\ldots,N_{plants}|$ P is a set of plants $\}$

E $\{ p|p =1,2,3,\ldots,NE_{plants}|$ E is a subset of existing plants that belong to set P, $E \subset P$ $\}$

O $\{ p|p =1,2,3,\ldots,NO_{plants}|$ O is a subset of optional plants that belong to set P, $O \subset P$ $\}$

C $\{c|c=1,2,3, ,\ldots,N_C|$ C is a set of products produced in industrial city$\}$

Q $\{q|q=1,2,3, ,\ldots,N_q|$ Q is a set of power type options in industrial city$\}$

$S_{c,p}\{s|s=1,2,3, ,\ldots,Ns|$ $S_{c,p}$ is a set of carbon sources produced in plant p associated with product c$\}$

K_p $\{k_p|k_p=1,2,3,\ldots,N_{CO2\ p\ sinks}|$ K_p is a set of carbon sinks in plant p$\}$

T $\{t|t=1,2,3,\ldots,T_{max}|$ T is a set of carbon treatment technology$\}$

The model formulation consists of a number of equality and inequality constraints, which are presented for plant modules and the integrated network of plant modules below.

3.1.3.1 Balances and Constraints

a. Plant Module

The product flow requirements in existing plants is given by equation (79).

$$L^{c}_{c,p} \leq F^{c}_{c,p} \leq M^{c}_{c,p} \qquad \forall\, c \epsilon C\ p \epsilon EP \qquad (79)$$

$F^{c}_{c,p}$ is the flow of product c in existing plant p that falls between a specified lower and upper flow bounds $L^{c}_{c,p}$, $M^{c}_{c,p}$ respectively. The product flow requirements in optional plants is given by equation (80).

$$L^{c}_{c,p}\, I^{o}_{p} \leq F^{c}_{c,p} \leq I^{o}_{p} M^{c}_{c,p} \qquad \forall\ c \epsilon C\ p \epsilon OP \qquad (80)$$

Where I^{o}_{p} is a binary variable (0,1) which defines the activation of an optional plant p. The product to methane intake to plant p is shown below.

$$F_{p} = \sum_{c \in C} F^{c}_{c,p}\, \varphi^{c}_{c,p} \qquad \forall\ p \epsilon P \qquad (81)$$

Where $\varphi^{c}_{c,p}$ is a parameter, which represents the required methane intake per product c in plant p. Carbon dioxide source flow is based on product production as given below

$$M_{s,c,p} = F^{c}_{c,p}\, \Phi^{c}_{s,c,p} \qquad \forall\ s \epsilon S_{c,p}\ c \epsilon C\ p \epsilon P \qquad (82)$$

Where $\Phi^{c}_{s,c,p}$ is a parameter associated with each defined carbon dioxide source s per product c in plant p. The plant power calculation is carried through equation (83).

$$P_{p,q} = \sum_{c \in C} F^{c}_{c,p}\, \varphi^{PW}_{c,p,q} \qquad \forall\ p \epsilon P\ q \epsilon Q \qquad (83)$$

Where $\varphi^{PW}_{c,p,q}$ is a parameter, which represents the specific required/generated power in plant p of type q. $\varphi^{PW}_{c,p,q} > 0$, represents a power surplus generated by product c in plant p, while $\varphi^{PW}_{c,p,q} < 0$ represents a power deficit needed by product c in plant p. $P_{p,q}$ is the power output from plant p with type q.

Each power type can have a limits of power type in plant, which is represented in the equation below

$$L^{p}_{p,q} \leq X^{p}_{p,q} \leq U^{p}_{p,q} \qquad \forall\ q \in Q\ p \in P \qquad (84)$$

$X^{p}{}_{p,q}$ is a variable which represent the power amount of type q used in existing plant ep and optional plant op respectively. While, $L^{p}{}_{p,q}$ and $U^{p}{}_{p,q}$ are the specified lower and upper allowed of power amount type q in plant p.

The power balance ensures that all amounts corresponding to each power type option in plant p does not exceed the total

$$\sum_{q\in Q}\sum_{p\in P} X^{p}{}_{p,q} = PR \qquad (85)$$

b. Network Superstructure

The raw source carbon flow can be allocated between an upper and a lower limits as shown below

$$L_{s,c,p} \leq R_{s,c,p} \leq M_{s,c,p} \qquad \forall\, s\epsilon\, S_{c,p}\ c\epsilon C\ p\epsilon P \qquad (86)$$

$R_{s,c,p}$ is the raw carbon flow from plant p source s associated with product c. $L_{s,c,p}$ and $M_{s,c,p}$ are lower and maximum carbon flow available from source s associated with product c in plant p. The mass balances around raw carbon sources s is given as follows:

$$R_{s,c,p} = \sum_{t\in T}\sum_{k\in K}\sum_{p\in OP} \varepsilon_t^t T_{s,c,p,k,p,t} I_p^o + \sum_{k\in K}\sum_{p\in OP} U_{s,c,p,k,p} I_p^o + \sum_{t\in T}\sum_{k\in K}\sum_{p\in P} \varepsilon_t^t T_{s,c,p,k,p,t} + \sum_{k\in K}\sum_{p\in P} U_{s,c,p,k,p}$$

$$\forall\, s\epsilon\, S_{c,p}\ c\epsilon C\ p\epsilon P \qquad (87)$$

The carbon dioxide component mass balance around the raw sources is given by

$$R_{s,c,p} y_{s,c,p} = \sum_{t\in T}\sum_{k\in K}\sum_{p\in OP} \varepsilon_t^t T_{s,c,p,k,p,t} y_{s,c,p,t} I_p^o + \sum_{k\in K}\sum_{p\in OP} U_{s,c,p,k,p} y^u_{s,c,p} I_p^o$$

$$\sum_{t\in T}\sum_{k\in K}\sum_{p\in P} \varepsilon_t^t T_{s,c,p,k,p,t} y_{s,c,p,t} + \sum_{k\in K}\sum_{p\in P} U_{s,c,p}\, y^u_{s,c,p} \qquad \forall\, s\epsilon\, S_{c,p}\ c\epsilon C\ p\epsilon P \qquad (88)$$

The total mass balance around carbon sinks k in plant p is given as:

$$F_{k,p}=\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in OP}\sum_{t\in T}\varepsilon_t^t T_{s,c,p,k,p,t} I_p^o+\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in OP}U_{s,c,p,k,p} I_p^o+\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in P}\sum_{t\in T}\varepsilon_t^t T_{s,c,p,k,p,t}+$$

$$\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in P}U_{s,c,p,k,p}$$

$$\forall\ k\epsilon K\ p\epsilon P \qquad (89)$$

While the sink component balance around the sink is met by

$$F_{k,p}Z_{k,p}^{min}\leq\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in OP}\sum_{t\in T}\varepsilon_t^t T_{s,c,p,k,p,t}y_{s,c,p,t}I_p^o+\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in OP}U_{s,c,p,k,p}y_{s,c,p}^u I_p^o+$$

$$\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in P}\sum_{t\in T}\varepsilon_t^t T_{s,c,p,k,p,t}y_{s,c,p,t}+\sum_{s\in S_{c,p}}\sum_{c\in C}\sum_{p\in P}U_{s,c,p,k,p}y_{s,c,p}^u$$

$$\forall\ k\epsilon K\ p\epsilon P \qquad (90)$$

All untreated sources have carbon dioxide concentration of the raw source:

$$y_{s,c,p}^u = y_{s,c,p} \qquad (91)$$

Any source can be connected to any sink subject to the sink minimum concentration requirement $Z_{k,p}^{min}$ and the sink flow requirement $G_{k,p}{}^{max}$ in as described below

$$F_{k,p}= G_{k,p}^{max} \qquad \forall\ k\epsilon K \qquad (92)$$

Equations (93) and (94) ensure carbon dioxide flow stays between the pipeline limits

$$L^{pipe}\ X_{s,\ c,p,k,p}\leq T_{s,\ c,p,k,p,t}\leq M^{pipe}X_{s,\ c,p,k,p} \qquad \forall\ s\epsilon\ S_{c,p}\ c\epsilon C\ p\epsilon P\ k\epsilon K\ t\epsilon T \qquad (93)$$

$$L^{pipe}\ X_{s,\ c,p,k,p}\leq U_{s,\ c,p,k,p}\leq M^{pipe}X_{s,\ c,p,k,p} \qquad \forall\ s\epsilon\ S_{c,p}\ c\epsilon C\ p\epsilon P\ k\epsilon K \qquad (94)$$

Where L^{pipe} is the lower flow limit and M^{pipe} is the upper flow limit of source-sink connection within a pipeline. $X_{s,c,p,k,p}$ is a binary (0,1) associated with flow of the treated and untreated streams for the pipeline connecting source s associated with product c in plant p connected to sink k in plant p. The mass balance of methane source and flow limits are given as follows in eq (95) and eq (96):

$$F_{methane} = \sum_{p \in P} F_p \qquad (95)$$

$$LF_{methane} \leq F_{methane} \leq MF_{methane} \qquad (96)$$

$F_{methane}$ is the total flow of methane to the industrial city. F_p is the methane flow to a plant p, $LF_{methane}$ is the lower methane flow available, while $MF_{methane}$ is the maximum methane flow available to the industrial city use. The total carbon dioxide from product c production in plant p is given as:

$$F^{CO2}{}_{c,p} = \sum_{s \in S_{c,p}} \sum_{c \in C} M_{s,c,p} \qquad \forall\ c \epsilon C\ \forall\ p \epsilon P \qquad (97)$$

While, the total power of the city is given as:

$$PR = \sum_{q \in Q} \sum_{p \in P} P_{p,q} \qquad (98)$$

The total power in the plant must meet a supply/grid export demand and is insured by the expression below.

$$LPR \leq PR \leq MPR \qquad (99)$$

Where PR is the power output in the city, LPR is the minimum possible power output of the city and MPR is the maximum possible power output of the city. PR also includes the summation of the power requirement of carbon dioxide streams compression that is furtherly explained in the work by Al-Mohannadi and Linke (2016).

The carbon integration network needs to meet the Carbon dioxide Emission Limit (CEL) for the industrial park. The Carbon dioxide Emission of the network (CE) is determined as follows:

$$CE = \sum_{p\in P} \sum_{c\in C} F^{CO2}{}_{c,p} - \sum_{p\in P} \sum_{k\in K} F_{k,p}{}^{CO2} (1-\eta_{k,p}) - \sum_{s\epsilon S} \sum_{c\epsilon Cp} \sum_{p\epsilon P} \sum_{k\epsilon K} \sum_{p\epsilon P} \sum_{t\epsilon T} T_{s,c,p,k,p,t}\, y_{s,c,p,t}\, \gamma_t + \sum_{p\in P} \sum_{k\in K} F_{k,p}{}^{CO2} \varepsilon_p^p \qquad (100)$$

Where,

$$CE \leq CEL \qquad (101)$$

γ_t is amount of carbon dioxide emitted from the treatment unit energy use, $F_{k,p}{}^{CO2}$ is the carbon dioxide flow into the sink, while η_k is the sinks efficiency and ε_p^p accounts for the power use carbon footprint. Non-negativity constraints are described the following variables, $T_{s,c,p,k,p,t}$, $U_{s,c,p,k,p}$, $y_{s,c,p,t}$, $y_{s,c,p}$, $M_{s,c,p}$, $F^c{}_{c,p}$, $F^{CO2}{}_p$, F_p, F_k , $X^p{}_{p,q}$ and PR.

3.1.3.2 Objective function

The objective is to identify the cluster setup that achieves maximum profit from the available natural gas. The profit is calculated as:

$$Profit = REV^c + REV^{CO2} – [Cost^M + Cost^{EP} + Cost^{OP} + Cost^{CO2} + Cost^{CI}] \qquad (102)$$

Where; the revenue from all products and associate by-products, REV^c is given as

$$REV^c = \sum_{p\in P} \sum_{c\in C} F^c{}_{c,p}\, C_c^c + \sum_{p\in P} \sum_{c\in C} \sum_{q\in Q} F^c{}_{c,p}\, C^{PW}{}_{c,p,q} \qquad (103)$$

Where $C^{PW}{}_{c,p,q}$ is the power price associated with product c in plant p for type q. The revenue from carbon dioxide sinks, REV^{CO2} is given as

$$REV^{CO2} = \sum_{p\in P} \sum_{k\in K} F^{CO2}{}_{k,p}\, C_{k,p}^{CO2} \qquad (104)$$

$C_{k,p}^{CO2}$ is the price paid for carbon dioxide to produce products in sinks.The cost of methane, $Cost^{M}$ is calculated as:

$$\mathrm{Cost}^{M}=\sum_{p\in P} F_p\ C_p^{M} \tag{105}$$

The cost of existing plant are given as

$$\mathrm{Cost}^{EP}=\sum_{p\in EP}\sum_{c\in C_p} C_{c,p}^{capex}{F^c}_{c,p}\ A\ +\sum_{p\in EP}\sum_{c\in C_p} {F^c}_{c,p}\ C_{c,p}^{opex}\ hy \tag{106}$$

A is the annualization factor, while hy accounts for the time conversion The operating cost parameter accounts for all raw materials (except natural gas and carbon dioxide), utilities, labor, and maintenance. The cost of optional plants are given as:

$$\mathrm{Cost}^{OP}=\sum_{p\in OP}\sum_{c\in C_p} C_{c,p}^{capex}{F^c}_{c,p}\ \ A+\sum_{p\in OP}\sum_{c\in C_p} {F^c}_{c,p}\ C_{c,p}^{opex} hy \tag{107}$$

As for the cost of carbon integration network Cost^{CI} are given by equations (108) to (111). The cost of the carbon integration network include costs of compression, pipeline network and treatment of carbon dioxide from the initial sources of CO_2 to their sink:

$$\mathrm{Cost}^{CI}=\mathrm{Cost}^{Comp}+\mathrm{Cost}^{Treatment}+\mathrm{Cost}^{Pipe} \tag{108}$$

$$\mathrm{Cost}^{Comp}=\sum_{p\in OP}\sum_{c\in C_p} C_{c,p}^{Comp,\ capex}\ \ A+\sum_{p\in OP}\sum_{c\in C_p}\ C_{c,p}^{Comp,\ opex} hy \tag{109}$$

$$\mathrm{Cost}^{Pipe}=\sum_{p\in OP}\sum_{c\in C_p} C_{c,p}^{Pipe,\ capex}\ \ A+\sum_{p\in OP}\sum_{c\in C_p}\ C_{c,p}^{Pipe,\ opex} hy \tag{110}$$

$$\mathrm{Cost}^{Treatment}=\sum_{t\in T}\sum_{k\in k}\sum_{p\in OP}\sum_{c\in C_p}\sum_{c\in Sc,p} T_{s,c,p,k,p,t}$$

$$C_{c,p}^{Treatment,\ capex} A\ \ +\sum_{t\in T}\sum_{k\in k}\sum_{p\in OP}\sum_{c\in C_p}\sum_{c\in Sc,p} T_{s,c,p,k,p,t}\ C_{c,p}^{Treatment,\ opex} hy \tag{111}$$

All costs have two components capital and operating, which make up the total costs. The capital costs parameters include equipment as a function of flow, pressure and distances while operating cost parameter include energy, manpower and maintenance.

3.1.4 Illustrative Example

The proposed methodology is illustrated using a case study of an industrial cluster that includes a set of existing and optional plants. namely a Liquefied Natural Gas (LNG) plant, Gas-to-Liquid (GTL) facility, a Cement plant, an Aluminum plant, a Natural Gas Fired Power Plant, a Renewable Solar Photovoltaic Plant (PV), Enhanced Oil Recovery (EOR), Saline Storage, Methanol plant (both a standard (A), and a carbon dioxide-receiving plants(B)) and a Greenhouse. The plants main products and approach required information are shown in Table 3-1.

Table 3-1: Industrial City Plant Information. Reprinted with kind permission from Al-Mohannadi et al (2017)

Plant	$M^{c}_{c,p}$ Max Flow	$\varphi^{c}_{c,p}$ tCH4/tProduct	$\Phi^{c}_{s,c,p}$ tCO_2out/tProduct	$\varphi^{PW}_{c,p,q}$ kWh/tProduct
Methanol (A)	5000	0.683	0.50	0.000
Cement	10,000	0.058	0.54	0.89
Aluminum	2000	2.180	6.00	0.000
LNG	8000	1.046	0.20	0.000
GTL	14,600	1.620	(A) 0.99	0.000
			(B) 3.03	
Methanol (B)	2, 600	0.000	0.09	0.000
Natural gas fired power plant	2,224	0.15 tCH42/MWh	0.4 tCO2/MWh.	$6.67x10^{3}$
Solar Power Plant	0.000	0.000	0.000	3.56kWh/kWp-d

Each plant has its utility system and performance that are left intact. All sources give dilute carbon dioxide at 7 wt%, 27 wt% in case of cement and with the exception of GTL that give dilute carbon dioxide at 7 wt% from the utilities and concentrated carbon dioxide at 100 wt% as a result of the reformer separation unit. Plants economic information are shown in Table 3-2.

Table 3-2: Plants Economic Information. Reprinted with kind permission from Al-Mohannadi et al (2017)

Plant	$C^{c}{}_{c}$ $/t product	$C^{capex}{}_{c,p}$ Capex(($/t$CO_2$)	$C^{opex}{}_{c,p}$ Opex($/t$CO_2$)	$C^{Treatment,Capex}{}_{s,c,p}$ $/t$CO_2$	$C^{Treatment,Opex}{}_{s,c,p}$ $/t$CO_2$
Methanol	442	460	20	38	10
Cement	85	320	30	30	8
Aluminum	1550	4650	990	38	10
LNG	370	250	0.08	38	10
GTL	850	1820	0.62	(A)0.00	0.00
				(B) 38	10
Alternative Methanol	442	2700	270	0	0
Natural gas fired power plant	0.02 $/kWh	1000 $/kWe	0.00	38	10
Solar power plant	0.02 $/kWh	1.05 $/We	0.00	0.00	0.00

The city’s power plant has an electrical capacity of 1 GW per year, with a 60% efficiency. The capital cost of the power plant 1,000 $/kWe (Seebregts et al, 2010) and the operating cost was calculated based on the methane intake. The power plant capacity could be replaced up to 20% by renewable energy. The capital cost of a solar panel was at 1.05 $/W (IRENA, 2012). The photovoltaic power producing efficiency was calculated based on the power output at peak capacity (Photovoltaic Plant Output, 2016). The power price was taken as 0.02 $/kWh (Kahramaa, 2015). The data used to implement the case study were obtained from literature for, GTL (Economides, 2005; Bao et al, 2010), Aluminum (Rosenberg and Simbolotti, 2012; European

Commission, 2014), LNG plant (Economides, 2005), EOR, storage (Al-Mohannadi and Linke, 2016; Metz et al, 2005; Global CCS Institute, 2011), cement (Cochez et al, 2010), methanol plant (A)(Perez-Fortes et al, 2016; Pellegrini et al, 2011; Methanex, 2015) and Methanol plant (B) (Mingard et al, 2003; Methanex, 2015) after the removal of the carbon dioxide embedded treatment costs. Units conversion was applied to get the given units in this case study (International gas union, 2012). The economic parameters were updated to 2014 using the chemical engineering cost indices (Chemical Engineering, 2013; 2015). Carbon dioxide identified sinks are shown in Table 3-3.

Table 3-3: Carbon Sinks Identification. Reprinted with kind permission from Al-Mohannadi et al (2017)

Plant	$G_{k,p}{}^{max}$ t/d	$Z_{k,p}^{min}$ wt%	$P_{k,p}^{CO_2}$ MPa	$\eta_{k,p}$ tCO_2 out of the sink/tCO_2 into the sink	$C_{k,p}^{CO2}$ \$/tCO_2 in the sink
CO_2 receiving Methanol	1710	100%	8.0	0.09	20.0
Greenhouse	1030	100%	15.0	0.5	5.0
Storage	8317	100%	15.0	0.0	-10.0
Enhanced Oil Recovery	8317	100%	15.0	0.0	30.0

A summary of the CO_2 source plants specifications is listed in Table 3, which includes information on the capacity, compositions, price, and CO_2 emissions parameter. Efficiency parameters γ_t and treatment removal ε_t^t were taken from Al-Mohannadi and Linke (2016). Power from the compression and transmission of the carbon integration was calculated using ε_p^p as described in Al-Mohannadi and Linke (2016).

Linear cost correlations were obtained from Kwak (2016). The work carries an exhaustive search and develops cost correlation that was then used in a carbon integration optimization. The search explores pipeline diameters, number of stages of compressors and the possibility of adding turbines in addition to exploring pressure drop and the needed thermodynamic properties Kwak (2016) The distances between sources and sinks ($H_{s,c,p,k,p}$) are given in Table 3-4 and were used in the calculation of the cost correlations that are outlined in section 3.14 Tables 3-6,7.

Table 3-4: Distances between plants in (km), $\mathrm{H}_{s,c,p,k,p}$. Reprinted with kind permission from Al-Mohannadi et al (2017)

Source/Sink	Greenhouse	Enhanced Oil Recovery	Saline Storage	Methanol (B)
Methanol (A)	20	12	12	10
LNG	25	4	4	8
Power Plant	26	7	7	11
GTL (1)	27	9	9	4
GTL (2)	27	9	9	4
Aluminum	24	8	8	3
Cement	25	6	6	10

Since the information and feasible options are identified, the equations from the previous section were implemented to allocate both natural gas and CO_2 to achieve the optimal economic performance while maintaining the carbon footprint limit. The operation duration for the plant is chosen to be or 20 years, while the time conversion is chosen to be 8760 hours per year. It should also be noted all prices were taken for the summer of 2015 and that the natural gas price used in this example are 135.95 $/t, a conversion from a price of 2.76 $/MMBtu (Kahramma, 2015; U.S. Energy, 2015). The Mixed Integer Linear Program (MILP) was solved using "What'sBest!" Lindo systems (2006) Lindo Branch-and-Bound solver for MS-Excel 2013 via a laptop PC with Intel Core i7 Duo processor, 8 GB RAM and a 64-bit operating System.

3.1.4.1 Results and Discussion

It was found that when the flow of methane in the city was restricted to 30kt/d and no carbon dioxide emission was imposed, the optimization selected Methanol, GTL and Cement plants to be operated to the full capacity of products. The MILP has 953 variables and 546 constraints. The solution time was 1 seconds. The results of the methane allocation is shown Figure 3-3.

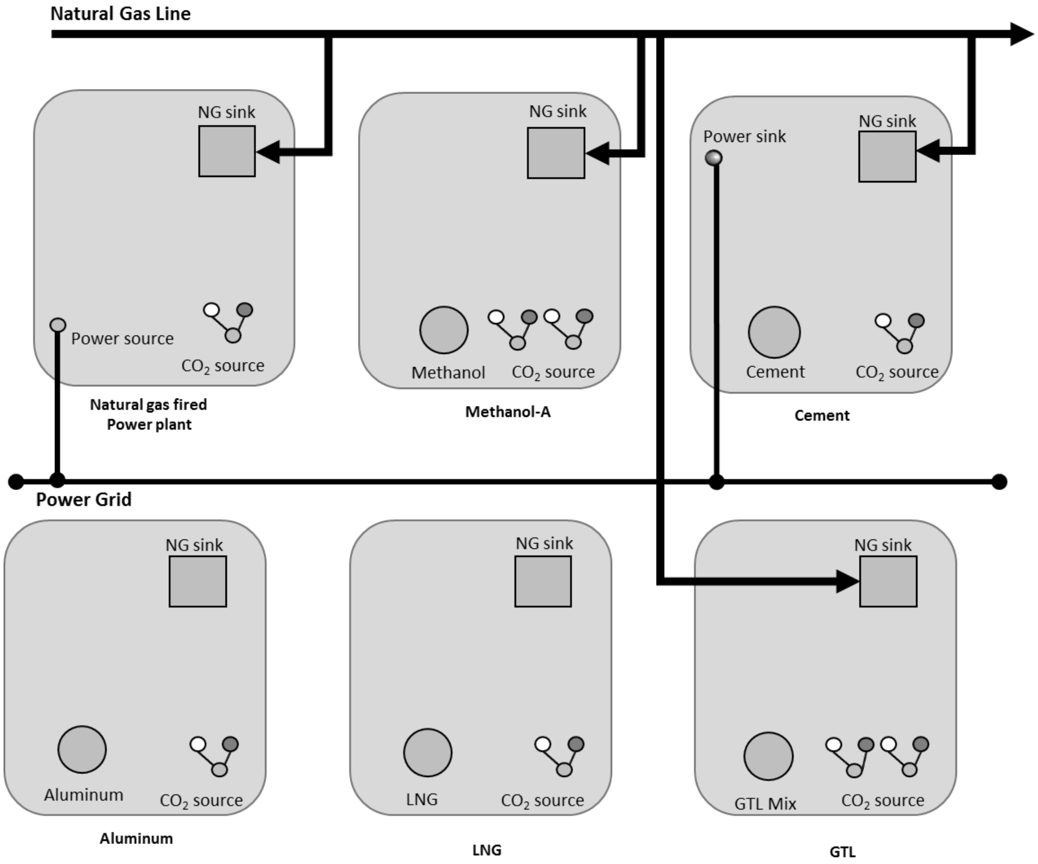

Figure 3-3: Methane allocation without any carbon constrains. Reprinted with kind permission from Al-Mohannadi et al (2017)

The city maintained a profit of 3.4 billion $/y and emitted 28 kt/y of carbon dioxide into the atmosphere. It was noticed that the natural gas fired power plant met the power requirement and exports by consuming natural gas and delivered the cement plant power needs. The optimization did not activate the renewable solar power option to satisfy the demand as burning methane as fuel was more profitable. It was observed that the LNG plant was turned off as well as the aluminum. This was attributed to the higher profit margin supplied by the Methanol, GTL and Cement sinks.

Once the carbon dioxide restrictions were applied to the city, the methane allocation shifts to maintain profitability. At 30% reduction of the city's emission, the profit remained at 3.40 billion \$/y. The MILP has 2139 variables and 547 constraints. The solution time was 1 seconds. The profit continuation at the same value was attributed the added revenue from selling the produced carbon dioxide to Enhanced Oil Recovery and the production of methanol in the Alternative Methanol sink, in addition to the products from the city without any reductions as the previous case. The power plant flow of methane was reduced and renewable solar power plant was activated. The selection of the solar power by the optimization can be attributed to the low cost of the panel and the profit generating opportunity of the saved methane. The amount of methane saved by PV corresponds to a value added of 14,000 \$/d. The connections of the city and product allocation can be seen in Figure 3-4 and Table 3-5.

Table 3-5: Methane Allocation at 30% Carbon Reduction. Reprinted with kind permission from Al-Mohannadi et al (2017)

Methane Sink		Unconstrained flow of methane, tCH_4/d	Product flow, unconstrained methane allocation	Flow of methane with 30% carbon constraint, tCH_4/d	Product flow, methane allocation at 30% reduction	Carbon dioxide allocation at 30% reduction target, flows in tCO_2/d			
						CO_2 Sink: Greenhouse	CO_2 Sink: EOR	CO_2 Sink: Storage	CO_2 Sink Methanol B
Methanol (A)		3,415	5,000 t/d	3,415	5,000 t/d	0	0	0	0
LNG		0	0	1,046	1,000 t/d	0	0	556	0
Gas fired Power plant		2,224	1,061,806 kWh installed	2,007	806,560 kWh installed	0	0	0	0
Solar Power Plant		0	0 kWh installed	0	201,640 kWh installed	0	0	0	0
GTL	(1)	23,652	14,600 t/d	23,532	14,526 t/d	0	8317	5376	688
	(2)					0	0	0	1,136
Aluminum		0	0 t/d	0	0 t/d	0	0	0	0
Cement		580	10,000 t/d	0	0 t/d	0	0	0	0
Total Methane		29,871 t/d		30,000 t/d					

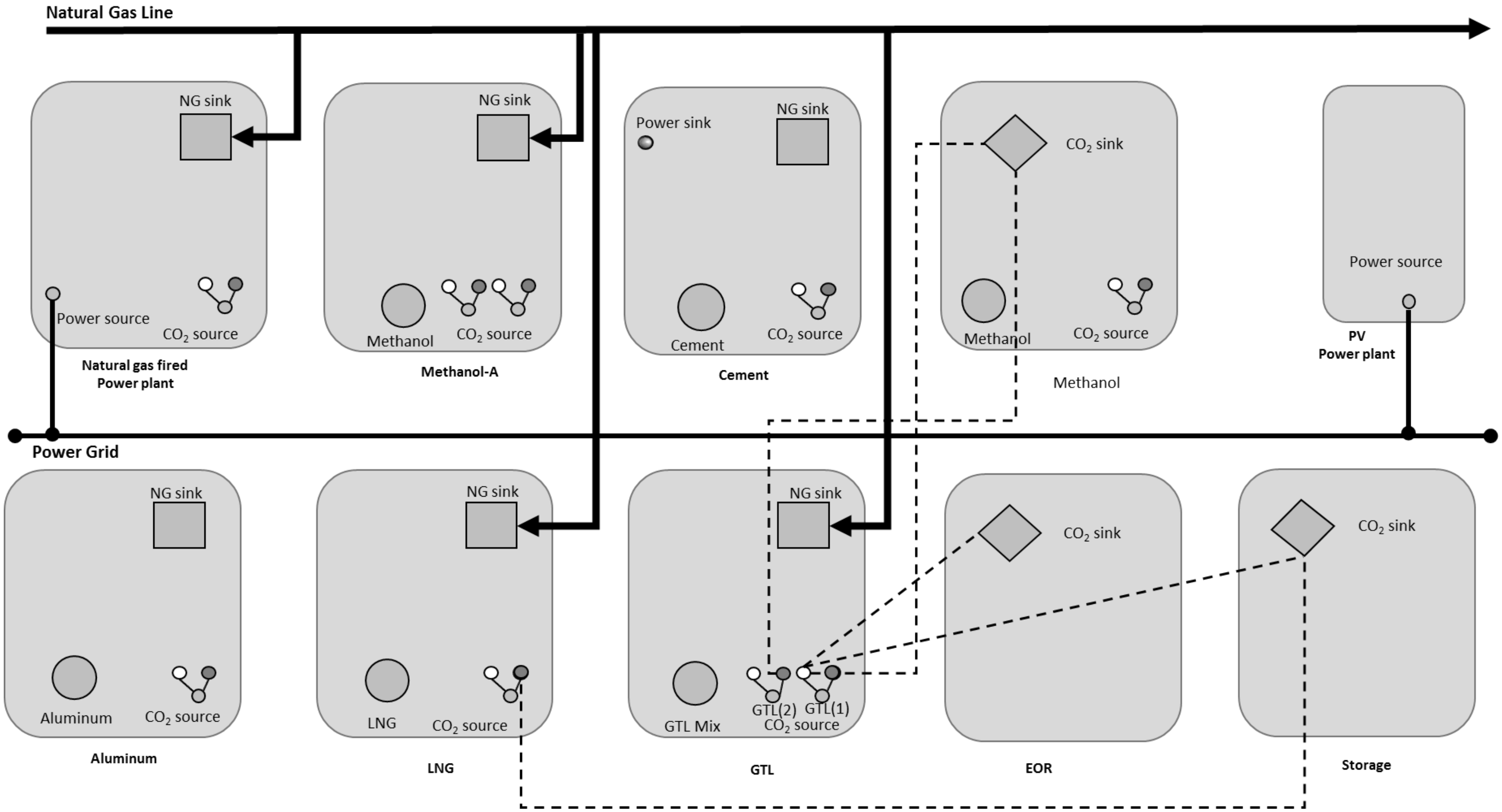

Figure 3-4: 30 kt/d Methane at 30% reduction of carbon dioxide emissions, dashed lines represent carbon dioxide exchange. Reprinted with kind permission from Al-Mohannadi et al (2017)

The optimization allocated methane to the Methanol, GTL and LNG plants and none to the cement plant. The shift from the cement plant was due to the higher carbon dioxide footprint that results from cement production. Moreover, the higher emission target also resulted in selection of the non-profitable storage sink that could store large amounts of carbon dioxide at a cost. The storage sink was supplied by treated pure carbon dioxide from the LNG stream and a portion of the GTL stream (1). In addition, connections appeared to the EOR sink, and Methanol (B) plant and were supplied by carbon dioxide from the GTL stream (1). The carbon receiving Methanol (B) sink was supplied additional carbon dioxide from GTL stream (2). To reduce the overall costs and reduce emissions.

At the higher carbon dioxide reduction target set to reduce 50% of the city's baseline emissions, the overall profit of the network was 2.8 billion $/y. It was observed that the methanol production remained at 5,000 t/d from the Methanol (A) plant, LNG was produced at 8,000 t/d while GTL products were produced at 9,500 t/d. The decrease of GTL capacity and increase of LNG can be attributed to the large carbon dioxide flow from the GTL plant and higher capital cost. The sinks of carbon dioxide were Methanol (B), supplied by a mix flow from source (1) and treated (2) of the GTL plant, the EOR sink was supplied from GTL source (1) and the Greenhouse, which received carbon dioxide from the treated LNG source.

Solving for a higher storage capacity showed that the greenhouse sink is deselected. This was due to its low carbon dioxide fixating efficiency making it a less attractive reduction option. From this case study it could be seen that the higher carbon dioxide targets would impose higher costs reducing the overall profitability of the industrial clusters. While the proposed method allows for the use of renewable energy in power producing, there could be additional natural gas savings and carbon dioxide emission reduction realized by allowing the use of waste heat or heat produced from renewable energy. Thus, further consideration of heat integration into the network would improve the overall network profitability and give a more holistic approach.

3.1.5 Linearization material

The linear cost correlations were obtained from Kwak (2016). The work considers the linearization of pipe-compression known lines in an existing city set up and flows, following Al-Moahnnadi and Linke (2016). The first step outline by Kwak started with an acquiring of the source-sink connection information. This was followed by an exhaustive search for the pipeline unit, compression and pumping units. For an assigned flow rate, the minimum compression cost and optimum cost of the pipe and pump are were obtained. Finally, the collected minimum cost data for every source-sink connection was plotted and expressed as a function of the carbon dioxide flow rate. Piecewise linearization work was conducted to increase the accuracy of the cost function. The resulting minimum cost transmission and compression correlation for treated and untreated flows are shown in Table 3-6 and Table 3-7 respectively. Where the sources of CO_2 are from the methanol plant (Methanol (A)), Liquefied natural gas facility (LNG), natural gas fired power plant (Power), Gas-to-Liquid plant (GTL), Aluminum plant (AL) and cement. While the sinks were Greenhouse, Enhanced Oil Recovery (EOR), Saline Storage and Methanol (B), which receives CO_2.

Table 3-6: Treated carbon dioxide correlations, cost in \$/yr. Reprinted with kind permission from Al-Mohannadi et al (2017)

Sink	Source	Flow Range CO_2 (MTPD)	$C^{pipe,\ capex}{}_{c,p}$ ($a\ T_{c,s,p} + b$)		R^2	$C^{comp,\ capex}{}_{c,p}$ ($a\ T_{c,s,p} + b$)		R^2	$C^{comp,\ opex}{}_{,p}$ ($a\ T_{c,s,p} + b$)		R^2
			A	b		a	B		A	b	
Greenhouse	Methanol (A)	50-1030	432	310,057	0.952	300	67,950	0.959	570	32,980	0.992
	LNG	50-1030	259	387,572	0.952	300	76,740	0.940	570	41,220	0.988
	Power	50-1030	561	403,075	0.952	300	78,700	0.937	570	42,800	0.988
	GTL(1)	50-1030	583	418,578	0.952	300	82,930	0.933	570	44,500	0.987
	GTL(2)	50-1030	583	418,578	0.952	300	82,930	0.933	570	44,500	0.987
	AL	50-1030	518	372,069	0.952	300	74,780	0.944	570	39,570	0.989
	Cement	50-1030	539	387,572	0.952	300	76,740	0.941	570	41,220	0.988
Enhanced Oil Recovery /Storage	Methanol (A)	100-2500	259	186,034	0.952	220	144,000	0.995	560	31,000	0.999
	LNG	100-2500	86	62,011	0.952	215	120,120	0.988	550	10,350	0.999
	Power	100-8300	46	218,887	0.926	217	129,300	0.997	550	18,110	0.999
	GTL(1)	100-8300	59	281,426	0.926	218	135,500	0.996	550	23,300	0.999
	GTL(2)	100-8300	59	281,426	0.926	218	135,500	0.996	550	23,300	0.999
	AL	100-8300	59	281,426	0.926	220	131,500	0.997	560	17,360	0.999
	Cement	100-8300	40	187,617	0.926	220	126,300	0.997	550	13,000	0.999
Methanol(B)	Methanol (A)	50-2500	216	124,023	0.952	230	61,400	0.993	530	12,100	0.999
	LNG	50-2500	173	124,023	0.952	220	58,530	0.995	530	9,700	0.999
	Power	50-2500	133	235,008	0.904	230	63,000	0.992	530	13,300	0.999
	GTL(1)	50-2500	48	85,458	0.904	220	52,800	0.997	520	4,800	1.000
	GTL(2)	50-2500	48	85,458	0.904	220	52,800	0.997	520	4,800	1.000
	AL	50-2500	48	85,458	0.904	214	51,400	0.998	520	3,600	0.999
	Cement	50-2500	121	213,644	0.904	225	61,400	0.993	530	12,100	0.999

Table 3-7: Untreated carbon dioxide correlations, cost in \$/yr. Reprinted with kind permission from Al-Mohannadi et al (2017)

Sink	Source	Flow Range CO_2 (MTPD)	$C^{pipe,\ capex}_{c,p}$ ($a\ U_{c,s,p} + b$)		R^2	$C^{comp,\ capex}_{c,p}$ ($a\ U_{c,s,p} + b$)		R^2	$C^{comp,\ opex}_{,p}$ ($a\ U_{c,s,p} + b$)		R^2
			A	B		a	B		a	b	
Greenhouse	Methanol (A)	50-1030	469	349,911	0.927	700	16,500	0.999	270	74,000	0.875
	LNG	50-1030	599	435,641	0.930	700	16,500	0.999	280	89,200	0.837
	Power	50-1030	609	454,885	0.927	706	16,500	0.999	290	92,300	0.830
	GTL(1)	50-1030	583	418,578	0.952	300	82,930	0.933	570	44,500	0.987
	GTL(2)	50-1030	633	472,380	0.927	700	16,500	0.999	290	95,300	0.822
	AL	50-1030	562	419,893	0.927	700	16,500	0.999	280	86,200	0.844
	Cement	50-1030	586	437,389	0.927	740	17,150	0.999	270	78,180	0.812
Enhanced Oil Recovery /Storage	Methanol (A)	100-2500	469	276,789	0.933	640	95,200	1.000	200	117,000	0.985
	LNG	100-2500	96	69,703	0.930	640	95,200	1.000	200	47,900	1.000
	Power	100-8300	56	228,186	0.935	640	95,200	1.000	200	73,800	0.995
	GTL(1)	100-8300	59	281,426	0.926	218	135,500	0.996	550	23,300	0.999
	GTL(2)	100-8300	72	293,382	0.935	640	95,200	1.000	200	91,100	0.991
	AL	100-8300	72	297,577	0.914	640	95,200	1.000	200	82,400	0.993
	Cement	100-8300	48	198,385	0.914	670	99,000	1.000	180	54,000	0.994
Methanol(B)	Methanol (A)	50-2500	469	230,658	0.933	690	25,000	0.999	120	43,300	0.918
	LNG	50-2500	96	139,405	0.930	690	25,130	1.000	110	37,300	0.938
	Power	50-2500	153	253,723	0.933	690	25,130	1.000	120	46,330	0.909
	GTL(1)	50-2500	63	73,292	0.953	220	52,800	0.997	520	4,800	1.000
	GTL(2)	50-2500	67	81,962	0.917	690	25,130	1.000	92	25,310	0.977
	AL	50-2500	67	81,962	0.917	690	25,130	0.999	87	22,310	0.986
	Cement	50-2500	168	204,904	0.917	720	26,130	1.000	70	21,020	0.987

3.1.6 Conclusion

The optimization-based approach that is included in this work helps develop network strategies that explore synergies between natural gas allocation, power generation and carbon dioxide reduction. This work was carried out with an overall aim of natural gas diversification through alternative conversion paths from raw materials to fuels, chemicals and products together with reducing carbon dioxide within the industrial cluster and carbon capture utilization and storage. A case study was presented to illustrate the application of the method on an industrial city planning with and without carbon restrictions. Major savings were obtained using the optimization based approach. The optimization problem takes into account multiple processes, the case of renewable power production and carbon utilization options, storage, treatment and transmission elements needed by the network. It was observed from the results that the natural gas utilization options change once an emission restriction is applied. Moreover, the additional revenue form utilizing carbon dioxide maintain the overall profitability of the industrial cluster, while abiding to lower emission targets. This helped mitigate some of the cost, once a more ambitious reduction target was imposed. The simultaneous evaluation of both natural gas utilization network and the carbon dioxide network in addition to exploring the role of applying renewable energy will be beneficial to policy makers in drafting climate change strategies.

3.2 Evaluating natural gas, heat and carbon networks

The development of sustainable clusters for the monetization of natural gas will not only aim at maximizing profits from natural gas conversions into fuels and materials, but also needs to meet CO_2 footprint constraints to align with global efforts to avoid dangerous climate change. Each natural gas monetization option is associated with different profitability as well as CO_2 emissions from energy inputs and CO_2 byproduct generation. To reduce CO_2 within an industrial cluster, several methods exists mainly energy efficiency and carbon capture utilization and storage (CCUS). Energy efficiency, which includes Heat Integration (HI) and energy management, reduces the emissions by reducing fossil fuel combustion. While natural gas monetization with CCUS and RE was assessed in the previous section, energy efficiency was not included. This section aim at developing an approach that integrate natural gas, energy and CCUS.

HI techniques have been implemented since the hike of energy prices in 1970s (Klemeš and Kravanja, 2013). The developed techniques have been applied for individual processes or site-wide level (Dhole and Linnhoff, 1993; Linnhoff and Hindmarsh, 1983). Varbanov et al. (2004) proposed a utility system model determine fossil fuel consumption and steam and power output of a site utility system. In terms of focus on carbon dioxide mitigation, Chae et al (2010) conidered fuel switching, the use of renewable energy and Carbon Capture and Storage (CCS). Yu et al (2015) studied the reduction of carbon dioxide based on exchanges of byproducts between firms in an industrial setting, including heat and waste but excluding carbon dioxide utilization and storage options. Hassiba et al. (2016, 2017) expaned Al-Mohannadi and Linke (2015) where the synergy between CCUS and HI were investigated in a step-wise approach and a simuatenous approach that also investigated the role of renewable steam geneation.

Chapter 3.1 presented a monetization of natural gas under emission targets approach, however, the method did not consider heat integration and missed opportunities to reduce costs and contribute into fuel savings. This work simultaneously considers the assessment of natural gas monetization paths with CO_2 and heat management options together to devise profitable industrial clusters with low CO_2 emission. The next sections include a description of the approach, and an illustrative example to highlight the benefits of exploring natural gas, CO_2 and energy synergy.

3.2.1 Methane, CO_2 and Energy Integration Approach

The overall goal is the identification of strategies for natural gas monetization in an industrial cluster under an overall CO_2 emission constraint. The attention is to focus on 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 and heat network for energy export or import, a plant model is shown in Figure 3-5.

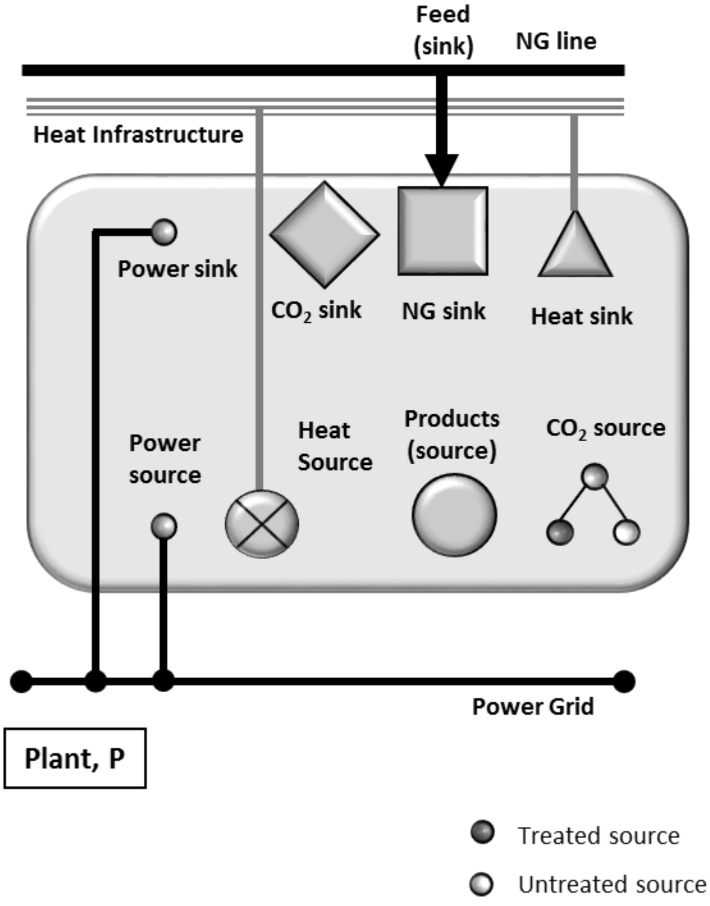

Figure 3-5: Updated plant representation

A common centeral utlity system is connected to the infrasturcture, shown in Figure 3-6. Waste heat from various processes to supply the carbon capture units or other processes within the city the required energy, instead of ejecting the excess heat into cooling utilities. Moroever, the model optimizing the amount of renewable energy, power and/or heat, in the network. Renewable energy option can be in a plant, p, connected to the power grid and the heat infrastructure. Renewable energy can be used as power or for steam geneartion enerting at a given steam level. The use of waste heat and incoperation of renewable energy in turn reduces the steam demand originated from the boiler and gas turbine, which reduces fuel combustion and increases the ratio of CO_2 avoided. In addition, savings can be realized as the fuel consumption is decreased leaving more natural gas to be monetized through value added products. Figure 3-6 shows the synergy options amongst natural gas receiving plant, HI, CO_2 integration in an industrial park simultaneously.

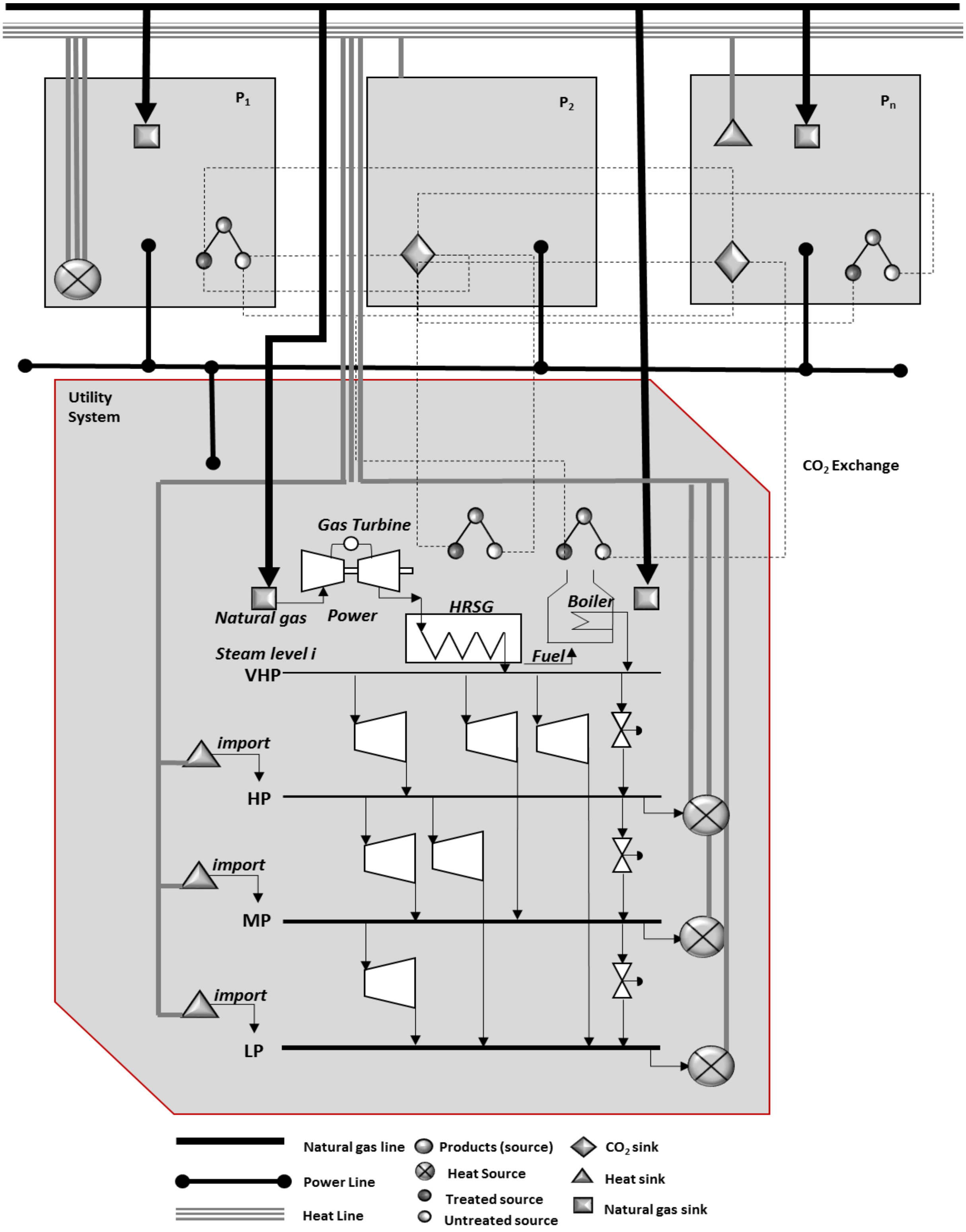

Figure 3-6: Network Superstructure

The goal is to determine the optimal selection of production plants to be included in the cluster, allocation of natural gas to each of the defined plants in the cluster, allocation of CO_2 sources to potential CCUS sinks and energy allocation (power, excess heat and renewable energy) across energy sources and sink.

The formulation of the optimization problem takes the form of a Mixed Integer Non-Linear Program (MINLP). Equality and Inequality constraints of the optimization problem include component and total mass as well as heat balances around sources and sinks. The model of natural gas, CO_2 and central energy integration is detailed in the next section.

3.2.2 Model Formulation

An optimization model is formulated to explore the superstructure representation described above. The following sets were used:

P { p|p=1,2,3, ... , N_{plants} | P is a set of plants}

E { p|p=1,2,3, ... , NE_{plants} | E is a subset of existing plants that belong to set P, $E \subset P$}

O { p|p =1,2,3,…,NOplants| O is a subset of optional plants that belong to set P, $O \subset P$}

C {c|c=1,2,3, …,N_C|C is a set of products produced in industrial city}

Q {q|q=1,2,3,…,Nq|Q is a set of power generation options (including renewable energy)
produced in plant p in industrial city}

H {h|h=1,2,3,…,Nh|H is a set of steam generation options (including renewable energy)
produced in plant p per level i in industrial city}

$S_{c,p}$ {s|s=1,2,3,…,Ns|$S_{c,p}$ is a set of CO_2 sources produced in plant p
associated with product c}

K_p {k_p|k_p=1,2,3, …,$N_{CO2,p}$sinks| K_p is a set of carbon sinks in plant p}

T {t|t=1,2,3, …,T_{max}| T is a set of carbon treatment technology}

M { m|m=1,2,3, ... , $N_{energy\ sources}$| M is a set of steam sources in plant p }

W { w|w=1,2,3, …, $N_{energy\ sinks}$| W is a set of steam sinks in plant p per}

I { i|i=1,2,3, … , $N_{steam\ levels}$| I is a set of steam levels}

J { j|j=1,2,3, …, $N_{turbine\ levels}$| J is a set of turbine levels}

G { g|g=1,2,3, ... , $N_{turbines}$| G is a set of steam turbine}

GT { gt|gt=1,2,3, ... , $N_{gas\ turbines}$| GT is a set of steam turbine}

3.2.2.1 Plant Module

The product flow requirements in existing plants is given by equation (97).

$$L^{c}_{c,p} \leq F^{c}_{c,p} \leq M^{c}_{c,p} \qquad \forall\, c \epsilon C\ p \epsilon EP \qquad (97)$$

$F^{c}_{c,p}$ is the flow of product c in existing plant p that falls between a specified lower and upper flow bounds $L^{c}_{c,p}$, $M^{c}_{c,p}$ respectively. The product flow requirements in optional plants is given by equation (98).

$$L^{c}_{c,p}\, I^{o}_{p} \leq F^{c}_{c,p} \leq I^{o}_{p} M^{c}_{c,p} \qquad \forall\, c \epsilon C\ p \epsilon OP \qquad (98)$$

Where I^{o}_{p} is a binary variable (0,1) which defines the activation of an optional plant p. The product to methane intake to plant p is shown below.

$$F_{p} = \sum_{c \in C_{p}} F^{c}_{c,p}\, \varphi^{c}_{c,p} \qquad \forall\, p \epsilon P \qquad (99)$$

Where $\varphi^{c}_{c,p}$ is a parameter, which represents the required methane intake per product c in plant p. Carbon dioxide source flow is based on product production as given as

$$M_{s,c,p} = F^{c}_{c,p}\, \Phi^{c}_{s,c,p} \qquad \forall\, s \epsilon S_{c,p}\ c \epsilon C\ p \epsilon P \qquad (100)$$

Where $\Phi^{c}_{s,c,p}$ is a parameter associated with each defined carbon dioxide source s per product c in plant p. Power calculation for each plant is shown in below

$$P_{p,q} = \sum_{c \in C} F^{c}_{c,p}\, \varphi^{PW}_{c,p,q} \qquad \forall\, p \epsilon P\ q \epsilon Q \qquad (101)$$

Where $\varphi^{PW}_{c,p,q}$ is a parameter, which represents the specific required/generated power in plant p of type q. $\varphi^{PW}_{c,p,q} > 0$, represents a power surplus generated by product c in plant p, while $\varphi^{PW}_{c,p,q} < 0$ represents a power deficit needed by product c in plant p. $P_{p,q}$ is the power output from plant p with type q. Each power type can have a limits of power type in plant, which is represented in the equation below

$$L^{p}_{p,q} \leq X^{p}_{p,q} \leq U^{p}_{p,q} \qquad \forall\ q \in Q\ p \in P \qquad (102)$$

$X^{p}_{p,q}$ is a variable which represent the power amount of type q used in existing plant p. While, $L^{p}_{p,q}$ and $U^{p}_{p,q}$ are the specified lower and upper allowed of power amount type q in plant p.The power balance ensures that all amounts corresponding to each power type option in plant p does not exceed the total

$$\sum_{q \in Q} X^{p}_{p,q} = P_{p} \qquad (103)$$

Heat balance calculation for each plant is shown in equation (112)

$$m_{m,h,p,i} = \sum_{c \in C} F^{c}_{c,p}\ \varphi^{I,h}_{c,p,h,i} \qquad \forall\ m \epsilon M\ h \epsilon H\ p \epsilon P\ i \epsilon I \qquad (112)$$

$$m_{w,h,i} = \sum_{c \in C} F^{c}_{c,p}\ \varphi^{E,h}_{c,p,i} \qquad \forall\ w \epsilon W\ p \epsilon P\ i \epsilon I \qquad (113)$$

Where $m_{m,h,p,i}$ is the steam flowrate recovered from an energy source process m of type h steam in plant p at steam level i. $\varphi^{I,h}_{c,p,h,i}$ is a parameter, which represents the steam surplus generated in plant p of type i. $m_{wp,i}$ is the steam flowrate needed from an energy sink w in plant p at steam level $\varphi^{E,h}_{c,p,i}$, represents a represents a steam deficit needed by product c in plant p at level i. Each steam level have a limits of power type in plant, which is represented in the equation below

$$0 \leq m_{m,h,p,i} \leq m^{max}_{m,h,p,i} \qquad \forall\ q \in Q\ p \in P \qquad (114)$$

$m^{max}_{m,h,p,i}$ is a maximum allowed of power amount type q in plant p.

3.2.2.2 *Utility System*

The utility system model used in this work is adjusted from Varbanov et al. (2004) and Hassiba et al (2017). The utility model accounts for gas turbines, boilers, Heat Recovery Steam Generation (HRSG) system and integrating gas turbine with HRSG. Natural gas is consumed in the boiler and gas turbine. The boiler energy balance is as follows:

$$Q^{BF}=\frac{1}{\eta^{Blr}}\, m^{stm}\Delta h^{gen} \tag{115}$$

$$\eta^{Blr}=\frac{Q^{stm}}{Q^{BF}} \tag{116}$$

Where $Q^{BF}$is the energy from natural gas combustion in the boiler needed to generate steam, η^{Blr} is the boiler thermal efficiency, $m^{stm}$is the boiler current steam load, Δh^{gen} is the heat required to generate one unit of steam and Q^{stm} is the energy needed to generate steam. Mass and energy balances are carried around the steam headers. The steam balance are modelled as follow:

$$\Sigma_i m_I^{inlet,hdr}= \Sigma_i m_i^{onlet,hdr} \tag{117}$$

Where $m_i^{inlet,hdr}$ is the mass flowrate of the steam into a steam header i. The inlet streams are from the following sources: HRSG, boiler, steam turbine, let-down station, heat recovered from an energy source plant or renewable energy source for each steam level:

$$m_i^{inlet,hdr}=\Sigma_{m\in M}\Sigma_{h\in H}\, \Sigma_{p\in P} m_{m,h,p,i}+\Sigma_{j\in J}\Sigma_{g\in G}\, m_{j,g,i}+m_i^{LS} \qquad i\in I \tag{118}$$

$$m^{stm}=\Sigma_{g\in G} m_{j,g,i}-m^{HRSG} \qquad \forall g\in G,\ \text{For } j=1 \tag{119}$$

$$m^{stm}\geq 0 \tag{118}$$

$$m_{j,g,i}\geq 0 \qquad \forall j\in J,\ g\in G,\ i\in I \tag{119}$$

$$m_i^{LS}\geq 0 \qquad \forall i\in I \tag{120}$$

Where $m_{m,h,p,i}$ is the waste heat recovered from an energy source process m of type h steam in plant p at steam level i, $m_{j,g,i}$ is the mass flowrate of steam through turbine g in turbine level j to steam header i, $m_i^{LS}$is the steam mass flowrate into header i through a let-down station and m_{HRSG} is the steam mass flowrate from the HRSG. $m_i^{outlet,hdr}$ is the steam mass flowrate at the header outlet. The outlet steam can be expanded via steam turbine, let-down stations, or supplied to an energy sink process:

$$m_i^{outlet,hdr}=\Sigma_{g\in G}\Sigma_{i\in I}m_{j,g,i}+\Sigma_{w\in W}\Sigma_{p\in P}m_{i,w,p}+\Sigma_{t\in T}\Sigma_{s\in S}\Sigma_{p\in P}m_{t,s,p,i}+m_{i+1}^{LS} \qquad i\in I \qquad (121)$$

Where $m_{i,w,p}$ is the steam demand of steam level i to energy sink w in plant p, and $m_{t,s,p,i}$ is the energy demand of treatment unit t in carbon source s in plant p

While the mass balance equation is linear, the energy balance is bi-linear. This is due to the energy balance across a steam turbine used to calculate the exhaust enthalpy h^{hdr}. The inlet $h^{inlet,hdr}$ is the specific enthalpy of steam entering the steam header and h^{hdr} is the specific average enthalpy of the steam header:

$$\Sigma_i m_i^{inlet,hdr}h^{inlet,hdr}= \Sigma_i m_i^{outlet,hdr}h^{hdr}=0 \qquad (122)$$

A steam turbine efficiency parameter was used to determine the steam turbine power output. The steam turbine model is shown below:

$$W_{j,g}=n_{j,g}m_{i,j,g}(\Delta h^{is}{}_{j,g}) \qquad \forall j\in J\ g\in G \qquad (123)$$

Where $W_{j,g}$ is the power generated by steam turbine g in turbine level j,and $n_{j,g}$ is the efficiency of the steam turbine p in turbine level j.$X_{j,g}$is a binary (1,0) associated with steam turbine. The value of the binary is 1 if the flow in the turbine is within the lower and upper limit, otherwise it is zero. $\Delta h^{is}{}_{i,j,g}$is the isentropic enthalpy across turbine g level j

The power is generated in the utility system through steam or gas turbines. The deficit power is imported from a power producing plants while the surplus power is exported to the grid:

$$P^{ST}=\Sigma_{j\in J}\Sigma_{g\in G}W_{j,g} \qquad (124)$$

$$P^{GT}= \Sigma_{gt\in GT}\eta_{gt}^{GT}Q_{gt}^{GT} \tag{125}$$

$$PR=\Sigma_{q\in Q}\sum_{p\in P}P_{p,q} \tag{126}$$

$$P^{total}=P^{ST}+P^{GT}+PR-P^{export} \tag{127}$$

Where P^{ST} is the power generated from steam turbines, P^{GT} is the power generated from gas turbines, PR and P_{export} are the power imported from the industrial city power plant and exported to the grid, respectively. PR is the power demand from industrial park processes.

The maximum power imported or exported into the grid limited to the utility system and industrial city policy, and the power plant capacity. This is modelled as following:

$$0\le PR \le P_{policy}^{import} \tag{128}$$

$$0\le P^{export}\le P_{policy}^{export} \tag{129}$$

Where P_{policy}^{import} and P_{policy}^{export} are the maximum power can be imported or exported to the grid set by the user, respectively. The methane mass flowrate from the utility system,

$$F_{Methane}^{utility}=(Q^{BF}+Q^{GT})\Phi^{CH4,utility}+\left(PR-P^{export}\right)\varepsilon_{p}^{CH4} \tag{130}$$

The CO_2 mass flowrate from the utility system,

$$F_{CO_2}^{utility}=(Q^{BF}+Q^{GT})\Phi^{CO2,\ utility}+\left(PR-P^{export}\right)\varepsilon_{p}^{p} \tag{131}$$

The heat flow rate from the gas turbine is given below

$$Q^{GT}=\Sigma_{gt\in GT}\frac{Q_{gt}^{GT}}{\eta_{gt}^{GT}} \tag{132}$$

In equations (131) to (132), $\Phi^{CO2,\ utility}$ is a parameter associated with each defined carbon dioxide per unit of energy, and ε_{p}^{p} is the carbon dioxide mass emission per unit of power. Where $\Phi^{CH4,\ utility}$ is a parameter associated with each defined methane per unit of energy, and ε_{p}^{CH4} is the of methane required per unit of power.

3.2.2.3 Network Superstructure

The raw source carbon flow can be allocated between an upper and a lower limits as shown below

$$L_{s,c,p} \leq R_{s,c,p} \leq M_{s,c,p} \qquad \forall\ s \in S_{c,p}\ c \in C\ p \in P \qquad (86)$$

$R_{s,c,p}$ is the raw carbon flow from plant p source s associated with product c. $L_{s,c,p}$ and $M_{s,c,p}$ are lower and maximum carbon flow available from source s associated with product c in plant p. The mass balances around raw carbon sources s are given as follows:

$$R_{s,c,p} = \sum_{t \in T} \sum_{k \in K} \sum_{p \in OP} \varepsilon^{t}{}_{t}\, T_{s,c,p,k,p,t}\, I^{o}{}_{p} + \sum_{k \in K} \sum_{p \in OP} U_{s,c,p,k,p}\, I^{o}{}_{p}$$

$$+ \sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \varepsilon^{t}{}_{t}\, T_{s,c,p,k,p,t} + \sum_{k \in K} \sum_{p \in P} U_{s,c,p,k,p} \qquad \forall\ s \in S_{c,p}\ c \in C\ p \in P\ b \in B \qquad (87)$$

$$R_{s,c,p}\, y_{s,c,p} = \sum_{t \in T} \sum_{k \in K} \sum_{p \in OP} \varepsilon^{t}{}_{t}\, T_{s,c,p,k,p,t}\, y_{s,c,p,t}\, I^{o}{}_{p} + \sum_{k \in K} \sum_{p \in OP} U_{s,c,p,k,p}\, y^{u}{}_{s,c,p}\, I^{o}{}_{p} +$$

$$\sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \varepsilon^{t}{}_{t}\, T_{s,c,p,k,p,t}\, y_{s,c,p,t} + \sum_{k \in K} \sum_{p \in P} U_{s,c,p,k,p}\, y^{u}{}_{s,c,p} \qquad \forall\ s \in S_{c,p}\ c \in C\ p \in P \qquad (88)$$

The total and component balance around carbon sinks k in plant p are given as:

$$F_{k,p} = \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in OP} \sum_{t \in T} \varepsilon^{t}{}_{t} T_{s,c,p,k,p,t}\, I^{o}{}_{p} + \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in OP} U_{s,c,p,k,p}\, I^{o}{}_{p}$$

$$+ \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in P} \sum_{t \in T} \varepsilon^{t}{}_{t} T_{s,c,p,k,p,t} + \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in P} U_{s,c,p,k,p} \quad \forall\ k \in K\ p \in P \qquad (89)$$

$$F_{k,p}\, Z_{k,p}{}^{min} \leq \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in OP} \sum_{t \in T} \varepsilon^{t}{}_{t} T_{s,c,p,k,p,t}\, y_{s,c,p,t}\, I^{o}{}_{p} + \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in OP} U_{s,c,p,k,p}\, y^{u}{}_{s,c,p}\, I^{o}{}_{p} + \sum_{s \in S c,p} \sum_{c \in C} \sum_{b \in B} \sum_{p \in OP} \sum_{t \in T} \varepsilon^{t}{}_{t} T_{s,c,p,k,p,t}\, y_{s,c,p,t} + \sum_{s \in S c,p} \sum_{c \in C} \sum_{p \in OP} U_{s,c,p,k,p}\, y^{u}{}_{s,c,p}$$

$$\forall\ k \in K\ p \in P \qquad (90)$$

All untreated sources have carbon dioxide concentration of the raw source:

$$y^{u}{}_{s,c,p} = y_{s,c,p} \qquad (91)$$

Any source can be connected to any sink subject to the sink minimum concentration requirement $Z_{k,p}{}^{min}$ and the sink flow requirement $G_{k,p}{}^{max}$ in as described below

$$F_{k,p} \leq G_{k,p}{}^{max}; \qquad \forall\ k\epsilon K \qquad (92)$$

Equations (93) and (94) ensure carbon dioxide flow stays between the pipeline limits

$$L^{pipe}\ X_{s,\ c,p,k,p} \leq T_{s,\ c,p,k,p} \leq M^{pipe} X_{s,\ c,p,k,p} \qquad \forall\ s\epsilon\ S_{c,p}\ c\epsilon C\ p\epsilon P\ k\epsilon K \quad (93)$$

$$L^{pipe}\ X_{s,\ c,p,k,p} \leq U_{s,\ c,p,k,p} \leq M^{pipe} X_{s,\ c,p,k,p} \qquad \forall\ s\epsilon\ S_{c,p}\ c\epsilon C\ p\epsilon P\ k\epsilon K \quad (94)$$

Where L^{pipe} is the lower flow limit and M^{pipe} is the upper flow limit of source-sink connection within a pipeline. $X_{s,\ c,p,k,p}$ is a binary (0,1) associated with flow of the treated and untreated streams for the pipeline connecting source s associated with product c in plant p connected to sink k in plant p. The mass balance of methane source and limits are as follows :

$$F_{methane} = \sum_{p\in P} F_p \ + \ F^{utility}_{Methane} \qquad (133)$$

$$LF_{methane} \leq F_{methane} \leq MF_{methane} \qquad (96)$$

$F_{methane}$ is the total flow of methane to the industrial city. F_p is the methane flow to a plant p, $LF_{methane}$ is the lower methane flow available, while $MF_{methane}$ is the maximum methane flow available to the industrial city use. The total carbon dioxide from product c production is given as:

$$F^{CO2}{}_{c,p} = \sum_{s\in S_{c,p}} \sum_{c\in C} M_{s,c,p} \qquad \forall\ c\epsilon C\ \forall\ p\epsilon P \qquad (97)$$

While, the total power of the city is given as:

$$PR = \sum_{q\in Q} \sum_{p\in P} P_{p,q} \qquad (98)$$

The total power in the plant must meet a supply/grid export demand and is insured by the expression below.

$$LPR \leq PR \leq MPR \qquad (99)$$

Where PR is the power output in the city, LPR is the minimum possible power output of the city and MPR is the maximum possible power output of the city.

The carbon integration network needs to meet the Carbon dioxide Emission Limit (CEL) for the industrial park. The Carbon dioxide Emission of the network (CE) is determined as follows:

$$\mathrm{CE}=\sum_{p\in P}\sum_{c\in C}F^{CO2}{}_{c,p}+F^{utility}_{CO_2}+\sum_{p\in P}\sum_{k\in K}F_{k,p}{}^{CO2}\,\varepsilon^{p}_{p}-\sum_{p\in P}\sum_{k\in K}F_{k,p}{}^{CO2}\,(1-\eta_{k,p}) \qquad (134)$$

Where,

$$\mathrm{CE}\leq\mathrm{CEL} \qquad (101)$$

$F_{k,p}{}^{CO2}$ is the carbon dioxide flow into the sink, while η_k is the sinks efficiency and ε_p^p accounts for the power use carbon footprint. $F^{utility}_{CO_2}$ is the CO_2 mass flowrate from the utility system Non-negativity constraints are described the following variables, $T_{s,c,p,k,p,t}$, $U_{s,c,p,k,p}$, $y_{s,c,p,t}$, $y_{s,c,p}$ $M_{s,c,p}$, $F^{c}{}_{c,p}$, $F^{CO2}{}_{p}$ F_p F_k $X^{p}{}_{p,q}$ and PR.

3.2.2.4 Objective function

The objective is to identify the cluster setup that achieves maximum profit from the available natural gas. The profit is calculated as:

$$\mathrm{Profit}=\mathrm{REV}^{c}+\mathrm{REV}^{CO2}-[\mathrm{Cost}^{M}+\mathrm{Cost}^{EP}+\mathrm{Cost}^{OP}+\mathrm{Cost}^{CO2}+\mathrm{Cost}^{CI}+\mathrm{Cost}^{UT}] \qquad (135)$$

Where; the revenue from all products and associate by-products, REV^{c} is given as

$$\mathrm{REV}^{c}=\sum_{p\in P}\sum_{c\in C}F^{c}{}_{c,p}\,C^{c}_{c}+\sum_{p\in P}\sum_{c\in C}\sum_{q\in Q}F^{c}{}_{c,p}\,C^{PW}{}_{c,p,q}+P^{Export}C^{PW} \qquad (136)$$

Where $C^{PW}{}_{c,p,q}$ is the power price associated with product c in plant p for type q and the revenue from carbon dioxide sinks, REV^{CO2} is given as

$$\mathrm{REV}^{CO2}=\sum_{p\in P}\sum_{k\in K}F^{CO2}{}_{k,p}\,C^{CO2}_{k,p}+F^{utility}_{CO2}C^{CO2}_{k,p} \qquad (137)$$

The cost of methane, $\mathrm{Cost}^{\mathrm{M}}$ is calculated as:

$$\mathrm{Cost}^{\mathrm{M}}=\sum\nolimits_{\mathrm{p}\in\mathrm{P}}\mathrm{F}_{\mathrm{p}}\ \mathrm{C}_{\mathrm{p}}^{\mathrm{M}}\quad+\mathrm{F}_{\mathrm{Methane}}^{\mathrm{utility}}\mathrm{C}_{\mathrm{p}}^{\mathrm{M}} \tag{138}$$

The cost of existing plants are given as

$$\mathrm{Cost}^{\mathrm{EP}}=\sum\nolimits_{\mathrm{p}\in\mathrm{EP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{C}_{\mathrm{c,p}}^{\mathrm{capex}}\mathrm{F^c}_{\mathrm{c,p}}\,\mathrm{A}\ +\sum\nolimits_{\mathrm{p}\in\mathrm{EP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{F^c}_{\mathrm{c,p}}\ \mathrm{C}_{\mathrm{c,p}}^{\mathrm{opex}}\ \mathrm{hy} \tag{106}$$

The cost of the utility system

$$\mathrm{Cost}^{\mathrm{UT}}=\ \mathrm{P}^{\mathrm{import}}\mathrm{C}^{\mathrm{PW}}+\sum\nolimits_{\mathrm{p}\in\mathrm{P}}\sum\nolimits_{\mathrm{m}\in\mathrm{M}}\mathrm{m}_{\mathrm{m,h,p,i}}\mathrm{C}^{\mathrm{Rnewable\ Steam}}{}_{\mathrm{h,i}} \tag{139}$$

A is the annualization factor, while hy accounts for the time conversion, where $\mathrm{C}^{\mathrm{Rnewable\ Steam}}$ is the renewable energy steam type h of level i imported to the city. The operating cost parameter accounts for all raw materials (except natural gas and carbon dioxide), utilities, labor, and maintenance. The cost of optional plants are given as:

$$\mathrm{Cost}^{\mathrm{OP}}=\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{C}_{\mathrm{c,p}}^{\mathrm{capex}}\mathrm{F^c}_{\mathrm{c,p}}\quad\mathrm{A}+\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{F^c}_{\mathrm{c,p}}\ \mathrm{C}_{\mathrm{c,p}}^{\mathrm{opex}}\mathrm{hy} \tag{107}$$

As for the cost of carbon integration network $Cost^{CI}$ are given by equations (108) to (111)

$$\mathrm{Cost}^{\mathrm{CI}}=\mathrm{Cost}^{\mathrm{Comp}}\ +\mathrm{Cost}^{\mathrm{Treatment}}+\mathrm{Cost}^{\mathrm{Pipe}} \tag{108}$$

$$\mathrm{Cost}^{\mathrm{Comp}}=\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{C}_{\mathrm{c,p}}^{\mathrm{Comp,\ capex}}\quad\mathrm{A}+\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\ \mathrm{C}_{\mathrm{c,p}}^{\mathrm{Comp,\ opex}}\mathrm{hy} \tag{109}$$

$$\mathrm{Cost}^{\mathrm{Pipe}}=\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\mathrm{C}_{\mathrm{c,p}}^{\mathrm{Pipe,\ capex}}\quad\mathrm{A}+\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\ \mathrm{C}_{\mathrm{c,p}}^{\mathrm{Pipe,\ opex}}\mathrm{hy} \tag{110}$$

$$\mathrm{Cost}^{\mathrm{Treatment}}=\sum\nolimits_{\mathrm{t}\in\mathrm{T}}\sum\nolimits_{\mathrm{k}\in\mathrm{k}}\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\sum\nolimits_{\mathrm{c}\in\mathrm{Sc,p}}\mathrm{T}_{\mathrm{s,c,p,k,p,t}}$$

$$\mathrm{C}_{\mathrm{c,p}}^{\mathrm{Treatment,\ capex}}\mathrm{A}\ \ +\sum\nolimits_{\mathrm{t}\in\mathrm{T}}\sum\nolimits_{\mathrm{k}\in\mathrm{k}}\sum\nolimits_{\mathrm{p}\in\mathrm{OP}}\sum\nolimits_{\mathrm{c}\in\mathrm{C}_{\mathrm{p}}}\sum\nolimits_{\mathrm{c}\in\mathrm{Sc,p}}\mathrm{T}_{\mathrm{s,c,p,k,p,t}}\ \mathrm{C}_{\mathrm{c,p}}^{\mathrm{Treatment,\ opex}}\mathrm{hy} \tag{111}$$

3.2.3 Illustrative Example

3.2.3.1 Given Setup

The proposed concept is illustrated in the following example, which is an industrial park that includes a set of existing and optional plants that receive processed natural gas, methane. Plants include a Liquefied Natural Gas (LNG) plant, Gas-to-Liquid facility, GTL, a Natural Gas Fired Power Plant and two Methanol plants (both a standard (A), and a CO_2-receiving plants (B)) and an existing utility system that has been designed for the given system. A base case was solved given the described plants.

The plants main products and approach-required information are shown in Table 3-8. Plants economic information and product costs are given in Table 3-9. Data presented were obtained from literature with conversion as explained in the (pervious chapter 3.2.4) Lifetime of the plants were assumed to be 20 years. Total natural gas available in the city is to 15 kt/d, the price of natural gas was taken to be 2.76 USD/MMBtu and power exported and imported at a price of 0.02 USD/kWh. The utility system capital cost is assumed to be already spent and the fuel, methane that is accounted as total expense, dominates the operating cost

Table 3-8: Given plant information

Plants		Max product capacity, t/d	tCH_4/t Product	CO_2 source point	CO_2 composition (wt%)	tCO_2 out/t Product
Methanol (A)		1,400	0.683	Off gases	7%	0.5
				Power & Heat	Connected to the utility system	
Gas-to-liquid (GTL)		5,700	1.62	Process	100%	0.99
				Off gases	7%	3.03
LNG		6,000	1.00	Connected to the utility system		
Methanol (B)		1,400	0	Purged	~3%	0.09
Power Plant		1,800	0.19 tCH_4/MWh	Gas turbine	7%	0.4
Utility System	Gas turbine	No limit	0.19 tCH_4/MWh	Gas turbine	7%	2.74
	Boiler		Eq(12) at 81%	Boiler	7%	

The LNG facility power generation unit is eliminated in this case study, instead it is allowed to import power from the utility site as can supply a reliable electrical power. To ensure the availability and reliability of the LNG plant, an emergency power generation facility is accounted for in the capex, for emergency design purposes (Aoki and Kikkawa, 1997). The natural gas power plant has a fixed power output of 350 MW that can be replaced up to 20% using renewable Photovoltaic (PV) generated power. PV is available at 0.065 USD/kWh (IRENA, 2016).

Table 3-9: Plant Economic Information

Plant	USD/t product	Plant capital cost parameter (\$/tCO_2)	Plant operating cost parameter ((\$/tCO_2)
Methanol (A)	442	460	20
GTL	850	1820	0.62
LNG	370	250	0.08
Methanol (B)	442	2700	270
Power Plant	0.02 USD/kWh	1000 USD/kWe	0.00

Within the industrial park, an option exists to convert CO_2 into a value added product through the production of methanol in plant Methanol (B). Table 3-10 shows all options considered including CO_2 utilization through Enhanced Oil Recovery (EOR) and CO_2 storage (CCS). Costs and data were based on Al-Mohannadi and Linke (2016).

Table 3-10: Carbon sinks identifications within city

Plant	Sink CO_2 flow t/d	Sinks CO_2 composition wt%	Pressure of CO_2 sinks MPa	tCO_2 out of sink/tCO_2 into sink	Price of CO_2 into Sinks USD/tCO_2
Methanol (B)	1710	100%	8.0	0.09	20.0
Storage	8317	100%	15.0	0.0	-10.0
EOR	8317	100%	15.0	0.0	25.0

Amine based carbon capture units were used to separate and treat the CO_2 streams , the capital cost of the treatment were adopted from Table 3-2 . CO_2 treatment efficiency parameters and treatment removal were taken from Al-Mohannadi and Linke (2016). The operating cost come from low pressure steam demand and power. According to Hassiba et al (2016), the amount of steam used was 1400 kg LP/t CO_2 while the power requirement was calculated using the following correlation for each source.

Power Treatment Parameter: $0.4 + \frac{16.4}{\text{CO2 mol\%}}$

Pipeline, compression and pumping costs were obtained using the method proposed by Kwak (2016) and used from the previous chapter, Table 3-6 and Table 3-7. Heat integration relevant information is presented in Table 3-11 and was based on Hassiba et al (2016) with GTL energy information from Martínez.et al (2013) and LNG power demand from Economides, (2005). Heat required for the given plants were supplied and connected to the utility system.

Table 3-11: Given heat integration information

Plants	Required steam and power			Waste heat recover steam generation	
	Steam level	Steam flow (t Stem /t Product)	Power demand (kWh./t Product)	Steam level	Steam generation (t steam/t Product)
Methanol (A)	HP	0.260	17.12	MP	1.48
	LP	0.096			
GTL				MP	4.73
				LP	1.689
LNG			350.00		

The design of the utility system has been adjusted from Varbanov et al (2004) and Hassiba et al (2017). The adjustments were made to allow variable capacity of the gas turbine with an assumed constant electrical efficiency of 38.3% and steam turbines at 80% efficiency, with no upper limit of power production or steam generation flowrate has been set for all steam turbines. Steam levels are shown in Table 3-12 and renewable steam generation options are shown in Table 3-1, adopted from Hassiba et al, (2017).

Table 3-12: Steam Levels

Steam level	Pressure (bar)
VHP	90
HP	48
MP	16
LP	2.7
Condensate	0.1

Table 3-13: Renewable Energy Heat Sources

Energy source	Steam level	Estimated cost (USD/t steam)	Maximum Use limit
Parabolic troughs (solar)	MP	15.4	3,024
Geothermal	LP	4.80	3,384

The MINLP optimization problem was solved using Lindo “What’sBest 9.0” (2006) for Microsoft Excel via a desktop PC with Intel Core i7 Duo processor, 8 GB RAM and a 64-bit operating system.

3.2.3.2 Results and Discussion

3.2.3.2.1 Case A: Existing Industrial City.

An industrial park baseline was established by developing an optimized solution, where only natural gas monetizing options were considered without constraints on carbon dioxide emissions, heat integration or renewable energy use in heat or power. The MINLP has 357 variables and 183 constraints. The solution time was 1 seconds. The solution is shown in Figure 3-7. A total of 15.0 k t/d of methane was allocated to methanol A, GTL, power plant filling them to the maximum capacity and 51% capacity of LNG. The total profit of the city was established at 1,369 million USD/y and the city a collective footprint of the base case cluster is 12.1 million tons of CO_2 emitted per year (33,212 MTPD). The total natural gas taken in the utility system was 150.7 tCH_4/d with an emission of 413.0 tCO_2/d

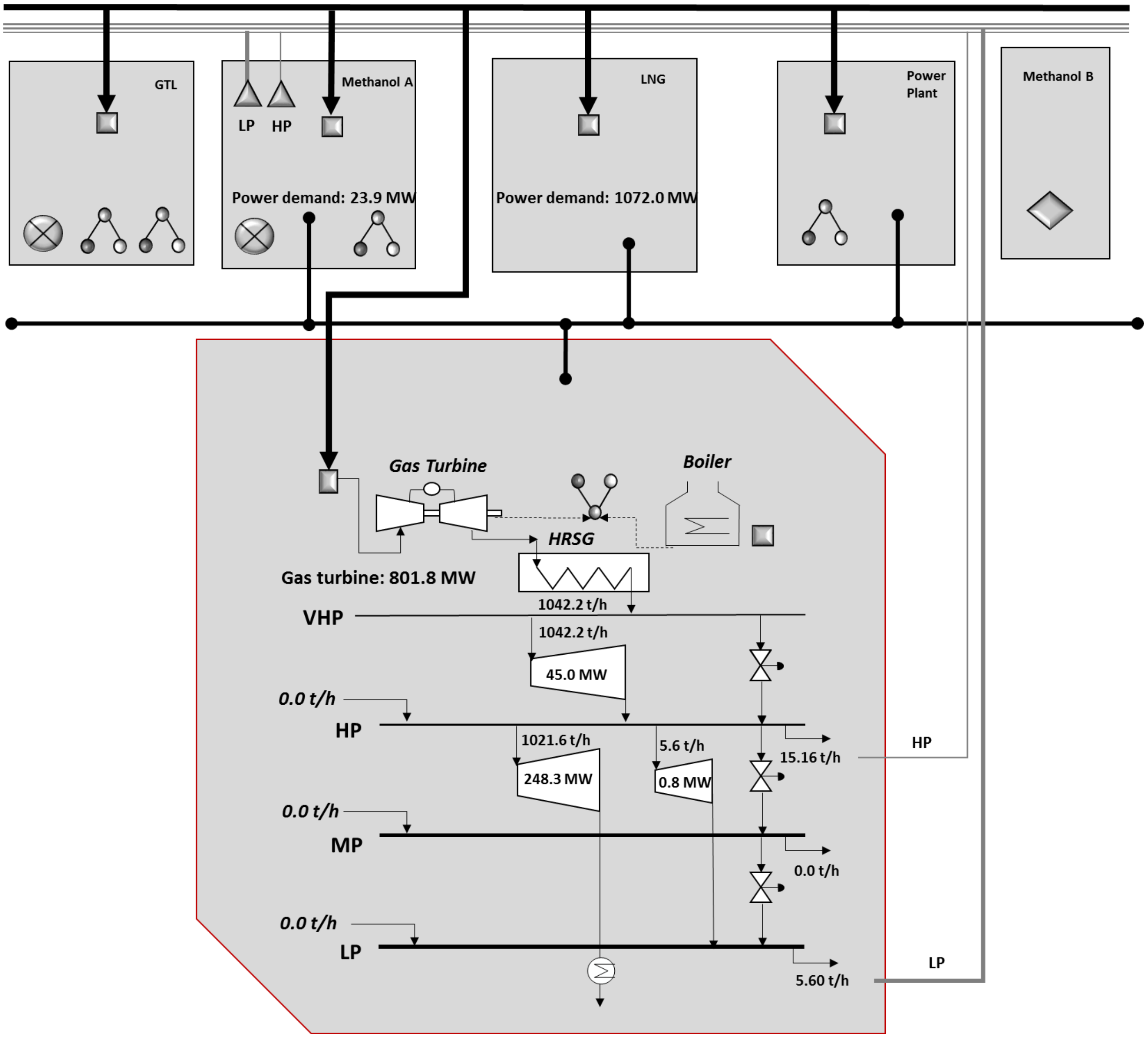

Figure 3-7: Case A: Existing industrial city base case

When excess heat was allowed to be imported from the industrial city plants to the utility system, the total profit of the network was 1,372 million USD/y compared to 1,369 million USD/y in the base case. The MINLP has 368 variables and 182 constraints, the solution time is 1 seconds. The increase in the profit comes from reducing methane in the utility site intake of 123.7 tCH_4/d, the saved methane was monetized in the LNG sink. The gas turbine capacity was 657.9 MW, and 447.5 MW from the steam turbines to meet the total demand. When renewable energy was included in the power and heat generation options, the total profit of the city increased to 1,390 million USD/y compared to 1,369 million USD/y in the base case, and the emission reduced to 11.4 million tons of CO_2. Methanol and GTL plants were activated to the maximum capacity and the LNG to 57% capacity Figure 3-8 shows the network. This increase was due to the activation of PV that replaced 20% of the power plant and saved natural gas which was allocated to the LNG. This link required extra power to be supplied to the LNG from the utility site where the gas turbine capacity was 723.1 MW and the total power produced from the condensing steam turbines was 494.5 MW. Waste heat from the GTL and methanol plant as well as the solar generated steam were used to satisfy the city's requirement and generate power. Solving for the synergy between natural gas monetization with heat and renewable energy integration and CCUS, the total profit of the city was 1,547 million USD/y compared to 1,369 million USD/y in the base case. The MINLP has 961 variables and 184 constraints, the solution time is 98 seconds. The added increase to the profit was due to the allocation of pure, untreated CO_2 from GTL (1) to both the methanol sink and EOR, which also saved emissions.

When a 50% CO_2 reduction target was imposed on the city with no mitigation measure, the total profit of the city was reduced to 479 million USD compared to 1,369 million USD/y with no target. The total methane allocated was reduced to 8.8 ktCH_4/d, to reduce emissions and meet the demand of the power plant. Methanol and LNG were activated to the full capacity, while the GTL plant was switched off. In the utility site, 292 tCH_4/d were consumed in the gas turbine which supplied 1,550.9 MW of power. The steam turbines produced 573.1 MW to meet the total power demand of 2,124 MW.

Imposing a 50% CO_2 reduction target on the heat and renewable energy integrated system, the total profit was 837 million USD/y. The total methane allocated was to 11.5 ktCH_4/d . Methanol and LNG were activated to the full capacity, while the GTL plant capacity was operated at 33% capacity. Renewable energy was used in power production in the power plant to the maximum 20% capacity, while MP steam from the solar thermal plant was used in the utility system. Integrating the solution with CCS, yielded a profit of 1170 million USD/y and the total methane allocated was to 14.9 ktCH$_4$/d. The higher profit margin than using RE and CCS was due to the ability to reduce the emission without reducing the amount of natural gas monetized. Methanol and LNG were activated to the full capacity, while the GTL plant was running at 69% capacity. The network also activated the PV use to 20% of the power plant .Treated CO$_2$ GTL (2) and untreated GTL (1) were used in the storage sink. Waste heat from GTL was used to satisfy heat and power demand from the CCS network.

When CCUS was integrated and 50% reduction target was imposed, the total profit of the network was 1,435 million USD/y compared to 1,369 million USD/y base case with no target imposed. The total methane allocated was to 15 ktCH$_4$/d, the network is shown in Figure 3-9. The MINLP has 973 variables and 185 constraints, the solution time is 21 seconds. Reducing 50% of the emission was still a profitable activity due to the added profit from the CCUS options. Methanol and GTL were activated to the full capacity while LNG production reduced to 56% capacity. Methanol B sink received CO$_2$ from treated GTL (2) and untreated GTL (1). EOR was filled by treated CO$_2$ from GTL (2) and storage was used with untreated GTL (1), which was least expensive source as it needs not treatment was placed in the most expensive sink. The waste LP steam from the GTL plant was used to cover some of the heat needed for the carbon integration network. Heat demand comes from the treatment units, which also requires power. Additional power required for compression and pumping for CO$_2$ allocation. When the emission target was increased to 80%, the total profit of the city was 1,206 million USD/y compared to a city profit of

1,369 million USD/y with no target emission. The total methane allocated was 14.8 ktCH4/d. Methanol and LNG were activated to the full capacity, while GTL was operated 68% capacity. The GTL reduction was due to the high emission associated, with two emission sources, and limited sink capacities. Methanol B. EOR, and the storage sink were filled to the maximum capacity. Renewable energy use was the same as with the 50% reduction. The utility site consumed 270 tCH4/d and emitted 739 tCH$_4$/d, with a gas turbine of 1435 MW to make up for the extra power demand of the LNG and carbon integration network.

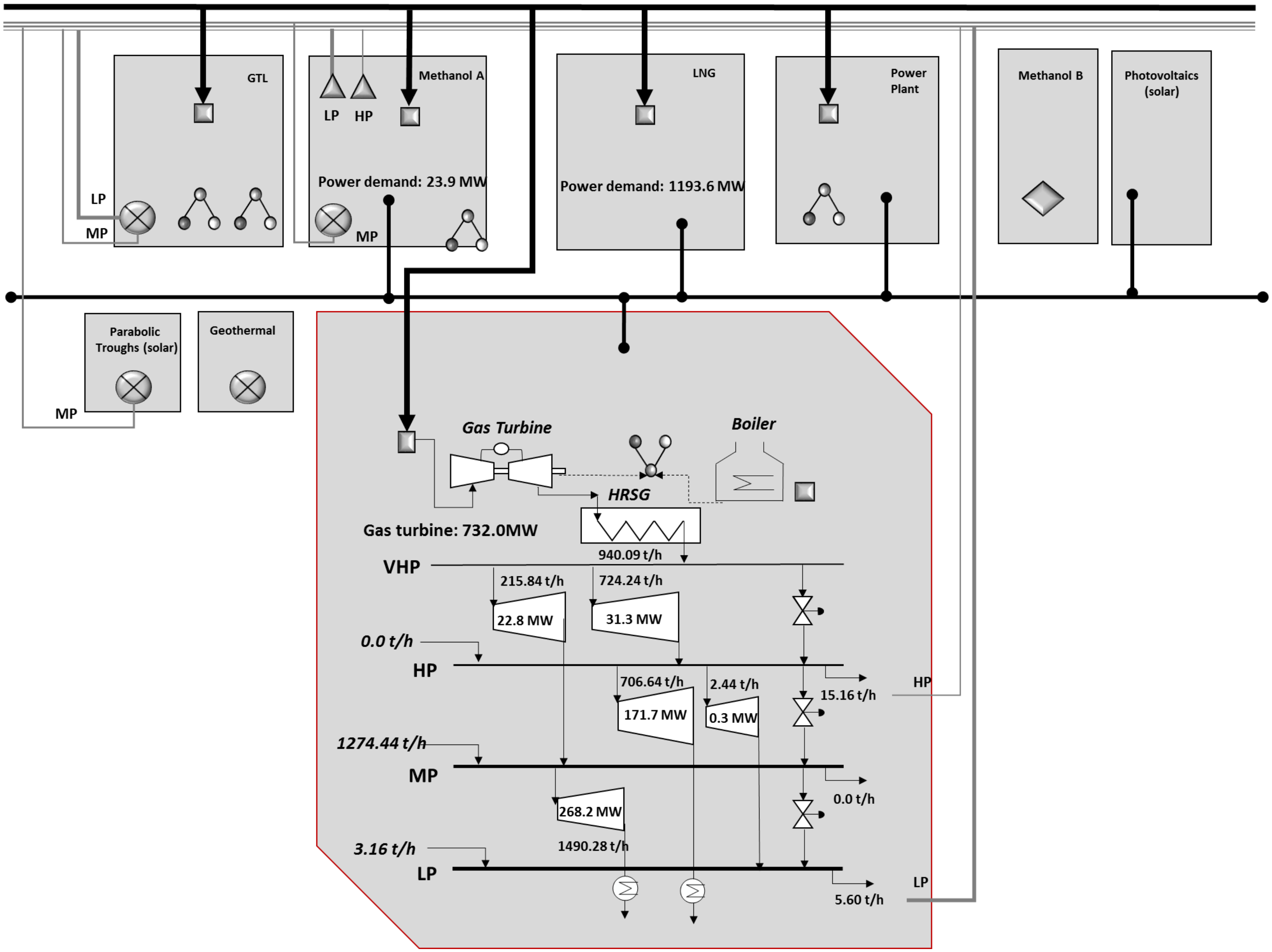

Figure 3-8: Case A-Gas Monetization with Heat and RE integration

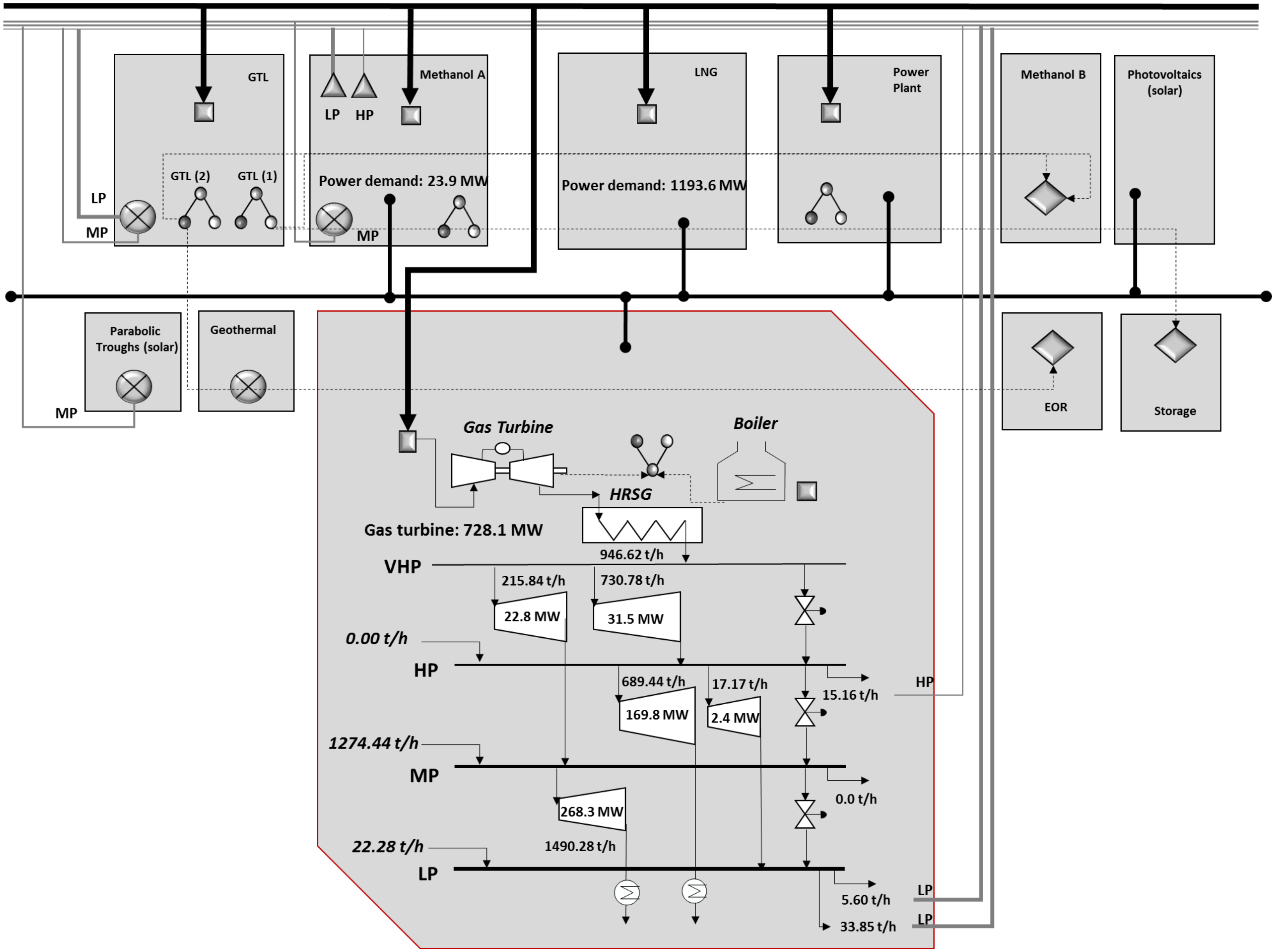

Figure 3-9: Gas monetization with Heat, RE and CCUS Integration at 50% reduction

3.2.3.2.2 Case B: Designing a new city.

The method was used to design a new city from the given set of plants. Allowing all plants to be optional and without a climate target imposed, the maximum profit generated was 2,165 million USD/y and an emission of 6.8 million tons of CO_2/y. The MINLP has 329 variables and 177 constraints. The solution time was 1 seconds. Methanol plant was activated a capacity of 19.5 kt/d. as it yielded a high return. The allocation and utility site are shown in Figure 3-10. The profit increased when heat and renewable energy was integrated and optimized, to 2,219 million USD/y. The network is shown in Figure 3-11. The total methane used was 15 kt/d, which was supplied to the power plant, utility site and methanol. Methanol received more natural gas, compared to the case with HI and RE integrated, as the power plant intake was reduced due to the generation of 20% of the power requirement using PV. Integrating the solution further with CCUS, the profit of the city was 2,335 million USD/y and reducing the emission to 5.7 million tCO_2/y. The MINLP has 955 variables and 181 constraints. The solution time was 58 seconds The increase in income was from the allocation of treated power plant CO_2 source into methanol B, filling the capacity of the sink.

When a 50%, emission reduction was imposed on the new city with reference to Base Case A emission, resulted in a city that produced methanol at 13k t/d and LNG at 4.2 k t/d and a total profit of 1,730 million USD/y. The MINLP has 342 variables and 181 constraints. The solution time was 1 seconds. The gas turbine capacity in the utility site was 1.26 GW and the emission was 652 t/d CO_2. When imposing the same target on a heat integrated city, the total profit was 2,127 million USD/y. Methanol was produced at 18 k t/d and LNG was at 927 t/d. PV was used to the maximum allowed capacity of 20% in the power plant. The utility site imported MP steam from solar thermal in addition to LP steam from geothermal, to reduce the amount of fuel consumed in the gas turbine, which had a capacity of 242 MW. When CCS was introduced as most likely proposed mitigation option, the total profit was 2,208 million USD/yr. The total natural gas consumed was 15 k t/d, which was allocated to methanol production at 20 k t/d, the power plant at 1,264 t/d and 44 t/d to the utility site. Storage received CO_2 from the treated methanol CO_2 source. The network reduced the amount of LP steam imported from geothermal and eliminated MP solar generated steam imported. This contributed to a reduction of the total cost which made mitigation using a combination of RE mix and CCS more economical than 100% RE use. For the same target and incorporating CCUS as a mitigation option in addition to RE. The network resulted in a 2,335 million USD/y profit, which is the design that results from incorporating CCUS without a target. The network is shown in Figure 3-12. The MINLP has 967 variables and 182 constraints. The solution time was 119 seconds. The maximum allowed methane was used and allocated to methanol production Maximum PV capacity was used to offset some of the power plant emissions. Methanol B was filled by treated CO_2 flows from the power plant. When 80% reduction target was imposed, the profit was 2,237 USD/y. The maximum methane capacity was used and allocated to methanol production. The CCUS network allocated treated methanol emission to methanol B, Storage and EOR, which received extra CO_2 from treated power plant.

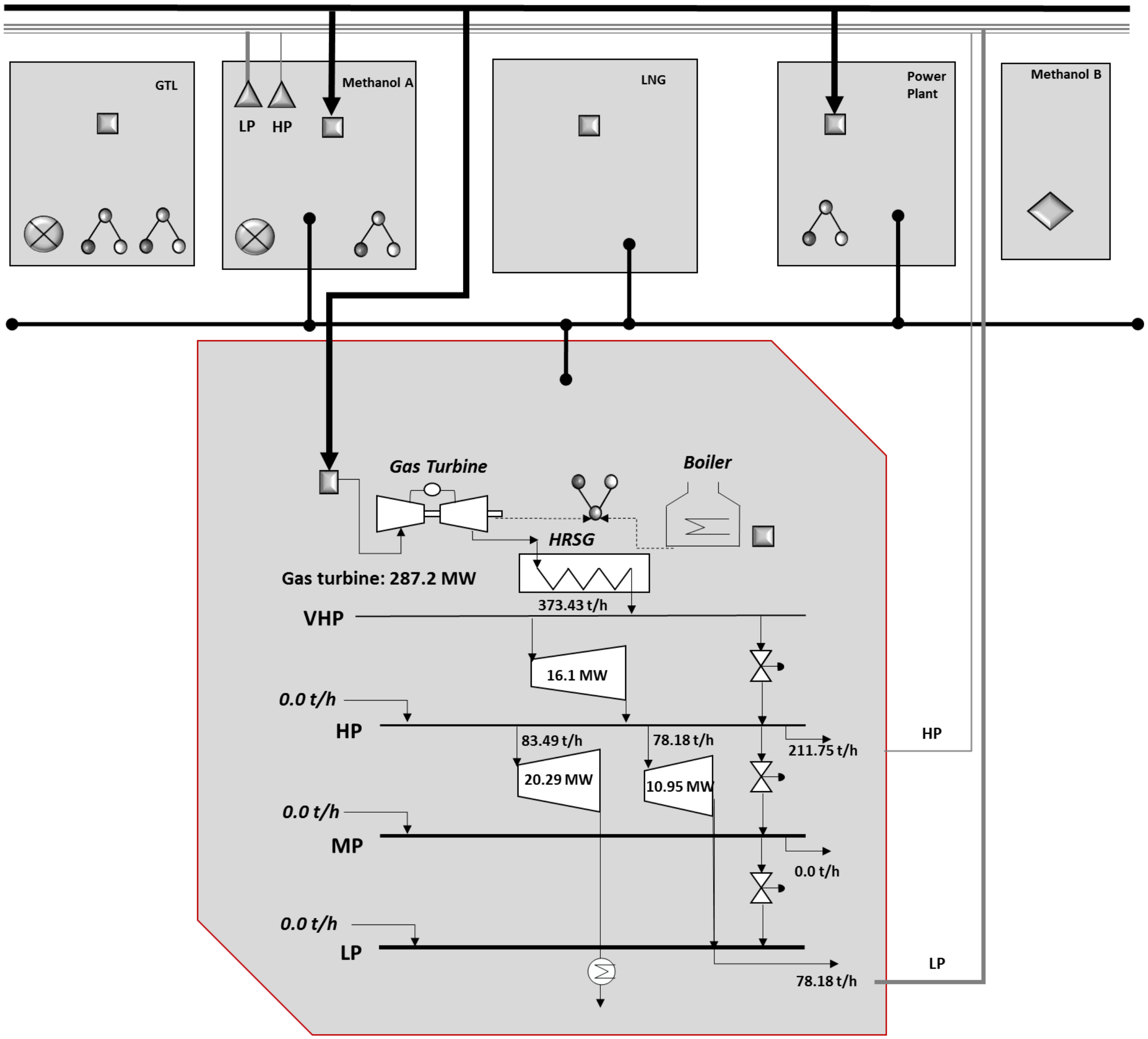

Figure 3-10: Case B-Natural Gas Monetization

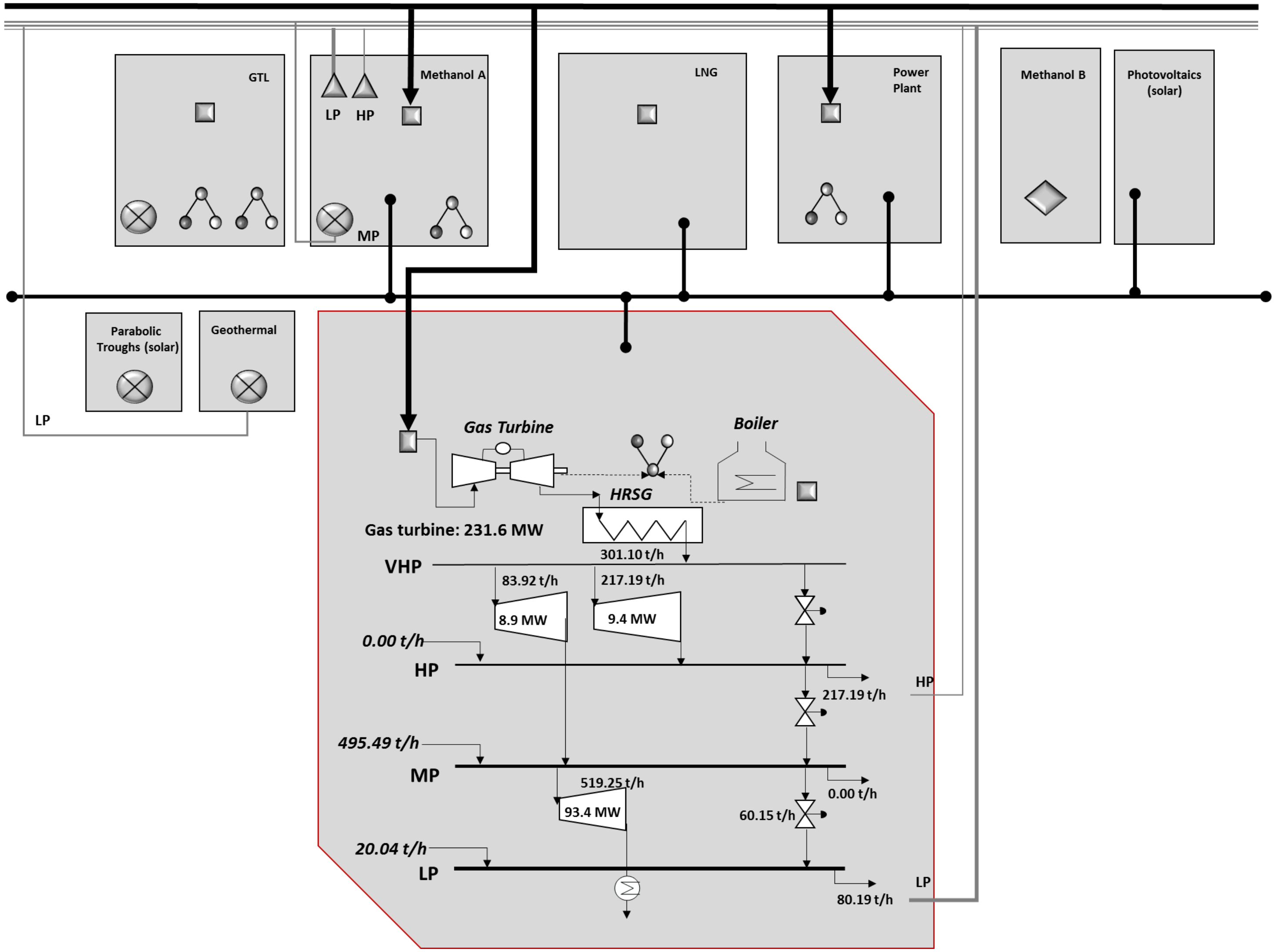

Figure 3-11: Case B-Natural Gas Monetization with Heat and R.E. Integration

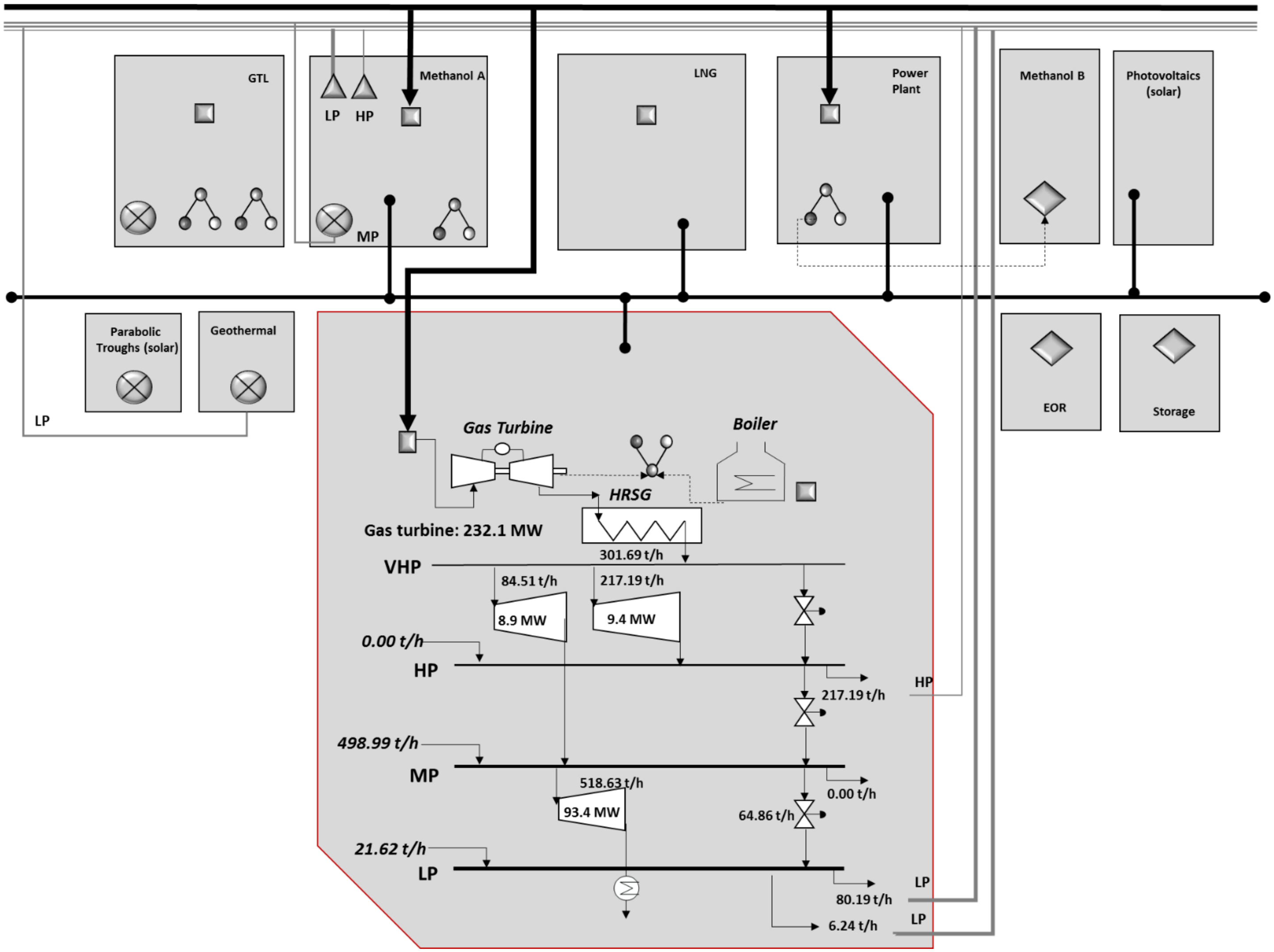

Figure 3-12: Case B-Natural Gas Monetization with Heat and CCUS-RE Integration for 50% reduction target

It can be observed from this example that heat integration with natural gas monetization can achieve savings, which enables more production of value added products. This is evident in the case of new city design under carbon targets. Moreover, renewable energy use in power production was more favorable than steam generation, for the case of solar in comparison to waste heat use and CCUS. A use of a mix between RE and CCS can be economical, than the use of RE solely. However, the use of RE and CCUS is the most profitable option. Future work should investigate the incorporation of more plants using a decentral heating system as the central system used in this work has assumptions that could limit further savings.

3.2.4 Conclusion

This chapter developed a systematic screening approach of natural gas monetization options with carbon dioxide and energy integration in an industrial cluster using a central utility system. The resulting optimization-based approach can synthesize integrated natural gas, carbon dioxide and energy networks for industrial cities that meet carbon dioxide emissions constraints while maximizing the profitability of natural gas use. An example is solved to illustrate the application of the approach and highlighted significant savings applying synergy. It was observed that the cost utilities needed for plants and CCUS networks was offset by reuse excess heat and reduced and in turn allowed the conversion of methane to value added products. Future work should include investigating the role of decentral energy integration as opposed to using a central system.

4 SUMMARY

4.1 Conclusions

In this work, several methods that assist in the design of sustainable industrial clusters under carbon dioxide emission targets and resource management strategies have been introduced. Methods that involve accounting for time, renewable energy, management of natural gas and power and central heat integration have been studied. The systematic multi-period CCUS and CCUS-RE integration approaches highlighted significant differences in economic impact of alternative footprint reduction policies. Whereas the synergetic method that explores natural gas allocation, heat and power generation and carbon dioxide reduction, give a holistic evaluation of economic diversification of natural resource centric economy under climate targets.

The consideration of time and planning horizon is important as most policies and strategies advocate carbon dioxide cuts or sequences of cuts depending on policy have to achieve a certain emissions reduction at a future date. In chapter 1, section 2 a method was developed designates a number of periods and in each period identifies allocation of carbon dioxide between sources and potential sinks to develop a low cost network. Capital and operating costs of connections, compression and treatment are compared simultaneously across all periods. While in chapter 2 section 2, in depth analysis of the connections and addition of RE was possible through a robust MILP. Effective natural gas or shale gas monetization is of increasing importance in many regions of the world. Natural gas can be monetized in many ways to value added products or can be used as fuel and each monetization route carries a different carbon emission. The challenge is to adhere to emission reduction targets, while maintaining profitability. Chapter 3.1 focused on developing a systematic, optimization-based approach to simultaneously determine natural gas monetization and carbon dioxide management through CCUS as well as renewable energy strategies. While section 3-2, the approach expanded to consider heat and power integration, closing the Natural gas (CH_4), CO_2 and Energy nexus. Each of the proposed frameworks allow cost-effective climate policies to be identified, by implementing a systematic design approach for industrial clusters integration network synthesis. Several case studies have been implemented to demonstrate each of the proposed methods

4.2 Future work

This work lays the foundation for further contributions to the process system engineering field especially in the design of sustainable industrial parks and climate strategy development. Future work can include:

- Incorporate the time element to the methane, carbon dioxide and energy network would give a more holistic approach and insights to aid designers and policy makers

- Incorporating water use, treatment and re-use with the energy, resource (natural gas) and carbon integration networks. This could be coupled with food production which would be crucial to sustainable development.

- Expand the representation to include multiple feedstock monetization to value added products. Feedstock can include biomass, coal and oil. Resource management is needed for economic diversification away from dependency on selling raw materials while meeting climate targets.

- Evaluate the integration networks using different metrics to assess sustainability on social, economic and environmental scales

- Explore the trade-offs between economics and sustainability metrics to assess performance using multi objective optimization.
- The representation expansion and added elements will need a better tool which can handle large scale non-linearities, complex inter dependability of elements and can provide exhaustive analysis.

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