DEVELOPING ECONOMIC TARGETS FOR STRATEGIC CARBON REDUCTION PATHWAYS

A Thesis

by

MOHAMMAD LAMEH

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Patrick Linke
Co-Chair of Committee,	Dhabia Al-Mohannadi
Committee Member,	Hamid Parsaei
Head of Department,	Arul Jayaraman

August 2020

Major Subject: Chemical Engineering

ABSTRACT

The rising concerns about the issue of climate change have led to the emergence of global efforts to mitigate the rising concentrations of CO_2 in the atmosphere. Different pathways for carbon reduction exist, however, the application of such strategies is minor relative to the available opportunities due to economic burdens. Given the variety of options, it is important to establish a decision-support tool that allows the identification of carbon reduction strategies with minimum cost. Recent developments in process integration have addressed the issue of designing carbon reduction pathways with minimum costs. However, no work has been done on developing a cost targeting method that gives quick insights on the economics of carbon mitigation. This work proposes a simple and effective technique that allows the quick determination of the lowest cost portfolios for the implementation of the different technologies for carbon reduction. Insights can be provided on the optimal carbon reduction pathways through developing cost curves. The method was applied to assess different planning strategies and the economics of carbon mitigation in different regions. The aim is to provide planners, policy makers, and analysts with a decision support tool that allows a quick identification of the optimal pathways.

ACKNOWLEDGEMENTS

I would like first to thank my advisors Prof. Patrick Linke and Dr. Dhabia Al-Mohannadi for their continuous help, support, and advice. They were really involved in my work and every step I took to accomplish my thesis was led by their significant guidance. Under their supervision I was able to gain significant knowledge in the topic and develop myself further as a researcher.

I would like also to thank Prof. Hamid Parsaei, my committee member, for his time and concerns. My thanks are also to the TAMUQ community, starting with the office of graduate studies who provided significant assistant from me as an international student since before joining the program. I would like to thank all the faculty who taught me a lot during my course of study. Special thanks for all the friends who I met and who had significant impact on my life during the past two years with all the encouragement and support.

I would like to thank my family, my parents and my in-laws for their non-stopping emotional support through their love, encouragement, and prayers. I am so grateful for having a special person always with me and by my side, my wife Ola Srour, who stood by me and helped me in the hard times to overcome any obstacle and to be able to accomplish this milestone.

Receiving my degree from TAMUQ is a great honor and a very big step in the path I have set for myself. So finally, I would like to thank all the people wo have helped me in my path before and after joining TAMUQ and allowed me to reach where I am today.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Prof. Patrick Linke (chair of the committee) and Dr. Dhabia Al-Mohannadi (co-chair) of the Department of Chemical Engineering and Prof. Hamid Parsaei of the Department of Industrial Systems Engineering.

All other work conducted for the thesis (or) dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by a fellowship from Texas A&M University at Qatar.

NOMENCLATURE

GHG	Greenhouse Gas
INDC	Intended Nationally Determined Commitments
CCUS	Carbon Capture, Utilization, and Sequestration
CCS	Carbon Capture and Sequestration
CCU	Carbon Capture and Utilization
EOR	Enhanced Oil Recovery
GH	Greenhouse
GTL	Gas to Liquid
MAC	Marginal Abatement Cost
C_{si}	Specific cost for capture and compression of emissions from source s_i
R_{dj}	Specific revenue from processing emissions in sink d_j
F_{si}	Flowrate of CO_2 available after capture from source s_i
F_c	Flowrate of CO_2 allocated to the capture unit
F_{dj}	Flowrate processing capacity of sink d_j
X_{net}	Net fixated CO_2 fraction
TR_{dj}	Total revenue from processing emissions in sink d_j
TC_{si}	Total cost for capture and compression of emissions from source s_i

$P_{s,d}$ Net profit from capturing and allocating emissions from source s to sink d

TP Total profit generated from the carbon network

η Efficiency of the unit

γ_s Power-related emissions factor for capture and compression

F_{emit} Flowrate of the produced CO_2 from the sources

F_{pinch} Flowrate of processed CO_2 corresponding to the profitability pinch

$F_{cost\text{-}neutral}$ Processed CO_2 flowrate corresponding to the cost-neutral carbon network

F_{ijmax} Maximum flowrate corresponding to introducing source s_i and sink d_j

C_{Ej} Specific total cost of the alternative energy source E_j

C_{Ei} Specific operation cost of the existing energy source E_i

ε_{Ei} CO_2 emissions factor of existing energy source E_i

ε_{Ej} CO_2 emissions factor of alternative energy source E_j

CT Carbon tax rate

IT Income tax rate

CF Process Cash Flow

CP Specific Carbon Price

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Global warming is a major environmental issue threatening the planet's stability due to its effect on various sustainability factors leading to losses in bio-diversity, water, and land[1]. Total CO_2 emissions in 2019 were estimated to be around 43.1 $GtCO_2$, 36.8 $GtCO_2$ of which were emitted by industrial activities and energy production[2]. These sources of emissions are referred to as stationary sources. Major stationary sources are iron steel, cement, and petrochemical plants[3], producing 31%, 27%, and 10% of the global industrial carbon emissions respectively[4]. It has been estimated that the demand for products from such industries will double by 2050[5]. With the increasing population and urbanization, and the development of technologies and economies, energy demand is expected to increase[6]. Consequently, carbon emissions are expected to increase further. To avoid the catastrophic consequences, Intergovernmental Panel on Climate Change (IPCC) has recommended that the global carbon emissions should decrease by 50%-80% by 2050[7]. Moreover, to fulfill the Paris Agreement's goal of limiting the global temperature rise to below 2^oC, countries have outlined their plans through Intended Nationally Determined Contributions (INDC)[8]. According to Rogeli et al[8], although INDCs will result in decreased global emissions upon implementation, a 3^oC warming is expected by 2100.

Therefore, the scientific community has given a great attention during the past years to the reduction of greenhouse gas emissions (GHGs), and many efforts have been initiated to develop emissions mitigation tools to guide the set strategies[9]. Emissions mitigation can take place through increasing the efficiency of the existing processes, relying on energy sources with lower or zero emissions, or through capturing the emitted CO_2 for storage or utilization[10]. Although implementing energy sources with lower carbon footprint has a significant role in mitigating GHG emissions, economic and social considerations remain obstacles in the required wide implementation path of such technologies[10]. In many cases shutting fossil fuel power plants will incur significant economic losses outweighing the environmental reward for the decision makers[11]. Consequently, the 50% emissions reduction target by 2050 cannot be achieved without the implementation of CCUS technologies[12]. On the other hand, the implementation of CCUS projects has not achieved the planned scales that allows their ultimate contribution to the worldwide carbon reduction. In Europe, 12 CCS projects were planned to be in operation by 2015, however, none has been executed [3]. According to the Global CCS institute, 26 CCS projects have been canceled due to economic burdens [13].

The high costs of sustainable implementation of renewable energy production and carbon capture as well as other social considerations affect the competitiveness of the existing industries in a country, and hence the economy [14]. The result is the failure of national and international commitments in reaching the planned targets as the emissions levels keep increasing. In the past 50 years, 500 recognized agreements were signed by different countries, however the emissions rate increased by 30×10^6 t CO_2/y between 1980 and 2014 [15]. The commitments are established based on plans and visions of future carbon reduction plans, and they include allocating to boost carbon reduction, as well as penalties and incentives through tax and subsidy policies which have direct impact on the industrial sector in a country. Hence, it is important to understand the economics associated with the different options for CO_2 reduction to design a strategy with the cheapest costs. The strategy should consider an optimal techno-economic system requiring the least costs and the political framework that ensures the feasibility of such system.

This work proposes a targeting tool that allows the quick assessment of different carbon reduction pathways for a group of emission streams. The method gives insights on the cost optimal carbon abatement through CCUS by developing cost curves for carbon supply and demand. The developed targets include: the minimum cost (or highest profit) of implementing the carbon network for a given carbon processing flowrate, the sources and sinks required to generate the optimal carbon network, and the CO_2 processing flowrates that correspond to the maximum profit generated by CCU and to the carbon network with zero costs. The method would then be developed to consider the secondary emissions generated from the carbon network in order to minimize the cost of the net carbon reduction. This would allow the comparison of CCUS with other pathways such as renewable energy to generate a holistic view on the cost-optimal carbon reduction. The approach identifies which sources and sinks need to participate in the established carbon network and which energy alternatives to utilize. The targets can then be used as benchmarks to assess the performance of carbon network and policy designs. The carbon tax is then investigated in the context of the developed targets, considering the different interactions between the different stakeholders.

Chapter II presents the existing literature on the decision support tools that are designed to help planners and policy makers in achieving optimal carbon reduction pathways. In Chapter III a graphical targeting tool is developed for optimizing carbon network implementation. The method will be illustrated through a demonstrative example. The method is then developed in Chapter IV to consider secondary emissions and to include other carbon reduction pathways such as renewable energy and planning under different criteria. The developed method will be used to show the effect of planning criteria on the total cost of carbon reduction. The impact of accessibility to different carbon reduction options is investigated through a case study with real data collected for three different geographic regions: Norway, Qatar, and Japan. The interactions between the different stakeholders: sources, sinks, and authority, are modelled in Chapter V, considering a traditional carbon policy: carbon tax, to analyze its performance towards achieving the developed targets.

CHAPTER II

LITERATURE REVIEW

This section summarizes different decision and policy support tools that have been developed in literature. The reviewed literature spans a range of different applications including carbon network planning methodologies and policy design and support models. Each tool is assessed in terms of the application to carbon reduction planning and the gaps are identified.

Process Integration Tools

Process integration is a comprehensive path approaching the wholeness of the process through process design, retrofitting, and operation [16]. Early applications go back to 1970s with the application of pinch analysis to minimize the external energy requirements of the process through heat integration [17]. Since then, process integration has been developed as an independent field with wide applications in sustainable and optimal design. The general framework of the process integration techniques can be described as follows: for a set objective (or objectives), optimal achievable targets can be developed to benchmark the optimal designs. Optimal designs can then be generated through identifying the possible alternatives and selecting the options that result in achieving the targets[18]. In this context, the planning tools developed in the process integration field can be categorized into targeting and design methodologies. The targeting tools are simple and give quick insights on the optimal achievable goals for the objective.

The design methodologies and more complicated and time consuming as they provide detailed pathways for achieving the goals.

The developments in the field of process integration have led to the emergence of new tools addressing the issue of optimizing the planning of carbon reduction projects. Manan et al[19] reviewed the research work in process integration for CO_2 emissions reduction. The review showed that different techniques are applied in the various stages from supply side energy management to the demand side management. Early applications of process integration in carbon reduction was through optimizing energy allocation between plants and reducing the energy-related CO_2 emissions [20]. Tan and Foo [21] developed carbon emissions pinch analysis for energy planning under abatement constraints. The methodology was applied for different regions in the Philippines and was later applied for different economic sectors in context of country's commitment to carbon reduction [22].

Process integration techniques have been also used for CCUS planning. Tapia et al[10] reviewed the tools applied for supporting decision-making in planning CCUS carbon networks. The main existing models are mathematical programming optimization and pinch analysis methods. Such approaches emerge from the philosophy of targeting design described earlier. Pinch analysis methods are simple targeting techniques used to develop quick insights based on collected data. The design problems are addressed through mathematical optimization by modelling the material and energy flows in the system and setting the allocations to optimize the objective. The targets and the design objectives included economic (minimizing costs) [23] and environmental (minimizing emissions) [24] considerations.

Algebraic and graphical targeting methods have been proposed to provide insights on the best implementation of CCS retrofitting[25] and optimal source-sink matching[26]. Illyas et al [27] developed a targeting technique to optimize CCS retrofit to the power sector as well as the compensatory power demand from renewable sources. Diamante et al [26] developed a pinch analysis targeting technique to match CO_2 sources to storage cites while minimizing the unused capacities of the reservoirs. The matching was constrained by the capacities and injectivity rates. Ooi et al [28] considered the time variability of the same problem and addressed a multi-period scheduling of the source-sink matching problem. Mohd Nawi et al [29] introduced the concept of CO_2 total cite planning through an algebraic pinch technique that maximizes the flow of CO_2 from sources to utilization sinks and minimizes CO_2 sequestration. All the developed targeting techniques aim to maximize the CO_2 flowrate into the various sinks considered in order to maximize the capacity of CO_2 reduction. However, the problem of planning a cost-optimal carbon network have not been addressed yet at the targeting stage.

Designing carbon networks through source-sink matching has been addressed through mathematical programming with different objectives. Tan et al [30] developed a multiperiod mixed integer non-linear programming model to maximize the CO_2 storage under temporal and physical constraints. The study was then developed to include the uncertainties associated with the capture and storage [31]. The level of details harnessed in the design approaches allows the optimization of the economics of CCUS implementation. Hasan et al [32] developed a linear programming model that allocates emissions from sources in the United States to enhanced oil recovery (EOR) sinks regionally and nationally while maximizing the profit. Al-Mohannadi and Linke [33] developed an optimization model that allocates captured emissions streams from sources to sinks to minimize reduction cost under carbon reduction constraints. The model considered the capability of mixing streams at the sinks, and different possible carbon sink technologies were investigated. The multi-period planning problem was then addressed to minimize the cost of the carbon network implementation over phases [34]. Hassiba et al [35] later included heat integration into the planning. Al-Mohannadi et al [36] introduced a methodology based on linear programming to optimize the economic outcome of natural gas monetization under carbon reduction constraints with various CCUS options.

Planning cost-optimal carbon networks for CCUS implementation has been addressed through process design methodologies. The tools are implemented through complicated and time-consuming procedures involving detailed modelling and optimization. Such approaches require computational power and may result in equally significant solutions which need further analysis. Having a final solution to the problem may not allow the understanding of the different available options and further insights are needed to assess the impact of the solution relative to other options. Hence, a cost-targeting technique is required which consider the economics of the carbon network. Such technique should provide quick insights on the available options to allow a high-level understanding of the system.

Moreover, the process integration techniques provide final optimal solutions disregarding the different interactions of the stakeholders affecting its implementation. This may lead to optimistic results which may not be feasible for all the stakeholders, affecting the implementation of proposed solution. Policy models have been developed to address the issue through defining the different stakeholders and modelling their interactions. Different policy frameworks have been investigated through such models to understand the feasibility of optimal solutions under multi-stakeholders' interactions. These tools are reviewed in the following section.

Policy Models

The optimal solutions for carbon reduction should be implemented in a political framework that ensures their feasibility. Planning carbon reduction is performed at the level of a political authority (government) which issue national and international commitments to reach a certain level of carbon reduction. The implementation of carbon reduction technologies to achieve carbon reduction is implemented at the level of industrial plant which produce the emissions. The implementation of carbon reducing technologies in many cases requires costs which make such pathways economically infeasible compared to venting the emissions. Hence the governments enforce a set of regulations referred to as carbon policies that impact the dynamics of the existing techno-economic system to ensure the economic feasibility of the carbon reduction set in the commitments. Designing such framework requires a deep understanding of the interactions between the different stakeholders. Different policy models have been developed in literature to describe such interactions and to investigate different policies and actions in terms of waste minimization through industrial symbiosis. This allows understanding the complexities of the system and obtaining more realistic results feasible under the defined interactions.

Agent Based Modelling

Agent-based modelling (ABM) is a computational method used in the study of technical, social, biological, and economic systems' dynamics [37]. It is a computing tool that allows the user to establish models composed of different interacting components and analyses the behavior of the system accordingly. In agent-based modelling, the decision makers are referred to as agents: autonomous entities with different characteristics able to interact with the environment and make dynamic decisions toward achieving defined goals [38]. Being able to address the various features of interactions through industrial parks, ABM was proposed to study the evolution of industrial symbiosis [39].

Different plants constituting industrial parks were modelled as agents [40], taking decisions concerning establishing symbiotic relations to reduce waste and emissions. The proposed models can be divided according to the way an agent is defined to perceive the environment into stochastic and deterministic. Bichraoui et al [41] focused on identifying the behavioral factors that foster industrial symbiosis through setting probabilistic input parameters. Another stochastic model was developed by Mantese and Amaral [42]. Agent based simulation was used to assess different indicators that reflect symbiotic performance. These stochastic models are tested over different hypothetical scenarios to compare between the obtained and the expected outcomes. The lack of proper validation limits the application and relevance of such models. The other approach of establishing agent-based models for industrial park defines the agents' features based on rational thinking rather than probabilistic outcomes. Ruiz and Romero [43] proposed a conceptual framework to model the operations taking place in an industrial park. Economic and environmental system objectives were identified, while individual companies had economic objective with environmental constraints. Such goals would induce collaborative relations between the plants leading to symbiotic relations which can reduce feedstock cost, waste disposal price, and taxation. Albino et. al [44] developed a model also considering the firms as autonomous agents taking decisions on whether to establish symbiotic links or not. All the firms aim at maximizing a fitness function which depends solely on the economic benefit of the connection. A later study [45] harnessed the proposed model to study the effect of introducing landfill taxation and subsidy policies on the symbiotic relations within industrial parks. Tang et al [46] established an agent-based model to investigate the application of carbon emissions trading scheme on the Chinese case. The main decision-making agents are the firms and the government. If the emission level is high, the firm consider investing in carbon-reducing technologies when the investment is economically feasible. The government agent allocates free carbon limit and control the carbon emission trade market, specifying the price of carbon quota exchanged. The model developed is a simulation tool and it was applied to investigate the effect of the various policy tools through sensitivity analysis.

The problem with multiagent modelling is the fact that the interpretation depends on many repeated runs with rational justification which is hard to be obtained for systems like countries implementing carbon reduction strategies. Although ABM is a versatile tool, its value is generally limited to the prediction of general trends of systemic behavior. The limited scope of these models and the lack of detailed data for calibration and validation are limitations that must be overcome to improve their usefulness and accuracy.

Game Theory

Game theory provides a framework to model interactions among different agents (now called players) acting rationally [38]. The interactions are defined by set of rules which are followed by each player to reach a desired outcome. Although game theory is applied within multiagent programming as a decision-making model that defines agents' actions and reactions, the surveyed literature focuses on game theory as an optimization framework that considers the different levels and actors of decision-making. Taking the industrial park context, interactions can be made either between two plants; one that produces wastes/ by-products, and one that uses them, or between a plant and the authority. Various research groups have been working on using game theory to model such interactions in order to better understand the factors affecting them and how to optimize the performance taking these interactions into consideration.

Cooperative game methodologies have been used to allocate the connection costs between the waste producer and the waste receiver. Yazdanpanah and Yazan [47] presented industrial symbiotic relations as cooperative cost-allocation games. Both waste producing and waste receiving plants can cut on waste treatment cost and resources cost respectively through initiating a symbiotic relation. The decision made depends on the costs paid before and after the connection. The intended cost allocation had to be stable and fair. A follow-up discussion by the authors [48] suggested introducing regulations to coordinate such interactions in order to stabilize an unstable but desired (by the authority) connection. Regulations are introduced as incentives (subsidies) on the connection cost so that the symbiotic relation become a win-win situation for both parties involved. Tan et al [49] presented an optimization-based cooperative game approach for systematic allocation of costs among plants in a symbiotic relation. Their approach is comprised of two steps: pooling the benefits and based on that a profit-sharing scheme is developed through linear programming. Although the linear programming approach allows the cooperative game technique to be integrated into other mathematical programming optimization methodologies, the two-step mechanism would require much effort to determine all possible optimal solutions of all possible coalitions. Moreover, the idea of fairness upon which the cooperative games are based may not hold in real life as each company will be looking for its best interest without giving much attention to the profitability of other players.

The other game theoretic approaches try to account for an authoritarian entity that govern the operations in the industrial park. In such case, decisions are made at two different levels: the upper level where the authority sets incentive and tax policies to drive the plants towards eco-friendly operations, and the lower level at which plants take decisions on how to operate in response to the policy set by the government. Such scheme results in a bi-level optimization problem, also called leader-follower game, which was firstly introduced by the economist H.F. Stackelberg and named Stackelberg Game. Ramos [50] applied Stackelberg game to optimize the superstructure of water network in an industrial park. Aguilar et al [51] proposed a bi-level fuzzy optimization model to determine a proper incentive policy that results in the plants adopting proper heat and solid waste network to minimize carbon dioxide emissions. Gao and You [52] applied Stackelberg game on the supply chain of shale gas between producer and processor. The shale gas producer was the leader, trying to maximize its profit while minimizing the overall emissions of the process. The processing plant was identified as the follower aiming at maximizing own profit. Bilevel programming approaches provide powerful solutions because each player is considered to act for its ultimate benefit.

As is the case with carbon network design, policy design methodologies are performed with the lack of targeting that can benchmark the performance of the generated policies. All the policy models implement complicated tools with many assumptions and the solutions are obtained without understanding the behavior under optimal performance. Hence it is important to develop a simple cost targeting technique to determine the optimal cost for carbon reduction and to understand the system with the various options at a higher level. This will allow better designs for both carbon networks and policies.

Marginal Abatement Cost Curves

In economics, cost curves are used to link the cost of production to its capacity. Different investment options with varying specific costs and production capacities can be represented on a cost vs capacity plot and arranged from the most economically viable to the least. Significant insights can be drawn that helps in optimizing the investment and operation of the available options. The concept of cost curves was first introduced in the 1970s amid oil price shocks to save oil and electricity consumption [53]. The early term for such tools was: conservation supply curves, and later they were developed for applications in carbon reduction policies and the term marginal abatement cost (MAC) curves emerged.

Marginal abatement cost curves have been used to support planners and policy makers in understanding economics of the carbon reduction pathways. Marginal abatement cost is the specific cost associated with a certain level of emissions reduction. It characterizes the economics of a carbon reducing technology. Marginal abatement cost curves are generated by representing each of the available carbon-reducing options as segments characterized by their MAC and their abatement capacities. The different options are ranked in increasing order of MAC to ensure the implementation of lowest cost pathways for a given reduction goal.

MAC curves been applied widely in literature. Morthorst[54] developed carbon reduction cost curves for a case study of Denmark, focusing on energy efficiency improvement options. Enkvist et al[55] presented a global study for the possible pathways toward carbon reduction, and arranged the different options in a cost curve. The carbon reduction pathways included building insulation, energy efficiency, alternative fuels, alternative energy sources, and carbon capture and sequestration (CCS). The study provided an overall worldwide vision for the total carbon reduction, disregarding changes in options between different countries and sectors. Naucler et al[56] updated the global abatement cost profile and performed a more detailed analysis for the major carbon producing sectors with different scenarios and sensitivity analyses. A global profile was presented beside abatement cost curves for individual sectors showing more detailed options. These studies gave an overall insight to the possible carbon reduction pathways, however, followed several assumptions that may affect the relevance of applications in specific contexts. For example, CCUS was considered as a general option with no regard to the cost variability between the different capture, utilization, and storage options.

Sector specific studies have been developed that focused on the application of MAC curves for carbon capture and utilization options. Dahowski et al[57] developed preliminary cost curve for the possible carbon storage sites in China. Similar studies were performed for different geographical regions including North America[58] and Europe[59]. These studies consider the transport and storage costs associated with each site, however, the cost of capture from the sources is disregarded. The economics of carbon capture were investigated [60] in a study where different emissions sources were surveyed and arranged based on the cost of the required carbon capture. Insights were established on what sources should be considered for future carbon capture and utilization projects. Another study was conducted where the MAC curve was used to compare between ten different carbon utilization technologies that are either implemented or developed enough to be implemented soon [61]. The different utilization options were arranged on the MAC plot, and the discussion was focused on the expected revenues and capacities of the investigated technologies.

The concepts implemented in MAC curves construction for CCUS options inspired work performed by Von der Assen et al[62] which proposed environmental-merit-order curve, considering the environmental impact of CO_2 capture from different CO_2 emitting sources. Current commercial carbon capture technologies are energy intensive process causing additional emissions and affecting the total efficiency of carbon reduction. The energy requirements of the capture depend on the properties of the emitted streams which vary between the sources. Each of the sources is represented on an environmental impact vs CO_2 supply rate and arranged from the least environmental impact (due to capture) to the most. The study aimed at providing a life cycle analysis of carbon capture, focusing on the secondary emissions resulting from the energy requirements.

MAC curves are powerful visualization tools that allow the results of extensive work to be represented and illustrated. They have shown effectiveness in communicating recommendations to policy makers where different technologies can be easily arranged from cheapest to most expensive and plotted against capacity. However, all the presented studies used the MAC curves as an illustration tool and not as a targeting technique. They dealt with the CCUS planning problem considering either carbon supply (sources) or carbon demand (storage and utilization), and none of the techniques give insights on the optimal carbon network formed between the sources of emissions and the different utilization and storage options simultaneously. Treating carbon network planning as a one-sided problem along with the other assumptions used to develop the MAC curves may omit some options that are considered in the optimization algorithms presented in the process integration design. Hence MAC curves cannot be implemented as targeting technique that gives quick insights on the optimal solution for carbon network planning.

From the literature work presented, it can be deduced that there are no targeting tools that address the problem of minimum cost carbon networks. There is a need for a targeting methodology that allows the identification of lowest-cost portfolios of carbon network easily and without going directly into the design. Hence, the proposed tool in this work will address this gap and will be used to develop quick economic targets, considering both sources and sinks for minimum cost carbon networks and carbon reduction. A carbon policy model is then developed to account for the interactions between the different stakeholders and to assess the performance of carbon tax relative to the developed targets. The next chapters will explain the methodologies of the proposed approaches.

CHAPTER III

SCOPE AND OBJECTIVES

The high-level challenge addressed in this work is to develop a targeting method that allows to quickly identify the lowest cost (or most profitable) portfolios of carbon reduction pathways for a given group of fixed sources. The work focuses on carbon reduction through CCUS options; however, the method will be developed to target the minimum cost of net reduction through carbon networks. This will allow the comparison with other CO_2 abatement technologies. Carbon reduction strategies are established through the political channels by following a set of penalizing or incentivizing legislations (carbon policy) that allows the stakeholders to endure the costs of implemented carbon reduction technologies. A policy framework model is then developed to evaluate an example of such policies: carbon tax, and the resulting carbon reduction portfolio is compared to the optimal operation of carbon reduction target.

The main objective is approached over different stages. The first step is to develop a targeting technique that detects the cost-optimal utilization and/or sequestration processing options for emissions reduction. Given is a set of stationary CO_2 emissions sources, and a set of candidate utilization and sequestration options (sinks). The method should identify which emissions sources should be processed, and which processing options (sinks) should be implemented. In order to address this problem, the proposed method needs to carefully consider the two main drivers of decision making, i.e. the specific cost (or profit) of emissions reduction across the different plants under study (emissions sources and sinks, and power sources) which is to be minimized, and the quantity of CO_2 processed, which constitutes the emissions reduction goal. A graphical approach is established that allows the identification of optimal carbon network through implementing CCUS, maximizing the profit generated from a carbon network for a set carbon processing flowrate.

After that, the secondary emissions from the carbon network are considered through an algebraic method that targets the minimum cost of net CO_2 reduction. The algebraic algorithm is more flexible in setting the optimization criterion and in including carbon reduction options other than CCUS. The algebraic technique developed can be used to investigate the economic impact of different planning criteria and of different carbon reduction options. Both methodologies are used to define several economic targets. The defined targets correspond to the maximum profit from carbon utilization and to cost neutral carbon reduction. The cost neutral carbon reduction can be performed through offsetting the costs of carbon reduction by the profit generated from carbon utilization. The algebraic technique is used to develop carbon abatement cost curves for different countries and to investigate the variations in the economics of carbon reduction.

The interactions among the stakeholders in the system are then modelled to incorporate carbon tax as carbon policy. The decisions taken by the stakeholders are controlled by the economics of the available options. Each plant emitting CO_2 can either pay for the carbon capture costs to reduce their emissions or pay the corresponding carbon tax. The impact of the carbon policy is investigated to evaluate the policy performance in comparison with the developed targets.

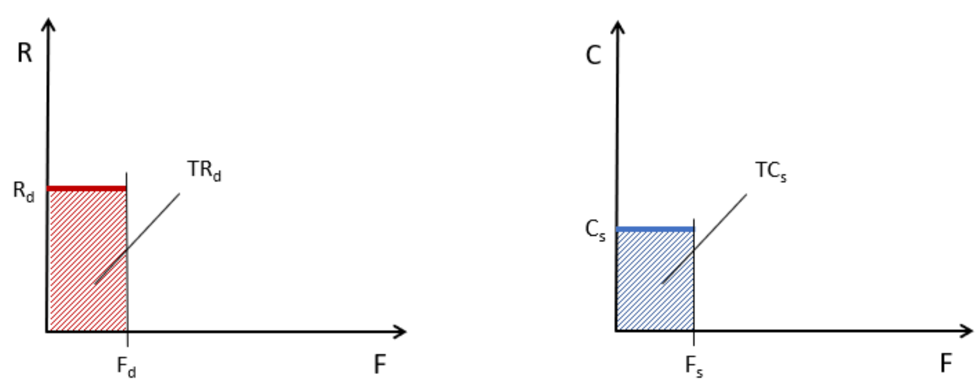
CHAPTER IV

A GRAPHICAL APPROACH FOR DEVELOPING ECONOMIC TARGETS FOR CARBON REDUCTION THROUGH CCUS

The proposed method for CCUS planning will consist of two plots, which allow an analyst to determine the minimum cost solution across a given set of CO_2 utilization and sequestration options D ($D = [d_1, d_2, \dots, d_n], n \in \mathbb{N}$) for a given set of CO_2 emissions sources S ($S = [s_1, s_2, \dots, s_m], m \in \mathbb{N}$) as well as the overall net CO_2 reduction. The sources produce streams at varying specifications, different from the requirements for the sinks to be able to treat the streams. To deliver the emissions flow to the sinks, they should be treated through capture and compression whose cost vary according to the source. Each source s_i is characterized by the specific cost required for capture and compression C_{si} and by the maximum flowrate it can allocate after capture F_{si}. On the other hand, the sinks process the CO_2 to produce value added products whose revenues vary depending on the sink's technology. Each sink d_j is characterized by the specific revenue generated from the value-added products R_{dj} and by the capacity flowrate of CO_2 processing F_{dj}. Treating the streams before reaching the sink and inside the sink generate secondary emissions which affect the total efficiency of carbon reduction. In the proposed method, the costs are analyzed in the two-dimensional space of specific CO_2 processing revenue R or cost C (e.g. in units \$/t CO2) vs. processed CO_2 flowrate F, whereas net CO_2 reduction is analyzed in the two-dimensional space of the net fixated CO_2 fraction X_{net} vs. processed CO_2 flowrate F.

Methodology

Consider a sink d processing a flow of CO_2 of F_d at a reference specification (purity, temperature, pressure) at a specific price R_d. Then, the sink can be represented as a horizontal line in R vs. F space (Figure 1a). The total revenue TR_d from processing is represented by the area between the sink line and the flow axis starting at the origin ($TR_d = R_d F_d$). A positive price of processing flow in a sink would result in a positive revenue, whereas a negative price of processing flow in a sink would result in a negative revenue, i.e. an overall processing cost. In terms of sink options, a sequestration sink will always result in a negative revenue, but CO_2 utilization options may exist for sinks, such as Enhanced Oil Recovery (EOR) or methanol production, that may afford to pay CO_2 prices greater than zero whilst meeting investment return expectations.



(a) **(b)**

Figure 1 The graphical representation of a sink (a) and a source (b)

Similarly, the source can be represented as a horizontal line in C vs. F space (Figure 1b). The total cost TC_s of supplying flow F_s is represented by the area between the source line and the flow axis ($TC_s = C_s F_s$). Unless a source of emissions is already at the reference condition, supply costs will typically include the cost of CO_2 capture and compression. The specific cost C_s depends on the characteristics of source s, i.e. its composition, pressure, temperature, flow, and technology choices made, e.g. the selected CO_2 capture technology.

In case of integration, i.e. the processing of a flow from source s in sink d, the net profit $P_{s,d}$ generated is represented by the area between the source and sink lines. Figure 2a shows the case of a profitable integration, while Figure 2b illustrates a loss-making integration. The maximum flow that can be processed across source s and sink d is given by: argmin(Fs, Fd). It is the minimum between what the source can supply and what the sink can process.

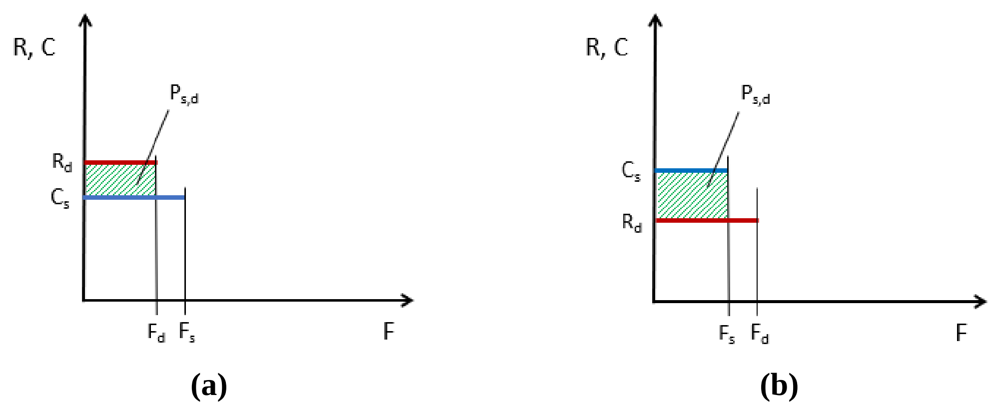
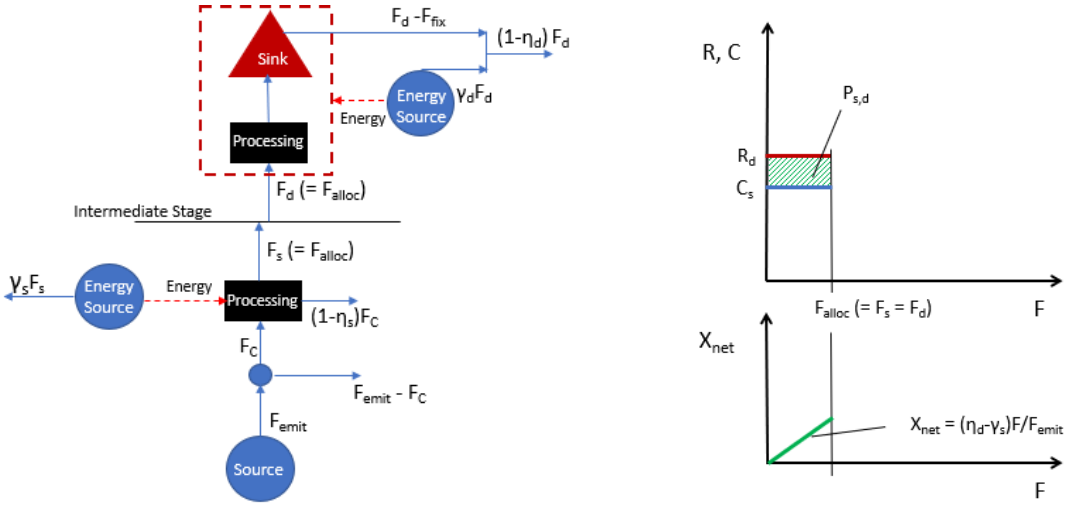


Figure 2 Graphical representation of a profitable (a) and non-profitable (b) CCUS application



(a) **(b)**

Figure 3 Leakage of CO_2 in processing (a) and its graphical representation (b)

The representation in Figure 3 (a) illustrates the CO_2 flows between a source and a sink. In many cases, there is a need to quantify the leakage of CO_2 flows from the original steam to establish the net CO_2 fixation achieved. Let η_s be the CO_2 capture efficiency at source to achieve the reference specification, which is defined as the fraction of CO_2 flow rate from the source F_s over the CO_2 flow of the original emissions stream fed into the capture process F_c. Further, let η_d be the net CO_2 fixation efficiency in the sink, i.e. the fraction of F_d received by a sink that is fixated either by sequestration or by fixation in a product in the case of utilization of CO_2 as a feedstock. Moreover, the energy associated emissions of the connection are accounted for through including the additional energy requirements into the problem. Let γ_s be the emissions factor associated with the power and energy requirements for processing the source stream (capture, compression, and heating/cooling). On the other hand, let γ_d be the emissions factor corresponding to the power and energy requirements for processing the allocated flow in the sink. With these efficiencies, the net amount of CO_2 fixated becomes: $F_{fix} = (\eta_d - \gamma_s) F_{alloc}$, where $F_{alloc} = F_s = F_d$, and the gross amount of CO_2 contained in the original emissions source becomes F_{emit}. The fraction of the original source emission fixated in a source to sink allocation of flow F can be calculated as $X_{net} = (\eta_d - \gamma_s) (F/F_{emit})$. This information can be conveniently tracked alongside the profitability of a source to sink allocation as shown in Figure 3 (b).

Consider a system with multiple sources with each source s_i characterized by C_{si} and F_{si}, and multiple options for potential sinks with each sink di characterized by R_{di} and F_{di}. All the sources and sinks can be represented in R or C vs F domain as discussed previously (Figure 4a and Figure 4b). Each horizontal segment represents a source or a sink assuming fixed cost and revenue over the corresponding processed flow interval.

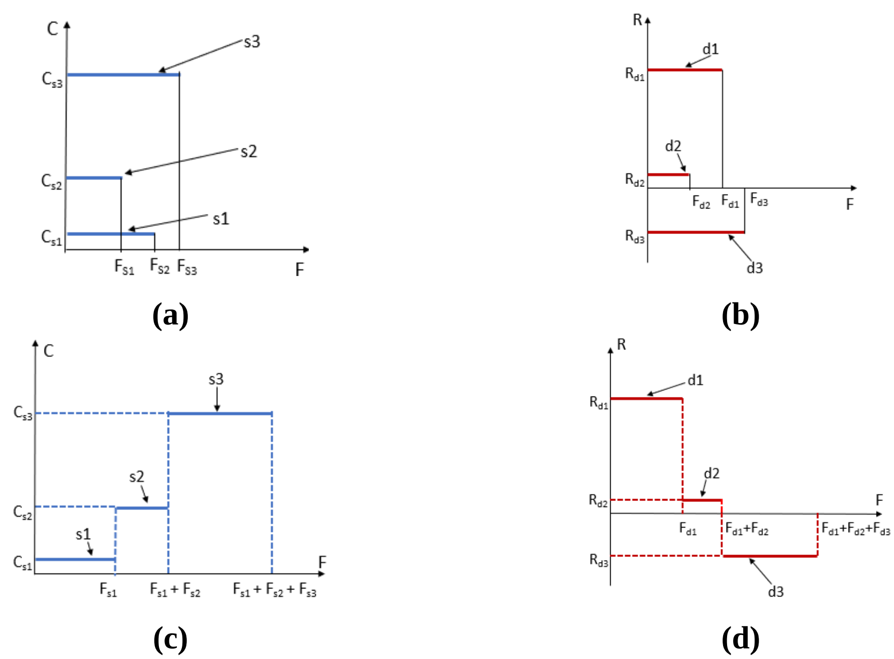
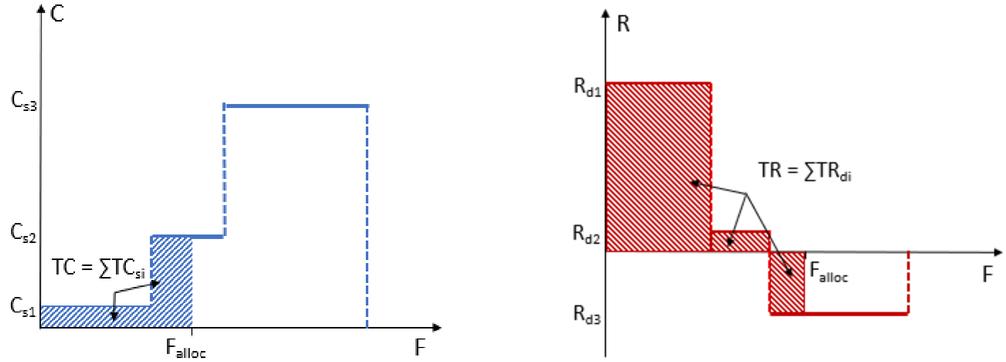


Figure 4 **Graphical representation of multiple sources (a), multiple sinks (b), the capture cost profile (c), and the utilization profit profile (d)**

Each allocation between a source and a sink results in a net profit making or profit loss as represented in Figure 2. In the case of multiple sources and sinks, the total profitability of the network is determined by subtracting the cumulative costs of carbon capture from the cumulative revenues of carbon utilization. To minimize the total cost of carbon reduction, the most profitable allocations are prioritized. Minimum carbon mitigation cost is achieved by allocating carbon from sources with minimal capture costs and implementing the most profitable sinks (with the highest revenues). Hence, the segments are arranged from the least capture cost to the highest for sources to obtain the carbon capture cost profile (Figure 4c) and from highest revenue to lowest for sinks to obtain the utilization revenue profile (Figure 4d).

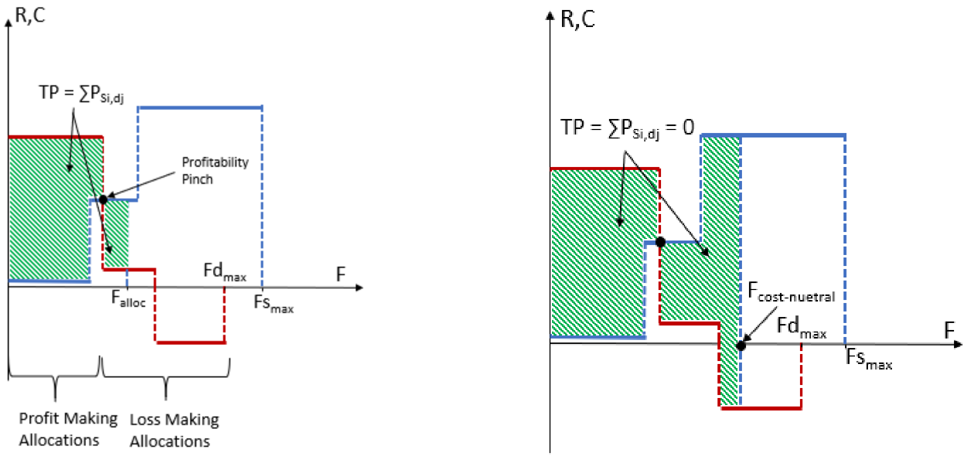
The total cost TC of capturing an overall flow F_{alloc} throughout the network is equal to the area between the source profile and the F-axis from F=0 to F= F_{alloc} (Figure 5a). The shaded region corresponds to the sum of the costs required to capture steams from each of the sources ($TC = \sum TC_{si}$). The total revenue TR generated from processing carbon at flow F_{alloc} in the sinks is present in the plot as the area between the sink profile and the F-axis from F=0 to F=F_{alloc} (Figure 5b). Like the total capture cost, the total utilization revenue is equal to the sum of the revenues generated by each sink ($TR=\sum TR_{di}$). As mentioned earlier, for the sinks with negative price, the total revenue is negative represented in the area below the F-axis.



(a) **(b)**

Figure 5 Graphical representation of the total capture cost in the supply profile (a) and the total revenue obtained from the utilization and storage options (b)

The total profit of the carbon network TP is the difference between the total revenue generated by the sinks and the total capture cost. It is the area between the capture cost profile and the utilization revenue profile (Figure 6a). A profit-making connection is between a sink and a source such that sink's segment is higher than the source's, otherwise the connection is loss-making. Since the source profile shows an increasing cost with flowrate while the sink profile shows a decreasing revenue with flowrate, a turn point exists that separates the connections with positive profit from the connections with negative profits (Figure 6a). The turn-point will be referred to as the profitability pinch. The most profitable network corresponds to a processed flow F which is equal to the flowrate at the profitability pinch F_{pinch}. Before the profitability pinch ($F <= F_{pinch}$), the connections are profit-making, and the net profit of the network increases with increasing the processed carbon flow. After the profitability pinch ($F > F_{pinch}$), the connections are loss-making and the net profit decreases with increasing the processed carbon flow.



(a) **(b)**

Figure 6 Graphical representation of the different economic targets showing the net cost of carbon reduction and profitability pinch (a), and cost-neutral carbon reduction limit (b)

The total cost of carbon reduction with allocated flow F_{alloc} is equal to the difference between net cost of loss-making connections and the net profit of the profit-making connections. The carbon allocation flow corresponding to cost-neutral implementation of CCUS is the flowrate $F_{cost\text{-}neutral}$ at which the area to the left of the profitability-pinch between F=0 and $F=F_{pinch}$ is equal to the area to its right between $F=F_{pinch}$ and $F=F_{cost\text{-}neutral}$ (Figure 6b). $F_{cost\text{-}neutral}$ represents the limit where CCUS can be applied optimally without any economic constraints assuming that the revenues from the sinks are used to cover the costs of capturing and processing.

The secondary carbon leakage from the network due to inefficiencies in capture technologies and sinks as well as the parasitic power requirements are taken into consideration in the overall net fixation plot (Figure 7). The plot in X_{net} vs. F space shows the fraction of carbon reduced from the carbon emitted by the sources as function of the allocated (processed) flow. Since each connection between a source si and a sink dj is characterized by the efficiencies and power requirements and the allocated flows F_{ij}, the plot is composed of different segments with varying slopes each representing the cumulative carbon reduction by the network.

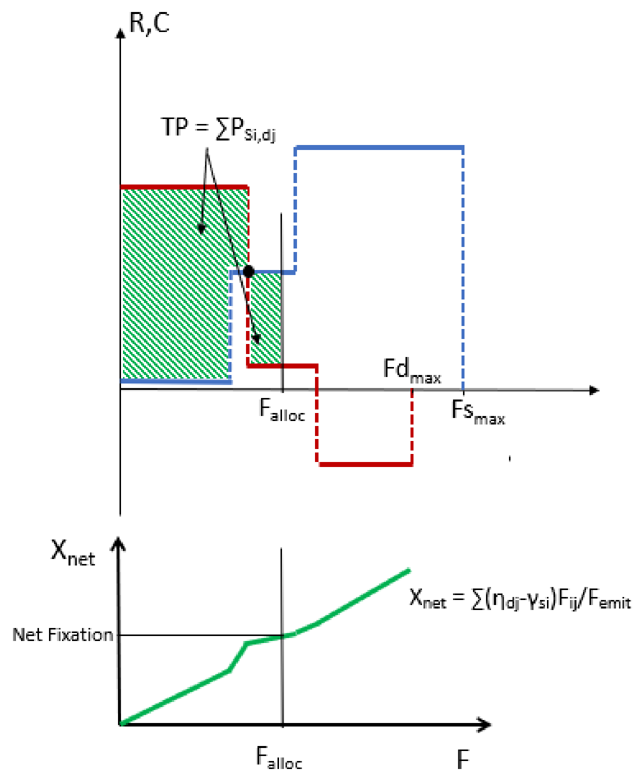


Figure 7 Net capture and leakage the overall carbon network

Illustrative Example

The proposed tool was demonstrated through a hypothetical case study. Several industrial sources of emissions are considered, including Gas-to-Liquid (GTL) plant, a cement plant, a methanol plant, and a gas fired power plant (generated 1 GW of electricity). Four possible sinks are taken into consideration and these include an enhanced oil recovery (EOR) facility, methanol production through dry reforming plant, a greenhouse, and an underground carbon sequestration unit. The economic data used in the example is determined from Al-Mohannadi et al [36]. The power emissions factors γ_{si} are determined from von der Assen et al[62] and they include the emissions associated from supplying heat to the capture process (post combustion, MEA) as well as electricity for compression. The capture cost varies among the sources as well because it depends on the composition of the captured stream. The total carbon footprint is 26.3×10^6 t CO_2/y out of which 24.25×10^6 t CO_2/y can be captured assuming 90% capture efficiency. The source's data is summarized in Table 1.

Table 1 Data collected for sources

Plant	**CO_2 production rate (10^6 tCO_2/y)**	**CO_2 purity (wt%)**	**Treatment Cost ($/t$CO_2$)**	**γ_{si} (tCO_2-emitted/tCO_2-captured)**
GTL - pure	4.12	100	0	0.03
Cement	1.53	27	38	0.27
Aluminum	3.67	7	48	0.29
Methanol A	0.71	7	48	0.26
GTL (b) - diluted	12.64	7	48	0.26
Power Plant	3.81	4	55	0.13

Table 2 summarizes the sink's information. The sinks considered span a range of CO_2 applications including chemical production, agriculture, and oil and gas industry. Carbon sequestration in saline aquifers is considered as well. The capacities of the sinks depend on the size of the demand on the products as well as the underground geology of the available area. All sinks require pure CO_2 streams.

Table 2 Data collected for sinks

Sink (d_i)	**F_{di} (10^6 tCO_2/y)**	**R_{di} ($/$tCO_2$)**	**η_{di}**
Enhanced Oil Recovery (EOR)	7	30	100%
Methanol B	3	20	99%
Greenhouse (GH)	2	5	50%
Storage	13	-10	100%

The streams captured from the emissions are assumed to be delivered to an intermediate stage with 100% purity and at 150MPa. The cost of processing the stream beyond capture is included in the capture cost. Sinks need to process the streams from the intermediate stage, and the cost of processing is included in the calculations for the revenues. The annualized capital cost of each plant is included as well with the assumption of 8670 annual operating hours and over 20 years.

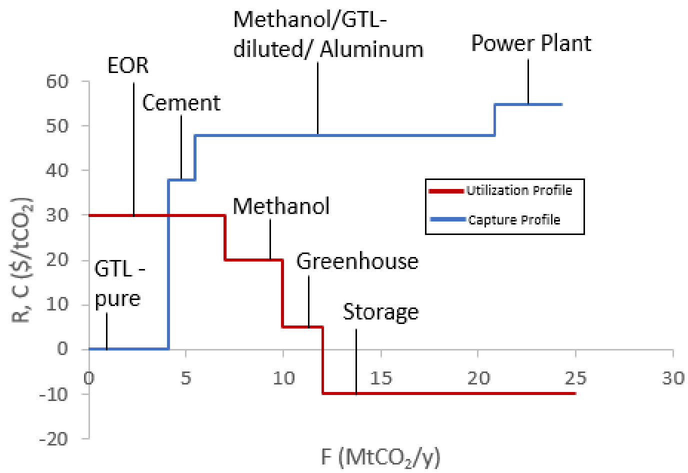


Figure 8 Utilization and capture profiles representing the sources and sinks of the case study

Capture cost profile and utilization profit profiles are plotted (Figure 8) with the available data in Table 1 and Table 2. For any given allocation target, sinks are implemented from the most profitable (EOR) to the least (storage). The network includes also the most profitable sources (ranked from the least capture cost (GTL-pure) to the most (Power Plant)).

Figure 9 summarizes all the different allocations corresponding to the different scales of CCUS implementation. Note that “Other Sources” stand for methanol, GTL-diluted, and aluminum as they all have the same capture cost in this example. All sources allocate pure CO_2 streams at the mentioned intermediate state. The allocation mechanism from the sources to the sinks vary depending on the decision-making procedures followed in the set carbon reduction policy. The exact flow allocation between the sources and sinks participating in the CCUS implementation depends on the stakeholder’s interactions.

Nonetheless, the net profit/cost and the carbon reduction associated with the size of the CCUS network will be the same.

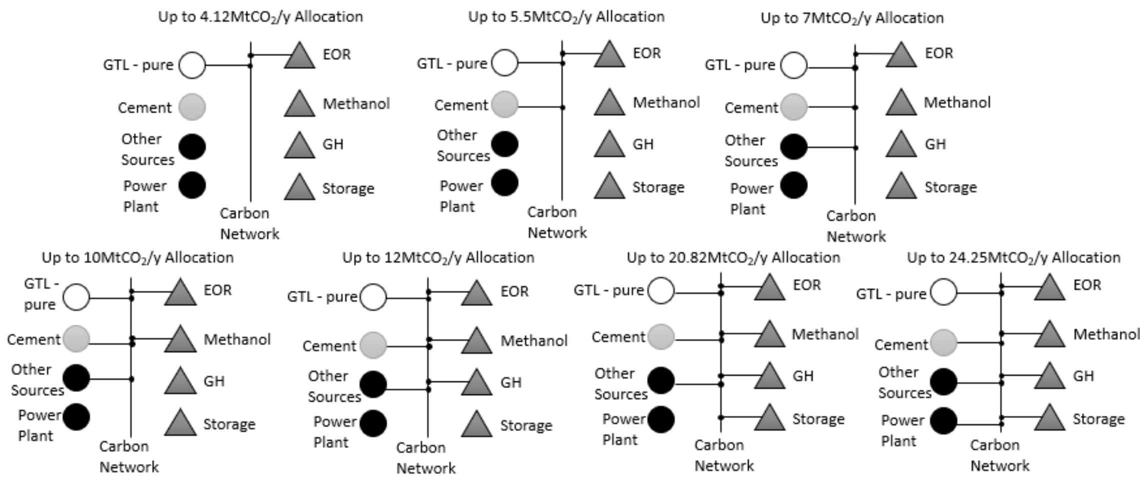


Figure 9 Illustration of the different possible carbon networks under different scales

The economic targets developed as the results of the profiles are present in Figure 10. The flow of allocated CO_2 stream corresponding to the maximum profit obtained from the CCUS network is $F_{pinch} = 4.12\times10^6$ tCO_2/y. This flow corresponds to the maximum implementation of the network between the most profitable sink (EOR) and the source with the highest CO_2 purity (GTL's reformer separation, i.e. GTL-pure). The maximum profit generated is the area between the capture and utilization profiles to the left of the profitability pinch, which is 123.6×10^6 \$/y. To the right of the profitability pinch, the net profitability decreases with the implementation of loss-making CCUS. The flow of allocated CO_2 corresponding the cost neutral CCUS network is around 10×10^6 tCO_2/y.

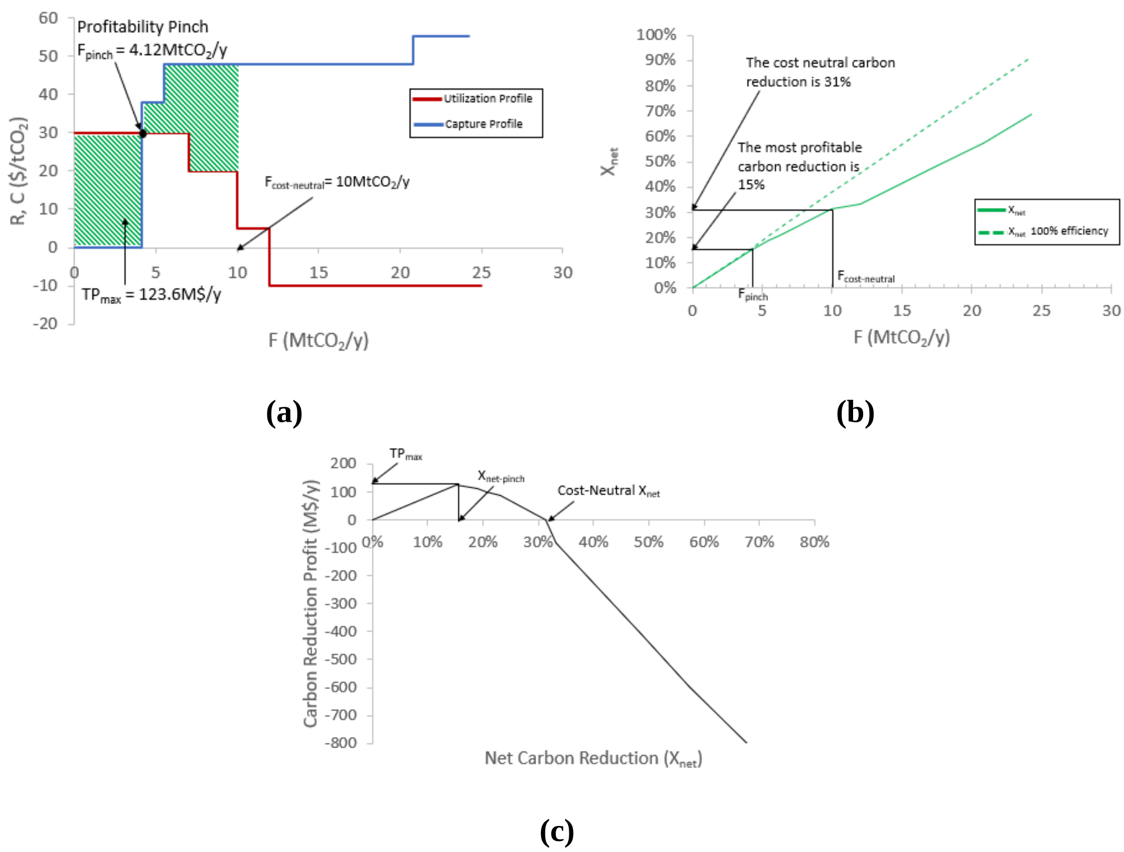


Figure 10 Economic targets in the case study illustrated on the capture and utilization profiles (a), net fixation profile (b), and the total profit profile (c)

The net carbon fixation associated with the flow allocated throughout the CCUS network is plotted in Figure 10 (b). All sinks operate with high efficiencies except for the greenhouse, which efficiency is η_d = 50%. The inefficiency appears in the deviation of the X_{net} profile from the 45° line (corresponding to 100% efficiencies in capture and utilization). The deviation is not significant due to the high efficiency of most sinks and the relative low capacity of the greenhouse. Moreover, the plot shows that the maximum profit (at $F=F_{pinch}$) is accompanied with 15.1% carbon reduction, and the cost neutral CCUS network ($F=F_{cost\text{-}neutral}$) is associated with 31% reduction. Any reduction targets beyond 31% would be accompanied with a net cost depending on the size of implementation. The maximum reduction target achieved under the proposed sinks is around 68.7%.

The net profit of carbon reduction is represented in Figure 10 (c). The net profit is calculated from the area between the source and sink profiles and plotted against the net carbon fixation factor. The plot shows the maximum profit as well as the cost-neutral carbon reduction. Implementing CCUS at maximum scale would cost 819×10^6 \$/y for a carbon reduction of 68.7%. This net cost of the ultimate reduction is equal to 45\$/tCO_2.

CHAPTER V

AN ALGEBRAIC APPROACH FOR THE DEVELOPMENT OF ECONOMIC TARGETS FOR CARBON REDUCTION

The graphical method described in Chapter IV allows the determination of the sources and sinks participating in an optimal carbon integration network and the corresponding minimum cost for a set network capacity. However, this may not necessarily result in a solution with minimum cost for a set level of carbon reduction. The graphical method presented does not consider the secondary emissions, as the net fixation of the network is traced and plotted and does not have any role in the solution which is only based on the economics of the CCUS. For example, consider a case were carbon can be allocated to one of two utilization technologies: a very expensive sink (negative revenue) with high fixation efficiency and a cheaper sink (but negative revenue as well) with low fixation efficiency. Allocating the CO_2 stream to the second sink will results in lower cost, however allocating the stream into the first option will result in a higher carbon reduction. Hence, the cost of the net carbon reduction may be higher for the case of the second sink although the technology itself is cheaper (per allocated carbon). Following the prioritization in the graphical procedure, the second sink would be the suggested option in the solution. However, in many cases it is important to minimize the cost for a certain level of carbon reduction, accounting for the secondary emissions. Considering the cost per carbon reduced allows the incorporation of abatement options other than CCUS which gives a wider view on the strategic carbon reduction.

In this chapter, an algebraic framework is proposed that helps in developing the targets defined in Chapter IV while considering the optimization of carbon reduction rather than that of carbon network. The system considers a set of existing sources S ($S = [s_1, s_2, \ldots, s_m], m \in \mathbb{N}$), a set of available sinks D ($D = [d_1, d_2, \ldots, d_n], n \in \mathbb{N}$). The sources are characterized by their secondary emissions (γ_s) and the required capture cost (C_s). The sinks are characterized by their efficiencies (η_d) and generated revenues from carbon utilization (R_d).

Methodology

The cost and the carbon fixation efficiency of a source-sink couple depends on both the source and the sink, hence, it is important to take both simultaneously in the arrangement and not each at a time as in the case of the targeting technique presented in Chapter IV. Figure 11 illustrates the steps followed in the proposed algebraic method.

The introduced algebraic procedure aims at minimizing the cost of carbon reduction for a set reduction target based on prioritizing the source-sink incorporation to the carbon network according to the marginal abatement cost MAC (i.e. the cost per reduced CO_2). Such analysis will make the solution comparable with other carbon reduction technologies, like shifting to cleaner energy sources, as the reference is the amount of carbon removed and not the amount of carbon allocated (which only applies to the case of CCUS). Hence, a mix between different carbon reduction options, including the carbon network, with minimum carbon removal cost for a given level of carbon reduction can be proposed.

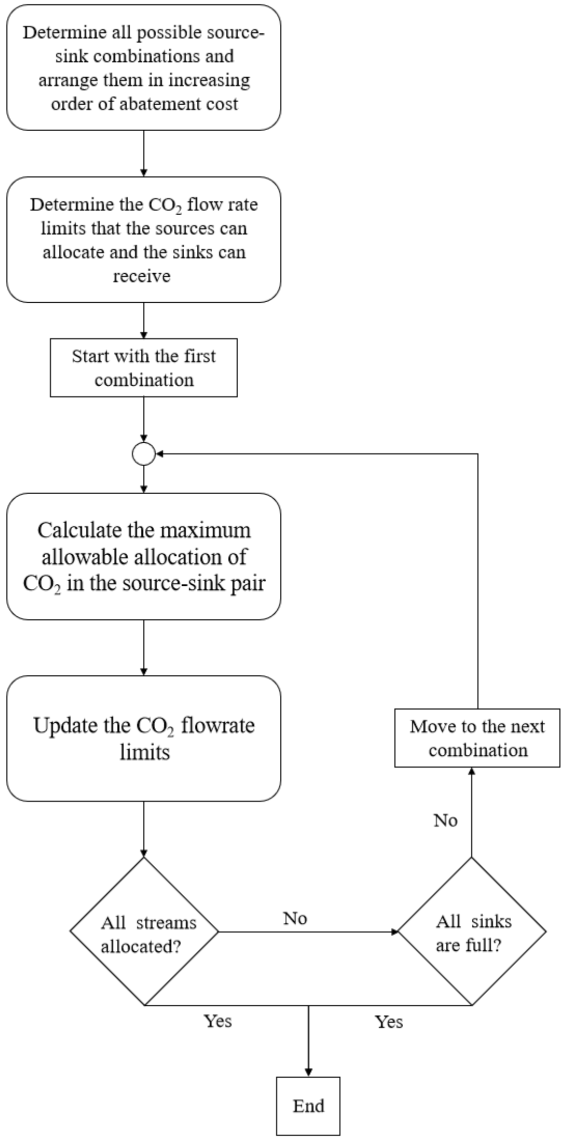


Figure 11 Flowchart of the algebraic methodology for planning the carbon network

The same data collected in the graphical procedure will be used as mentioned earlier (capture costs, utilization revenues, efficiencies and secondary emissions). All the possible combinations of source and sink pairs are considered, and the marginal abatement cost (MAC) of adding a source s_i and a sink d_j to the carbon network can be calculated as shown in (1).

$$MAC_{CCUSij} = \frac{C_{si} - R_{dj}}{\eta_{dj} - \gamma_{si}} \tag{1}$$

After calculating the abatement cost for each source-sink pair, all the options are arranged in an increasing order of MAC to prioritize the cheapest pathways. The amount of CO_2 available for allocation from the sources F_{si} and the capacities of the sinks F_{dj} are determined. Before any allocation, the CO_2 flowrate available by the source F_{si} is calculated assuming the source allocates all its emissions to the capture unit. Similarly, the capacity of the sink F_{dj} is taken as the maximum processing capacity described in the problem statement.

$$\mathrm{F}_{\mathrm{si}} = \mathrm{F}_{\mathrm{si}}{}^{max} \tag{2}$$

$$\mathrm{F}_{\mathrm{dj}} = \mathrm{F}_{\mathrm{dj}}{}^{max} \tag{3}$$

The allocation of CO_2 flowrate into each connection is performed starting from the first source-sink pair (with the lowest MAC). The flowrate allocated in each pair should be maximized as the allocations in the following pairs are more expensive. However, the allocation is constrained by how much flow the source can supply and how much flow the sink can process. To ensure that neither of these flows is exceeded, the maximum allowable allocation between a source s_i and a sink d_j is equal to the minimum between the flow available by the source and the capacity of the sink.

$$\mathrm{F}_{\mathrm{ijmax}} = \mathrm{argmin}(\mathrm{F}_{\mathrm{si}}, \mathrm{F}_{\mathrm{dj}}) \tag{4}$$

The allocation capacity of the first pair (k = 1) is equal to the minimum between the capturable CO_2 flowrate of the first source and the capacity of first sink. The remaining available flow from the source and the remaining capacity of the sink are updated by subtracting the allocated flowrate at the current iteration from the available flow from the source and from the capacity of the sink before the allocation. The flow availability and capacity of the sources and sinks excluded from the pair at the current iteration are not changed. Equations (3) to (6) summaries the updates performed at each iteration k for the availability and capacity of the flows for all the sources and sinks.

$$\mathrm{F_{si}} = \mathrm{F_{si}} - \mathrm{F_{ijmax}} \tag{5}$$

$$\mathrm{F_{dj}} = \mathrm{F_{dj}} - \mathrm{F_{ijmax}} \tag{6}$$

The procedure is repeated until either the sources allocate all the possible CO_2 available or until all the sinks reach maximum capacity. The result is a carbon neutral network designed based on prioritizing the source-sink pairs with the least carbon removal cost. The CO_2 abatement flowrate resulting from introducing each pair to the network is determined by multiplying the flowrate of the allocated CO_2 stream by the net efficiency of the pair $(\eta_j - \gamma_i)$. The updated MAC curve can then be constructed which considers CCUS planning as a two-sided problem. It allows the comparison between CCUS and other carbon reduction technologies. Accordingly, the cost optimal strategies for given levels of carbon reduction can be identified.

The economic targets developed in the graphical method can be determined for the carbon network developed through the algebraic technique. The profit obtained from each allocation P_{ij} is the product of the corresponding net profit $(R_{dj} - C_{si})$ and the flowrate

F_{ij}. The cumulative profit TP corresponding to a set abatement level is the summation of the profit of all the connections until the planned carbon reduction level is achieved. Profitability pinch is achieved when maximum carbon flow is allocated in all the profit-making connections ($R_{dj} - C_{si} > 0$). The total allocated flow at the profitability pinch F_{pinch} is equal to cumulative allocated flow at which TP achieves its maximum. $F_{cost\text{-}neutral}$ is equal to cumulative allocated flow at which TP = 0.

Developing Targets for Different Planning Criteria

The application of the algebraic methodology allows the planning according to the different criteria to be more flexible. Different criteria other than MAC can be applied and the same procedure can be followed for calculating the flows remains the same. For example, the same results of the graphical method in Chapter IV can be obtained through arranging the source-sink couples in decreasing order of profit ($P_{ij} = R_j – C_i$) which ensures the maximization of the profit collected for given carbon network scale. This is the case where a group of industrial stakeholders decide to invest in CCUS projects, allocating funds based on the scale of the proposed projects. The environmental merit-order[62] arranges the sources in increasing order of capture emissions factors in order to minimize the emissions associated with the carbon network. taking the sink's efficiency into such criteria, the algebraic method can be applied for an environmental planning through arranging the source-sink couples in the increasing order of the net efficiency of the pairs ($\eta_j - \gamma_i$).

The three different criteria were applied to the sets of sources and sinks of the case study presented in Chapter IV. The generated profiles represent the source-sink pairs characterized by the planning criterion and the allocated flow. Figure 12 shows the results generated for maximizing the profit for a given network size. Figure 13 shows the profiles generated from planning the network based on the environmental merit order. Figure 14 shows the profiles generated for a network with maximum MAC.

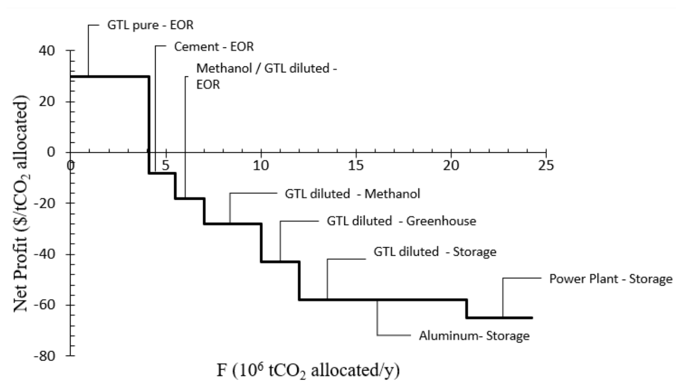


Figure 12 Carbon network profit profile planned according to the "Net Profit" criterion

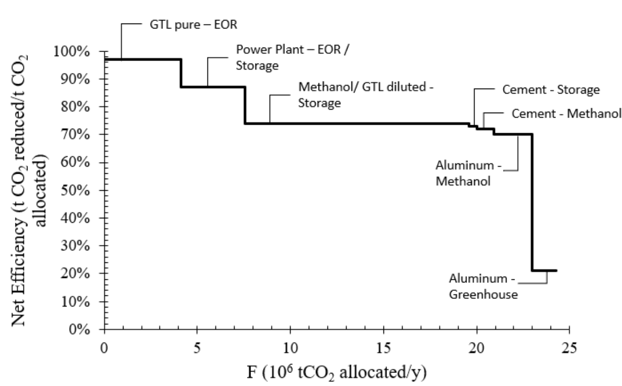


Figure 13 Carbon network fixation efficiency profile planned according to the "Environmental" criterion

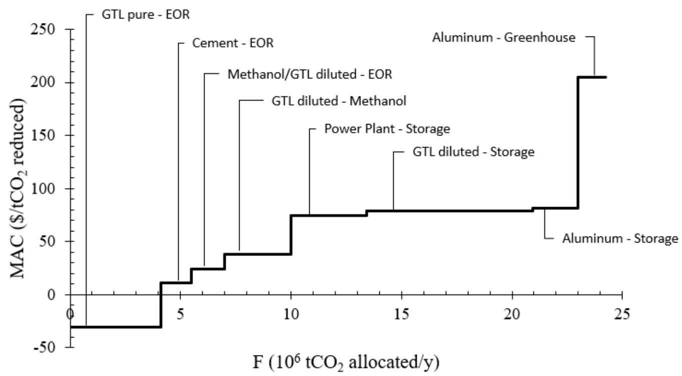
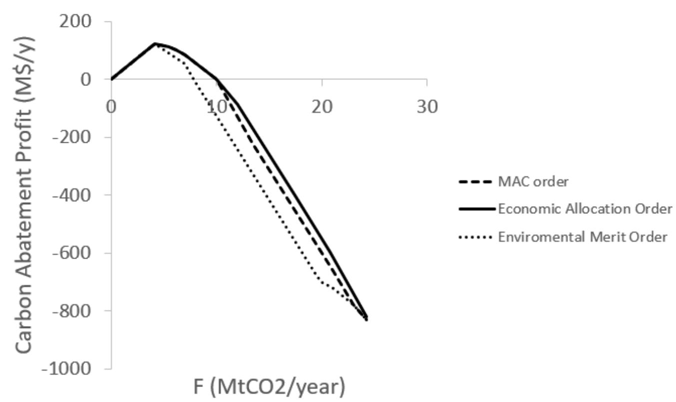


Figure 14 Carbon network cost profile planned according to the “MAC” criterion

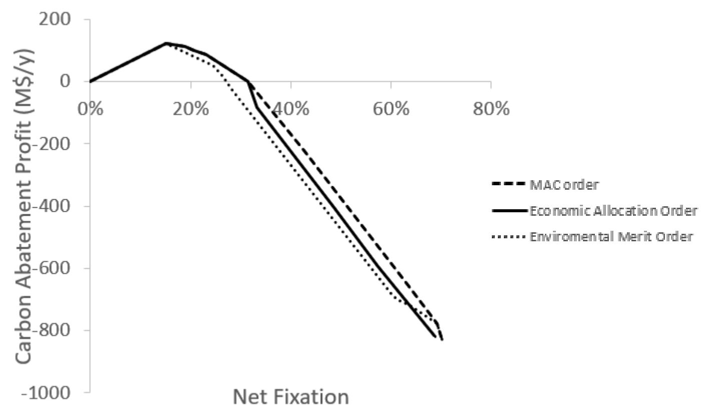
As seen from the figures, the varying prioritizations lead to the emergence of different source-sink couples, and consequently different carbon network profile for a given network scale. The “Net Profit” prioritization and the corresponding network has already been discussed in illustrative example of Chapter IV. The “Environmental” led to changes in the layout where the storage, which is the most expensive option and the least favorable from the “Net Profit” perspective, was prioritized over the revenue-generating methanol and greenhouse options due to its higher efficiency. Following the same trend on the source’s sides, the capturing the emissions from the power plant, which is the most expensive option, was prioritized over the cheaper capturing of the streams from other sources since the emissions factor of capturing CO_2 from the power plant stream is less. Such contradiction shows that planning carbon reduction through CCUS from only the economic perspective may not lead to an efficient reduction and depending solely the environmental criterion may be too expensive.

Minimizing the MAC takes into consideration both the economic and environmental perspective, as the expensive source-sink pairs are prioritized over cheaper ones only if they have much higher removal efficiency worth the higher investment. Comparing the capture of the power plant effluent and that of the GTL, the economic benefit upon implementation with EOR or methanol utilization options makes the capture from power plants less cost efficient since it is more expensive (capturing from power plant is 7$/t$CO_2$ more expensive than capturing from the GTL-diluted). However, when the capture is accompanied with utilization in carbon storage (an expensive sink option), the network becomes much more expensive (net profit is very low) that the capture from power plant becomes more efficient (since capture from power plant produces less emissions than capture from GTL-diluted). Such insight proves the importance of considering both the supply and demand economics and technical properties when planning for CCUS implementation.

Figure 15 shows the total profits generated from the carbon networks planned according to the different criteria as function of the allocated flows and the net fixation.



(a)



(b)

Figure 15 Total profit generated from the different criteria plotted against carbon allocated (a) and net fixation (b)

The profit profiles in Figure 15 shows serve to back up the discussion presented earlier, where the profit is maximized against the network scale for the "Net Profit" criterion, while it is maximized against the fixation for the "MAC" criterion. The environmental planning is accompanied with lower profit whether for a given network scale or a given fixation efficiency. The economic targets can be obtained from the profit profiles as well. Since all criteria gave the same solution before the profitability pinch (allocating CO_2 from GTL-pure to EOR), the profitability pinch and the maximum network profit are the same. The differences appear beyond the pinch, where the cost-neutral carbon fixation for the environmental arrangement (27%) is lower compared to that of the "Net Profit" arrangement or "MAC" arrangement (both gave 31% cost-neutral fixation). Although the differences between the results of the "Net Profit" arrangement and the "MAC" arrangement are not significant for the presented case study, the generalization of the findings applies over the whole range of carbon allocation and carbon reduction.

Including Alternative Energy Options to the MAC Curve

Considering only the profit per allocated carbon as present in the graphical technique would result in difficulties in comparing the carbon network as a carbon reduction option against other technologies. However, generating the MAC curve of the carbon network profiles allows solves this issue since all carbon reduction technologies share the MAC property that defines the economic efficiency of the options. Hence the MAC curves allow the illustration of a holistic planning with minimal cost of carbon reduction.

Another option for reducing CO_2 emissions is implementing alternative energy technologies with less emissions levels than the ones already implemented. Consider a set of the different alternative energy options E ($E = [E_1, E_2, \ldots, E_p]$, $p \in \mathbb{N}$). Each of the alternative energy sources requires a capital investment and operational costs C_E (in \$/kWh) and may emit CO_2 at levels ε (in tCO_2/kWh) lower than the existing energy generation processes. Note that already existing energy sources requires only operational costs. The MAC of shifting from an energy source E_i to a cleaner energy source E_j is defined in Eq (7).

$$MAC_{Eij} = \frac{C_{Ej} - C_{Ei}}{\varepsilon_{Ei} - \varepsilon_{Ej}} \quad (7)$$

The capacity of carbon removal through replacing an existing power source E_i by an alternative power source E_j is equal to the minimum power generation capacity between the two sources multiplied by $(\varepsilon_{Ei} - \varepsilon_{Ej})$. Energy shifting can then be represented as a segment on the MAC curve.

For the case study previously discussed, consider an option for implementing solar panels that can generate up to 50% of the existing capacity of the existing capacity of the gas fired power plant (producing at 1GW of electricity). Hence, the renewable energy option (with ε_{Ei}=0) can reduce 1.9MtCO2-reduced/y without any secondary emissions. Based on the capital cost of solar panels[63] annualized over 20 years of operation with 8760 working days per year, the MAC for solar panels is calculated to be around 31$/tCO2-reduced. The abatement cost curve for power related emissions is shown in Figure 16.

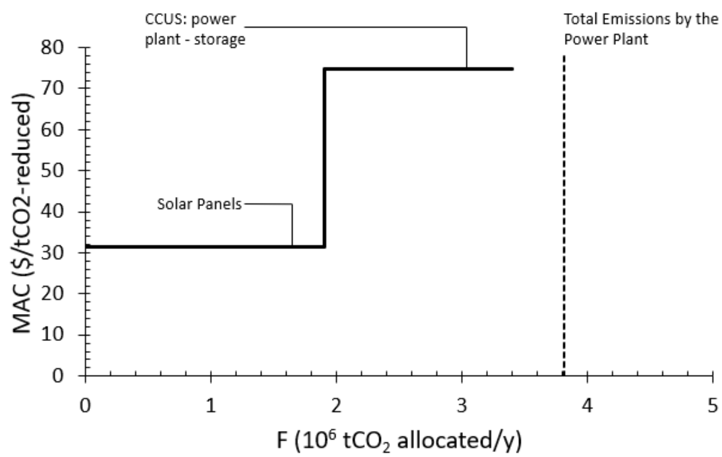


Figure 16 The MAC curve of power-related emissions

The solar panel option is cheaper than CCUS for reducing emissions from power plant. The capacity of the carbon reduction from the power plant emissions is adjusted considering the emissions after downscaling the plant by 50% along with the efficiencies of carbon capture and utilization options.

The total abatement cost curve can be updated considering the addition of solar panels and the change in capture capacity of the power plant as shown in Figure 17.

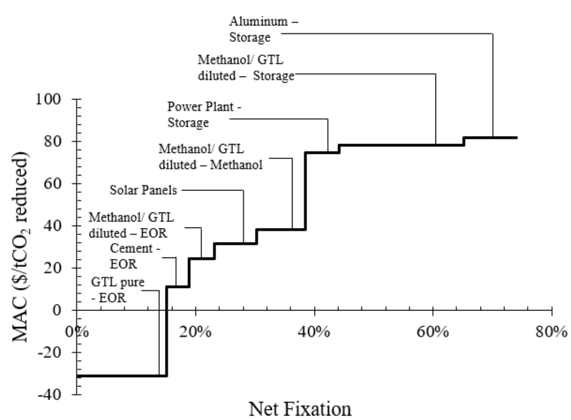


Figure 17 MAC curve including CCUS and energy shifting

The range of abatement cost decreased with introducing the solar panel (-30$/tCO2-reduced up to 81.7$/CO2-reduced) since GH (the low efficiency option) cannot be implemented under the capture capacity constraint (i.e. all emissions are allocated without the need of GH). The cost of the solar panel lies in the middle of the cost range. The carbon network (CCUS) is more cost efficient than solar panel until network fixation of 23%. Beyond that, a mix between solar energy and CCUS would be the optimal pathway for carbon abatement. Introducing the solar panel to the planning increases the capacity of carbon reduction from 68% to 74% as well as the cost-neutral carbon fixation from 31% to 32.8%, as the renewable energy option is highly efficient with no secondary emissions produced during operation. The average carbon reduction cost associated with the implementation of reduction projects at full capacity is 40$/tCO2-reduced.

Developing Targets for Different Geographic Regions

Countries often choose a variety of CO_2 reduction options to define their carbon reduction strategies and commitments toward the climate change problem. Unfortunately, these commitments, in many cases, fail to reach the targets and the emissions levels keep increasing. This failure is attributed in many cases to the costs associated with the chosen pathways, and the corresponding consequences on the competitiveness of the existing industries and the economy [14]. The costs vary between countries depending on the availability of options like renewable energy sources or CCUS options. Consequently, the allocation of funds to implement or incentivize the existing industries to adapt mitigation methods differ according to the geographic region. This section investigates the implementation costs of different carbon reduction pathways focusing on power alternatives and CCUS implementation for three different geographic regions: Qatar, Norway, and Japan.

The chosen countries exhibit variations in the availability of carbon utilization options as well as energy resources. Both Qatar and Norway depend on the oil and gas industry as they are located above producing reservoirs, which allows the utilization of CO_2 in EOR. Japan, on the other hand, is not an oil and gas country and cannot implement CO_2 for EOR applications. Japan is located over a complicated geological structure [64], which makes CO_2 sequestration in the available water beds risky and more expensive. Energy prices differ between the countries under study, with 0.04 $/kWh in Qatar, 0.1 $/kWh in Norway, and up to 0.2$/kWh in Japan [65]. These differences would affect the operating cost of an energy-intensive carbon capture process. Norway manages a sustainable industry by successfully using renewable sources of energy that cover the demand. Qatar scores the highest emissions per capita worldwide, being a country with a small population and large scale industry [66]. Power in Qatar is currently generated from natural gas-fired power plants. Japan contributed by around 3 % of the total CO_2 emissions worldwide in 2016 [67], relying heavily on fossil fuels for energy generation. Table 1, Table 2, and Table 3 show the data for the sources in the three countries.

Qatar's emissions level from the oil and gas industry were determined based on production rates retrieved from Alfadala and El-Halwagi [68] and emissions factors from Al-Mohannadi et al. QatarSteel [69], and emission from power generation was obtained from [70]. Capture and compression cost data (C_i) were obtained from Al-Mohannadi et al [36] through summing the operating cost and the annualized capital cost. Post-combustion MEA absorption was considered as the capture process, and compression was set to achieve a pressure of 150 MPa. Energy associated emissions for capture and compression (γ_i) were obtained from von der Assen, Müller [62].

Table 3 Qatar's emissions sources and the corresponding parameters

Source	**CO_2 Produced (10^6 tCO_2/y)**	**C_i ($/$tCO_2$)**	**γ_i (t CO_2-produced/tCO_2-captured)**
GTL C U	7.43	2.50	0.04
Natural Gas Processing	2.60	2.50	0.04
Steel	3.47	30.50	0.13
Cement	3.79	32.50	0.27
Fuel Combustion	42.22	36.54	0.10
Power Plant (NG)	18.06	40.17	0.13

Emissions rates from the sources in Norway and Japan were obtained from the database of the United Nations Framework Convention on Climate Change [71]. The operating costs of capture and compression were adjusted according to the variations in energy prices between the three countries. Energy related emissions from capture and compression were neglected for Norway since clean renewable energy sources are expected to supply energy for the introduced processes. The cumulative contributions of the sources considered to the total emissions of each of the countries are as follows: 78 % for Qatar, 60 % for Norway, and 65 % for Japan.

Table 4 Norway's emissions sources and the corresponding parameters

Source	**CO_2 Produced (10^6 t CO_2/y)**	**Ci (\$/t CO_2)**
Natural Gas Processing and Ammonia	1.96	3
Ferroalloys	2.64	36
Cement and Lime	0.98	38
Fuel Combustion	15.46	42
Public Electricity and Heat Production	1.83	46
Refineries	0.84	46
Aluminum	1.94	48

Table 5 Japan's emissions sources and the corresponding parameters

Source	**CO_2 Produced (10^6 t CO_2/y)**	**Ci (\$/t CO_2)**	**γi (t CO_2-produced/t CO_2-captured)**
Chemical Industry	3	4.4	0.04
Steel	6	61.4	0.13
Cement and Lime	32	63.4	0.27
Power - Coal	211	66.2	0.10
Power - Oil	39	66.2	0.12
Fuel Combustion	286	67.4	0.10
Power - NG	168	71.1	0.13
Refineries	36	71.1	0.25

Three different options were considered for carbon sinks: EOR, methanol production from water splitting, carbon utilization in horticulture (greenhouses), and carbon sequestration. Carbon revenues were obtained from Al-Mohannadi et al [36], and their values are: 30 \$/t CO_2 for EOR, 20 \$/t CO_2 for methanol, and -10 \$/t CO_2 for sequestration, applicable for Norway and Qatar. Sequestration cost for Japan was taken at 20 \$/t CO_2. The capacities were estimated based on conventional scales of already existing technologies. Solar energy option was considered for Qatar, assuming a capacity of 20 % of total demand, with the price estimated from EIA [72]. Since Qatar is a major producer of natural gas, the operating cost of the existing power plants was neglected (no fuel import cost). Different energy options were considered for Japan, including solar energy, wind, hydroelectric energy, and nuclear energy. Fuel switching from coal to oil or gas and from oil to gas was found to be cost-wise inefficient as the resulting carbon reduction is small relative to the incurred costs. The prices were obtained from Reuters [73]. The operating costs of the existing power plants were assumed to be the prices of imported fossil fuels, which were obtained from Momoko, Yorita [74]. The capacities for the alternate energy sources were determined from Kato and Kurosawa [75].

Figure 18, Figure 19, and Figure 20 show the results for the abatement cost curves of the three countries under study. The results show that carbon capture and utilization present feasible carbon reduction pathways that would allow profit generation in both Norway and Qatar. This is due to the availability of high purity carbon streams that do not require expensive capture. Reducing CO_2 in Qatar from the point sources under investigation by 11 % would generate a net profit of 180×10^6 \$/y. A net profit of 53 ×

10^6 $/y can be generated from implementing EOR in Norway as a carbon utilization option to reduce emissions by 8 %. The cost-neutral carbon fixation in Qatar is 17% of the considered total emissions, while that of Norway is 22%.

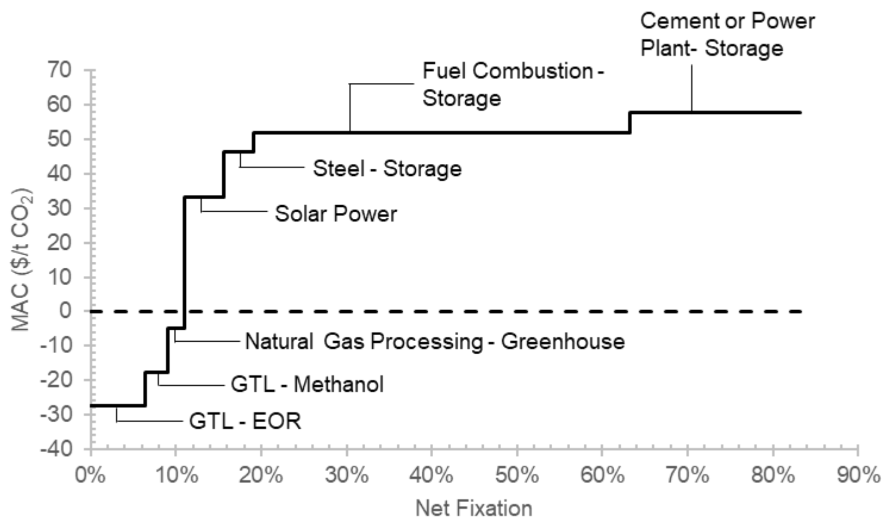


Figure 18 Qatar's abatement cost profile

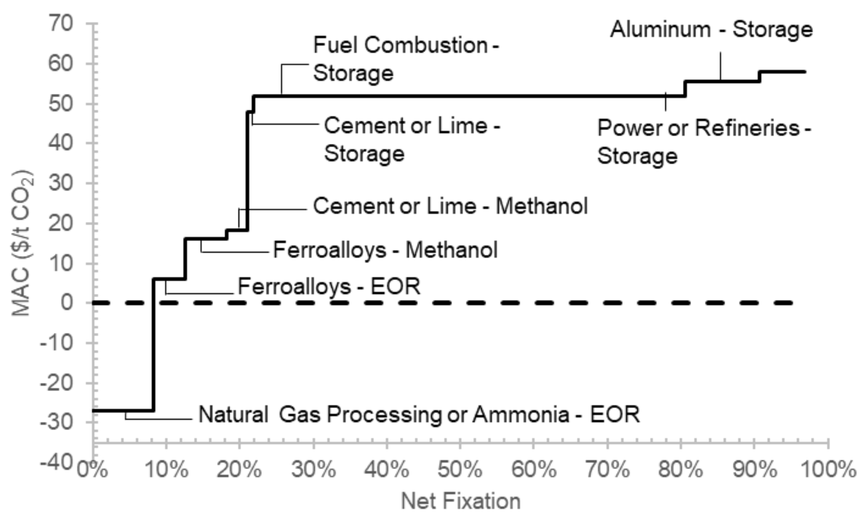


Figure 19 Norway's abatement cost profile

The profit margin of CCU in Japan is narrow since the capacity of the utilization option considered (methanol) is negligible compared to the emissions rate. The major CO_2 emissions in Japan have low purity since they are mainly produced from the power sector, requiring high capture cost, especially with the high electricity prices. Energy generation from alternate sources presents another expensive solution for Japan. The results show that switching coal energy to nuclear as well as capturing and sequestering emissions from industrial combustion present the cheapest options costing around 100 \$/t CO_2 reduced. Fuel switching from natural gas is the most expensive (310 \$/t CO_2) because of the low emissions produced from natural gas power plants relative to coal and oil-fired plants. Power switching from natural gas to solar energy shows Qatar's different position in the abatement profile due to the ease of implementation of solar energy, which resulted in a cheaper system. Natural gas to solar energy switching (31 \$/tCO_2) is cheaper than carbon sequestration in Qatar (48-58 \$/tCO_2), and it needs to be prioritized directly after the profitable CCU options.

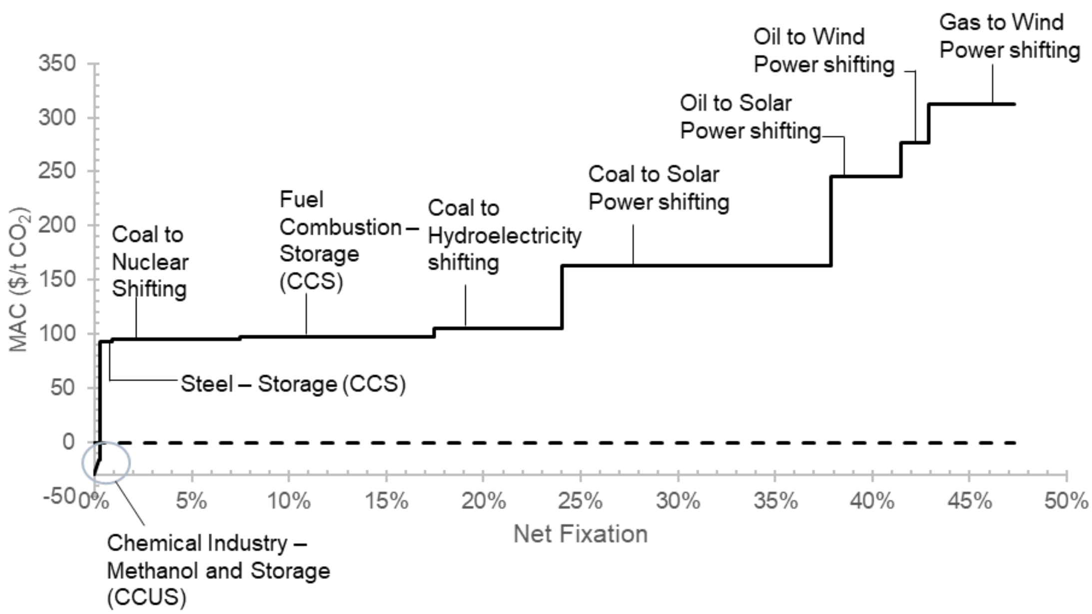


Figure 20 Japan's abatement cost profile

The MAC curves developed provides general insights that can support the decisions of planners and policymakers in setting carbon reduction strategies. The comparison between the different options for each country shows how the same technology can vary widely in cost. Qatar's most optimal pathways are in the area of CCU and solar energy. Japan's strategy should focus on decreasing the energy requirements, re-establishing nuclear power to replace coal, and sequestering carbon generated from fuel combustion. Norway's low carbon emissions level allows the application of CCUS technologies to have a significant role in decreasing the remaining emissions from point sources.

CHAPTER VI

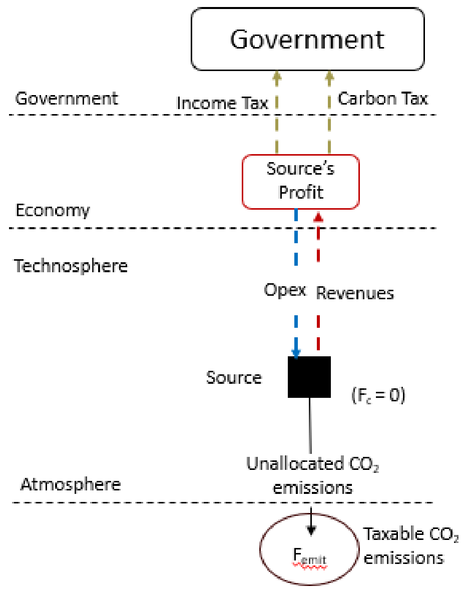
ASSESSING CARBON TAX IN THE CONTEXT OF DEVELOPED METHODS

In the described approaches, sources are assumed to allocate pure CO_2 streams to a shared carbon network from which the streams are then delivered to the sinks. Such mechanism does not consider the interaction between the different stakeholders, and how the decision of each component may impose constraints affecting the overall solution of the problem. Consequently, the result of a carbon policy that intend to achieve a set level of carbon reduction for a minimal cost may not be the optimal solution. In this section, the system is defined as a game composed of the different players: the sources and the sinks, and a planning authority which set the policy parameters. That is to allow the assessment of the performance of the carbon tax under the various interactions.

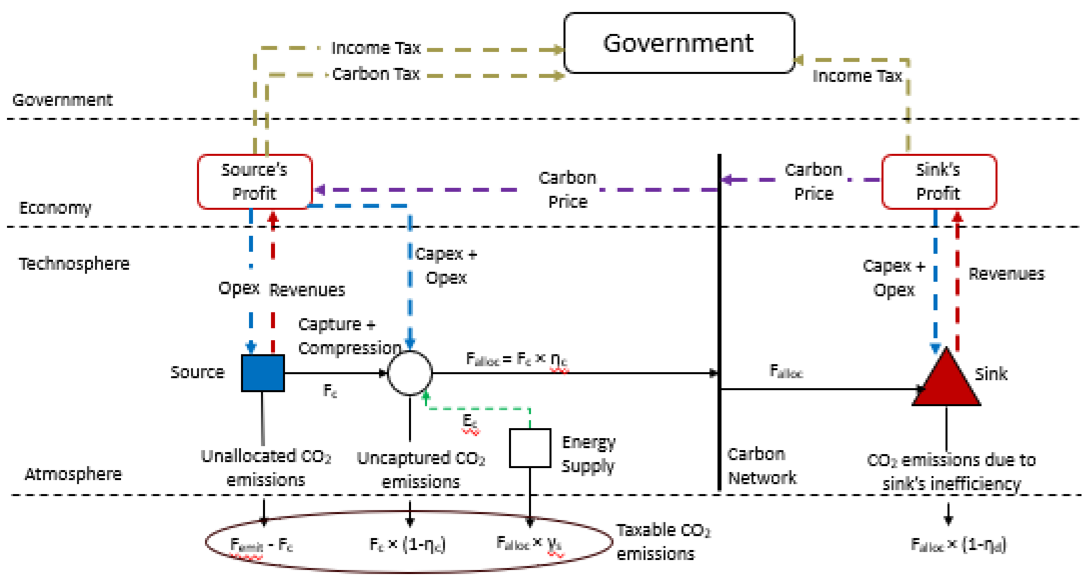
Traditional carbon policies include carbon taxation, carbon-reducing technology subsidy, and carbon emissions trading scheme, and they are enforced by the political authorities (governments) in order to achieve a set level of carbon reduction defined in national and international strategies and commitments. Carbon taxation obliges the polluters to pay the government a fee for emitting CO_2. If the tax is high enough, stakeholders would be convinced to invest in carbon-reducing technologies to reduce their emissions. carbon-reducing technology subsidy can incentivize the stakeholders to invest in carbon-reducing technology as the government would be covering a fraction of the expenses incurred due to the low-carbon transition. In the carbon trading scheme, emissions cap is set for every plant above which no CO_2 is allowed. Plants which can reduce CO_2 at low cost can sell its emissions permit to plants that require high cost for the low-carbon transition. This ensures that technologies with lowest costs are implemented.

The work presented in this chapter investigates the performance of carbon tax on the implementation of CCUS and alternative energy options, and it assesses the resulting solution due to the interactions with respect to the targets developed in the described methods. Other carbon policies are out of the scope of the presented investigation as the aim of this chapter is to provide an outlook on possible future work that can be done in designing carbon policies based on the targets developed in the tools described earlier. The economic impact of the policies is examined through studying the additional costs paid (or revenues collected) by the different stakeholders due to the policy.

Consider a set of existing emissions sources S ($S = [s_1, s_2, \ldots, s_m]$, $m \in \mathbb{N}$) characterized by the capture and compression costs (C_{si}) and emission (γ_{si}), and a set of available sinks D ($D = [d_1, d_2, \ldots, d_n]$, $n \in \mathbb{N}$) characterized by the utilization/storage economics (R_{dj}) and fixation efficiency (η_{dj}). Power sources E ($E = [E_1, E_2, \ldots, E_p]$, $p \in \mathbb{N}$), are characterized by their emissions level ε_k and costs C_{Ek}. Carbon reduction planning is performed at the level of the government which sets the carbon reduction target. The implementation of carbon reduction technologies is performed at the level of the industrial stakeholders (owning the plants and represented by S, D, and E). The sources pay for carbon capture and the power plants pay for upgrading to cleaner power sources if implemented. The sinks pay the sources for the allocated CO_2. The decisions taken by each industrial stakeholder aim to maximize its net profit. The sources decide either to vent their emissions and pay the carbon tax or to invest in carbon capture based on the revenues. The sinks decide to participate in the carbon network if the carbon price allows it to generate profit. Power sources decide whether to vent their emissions, capture them, or reduce them through renewable energy depending on the economics of the different options. The government sets the carbon tax to incentivize enough sources toward the low-carbon transition. The different interactions considered in the system are shown in Figure 21.



(a)



(b)

Figure 21 The interactions between the source, sink, and government without the carbon network (a) and with the carbon network (b)

Developing the Model

Under the described scheme, the carbon tax is defined as the fee paid by CO_2 sources to the government for every ton of CO_2 emitted to the atmosphere. The tax is proportional to the amount of CO_2 emitted, and its rate CT is set by the authority. Sinks do not pay the carbon tax as the processes operated are carbon negative: more carbon is fed to the process than the carbon produced due to the inefficiency.

$$\text{Carbon Tax} = CT \times [F_{emit} - F_{alloc\text{-}s} \times (1-\gamma_s)] \quad (7)$$

Considering the CCUS options; when a source participates in the carbon network, it gets paid for the allocated CO_2 at specific carbon price CP (in \$/tCO_2 for example) determined by the market equilibrium (Carbon Price = $F_{alloc\text{-}s} \times CP$). The source funds the installment and operation of CO_2 capture and compression (Capture Costs = $F_{alloc\text{-}s} \times C_s$) which reduces the paid carbon tax (since it will be reducing CO_2). The monetary flows to the source are represented in Figure 21a. If the source decides not to participate in the carbon network, the system would be as illustrated in Figure 21b. Since the source's decisions are economically driven, the source would choose to participate in the carbon network only if the profit generated (Source's Profit in Figure 21b) is higher than that if the source did not participate (Source's Profit in Figure 21a). The source's revenues and operating costs (Process Cash Flow = CF = Revenue - Opex) do not change upon participation in the carbon network assuming the same production level is maintained. The income tax is the fraction of the profit collected by the government based on the income tax rate IT. The source's profit when the source participates in the carbon network and when it does not participate can be calculated as shown in equations Eq.8 and Eq.9 respectively.

$$\text{Source's Profit (with CCUS)} = [(\text{CF} + \text{F}_{\text{alloc-s}} \times \text{CP}) - (\text{F}_{\text{alloc-s}} \times \text{C}_{\text{si}} + \text{CT} \times [\text{F}_{\text{emit}} - \text{F}_{\text{alloc-s}} \times (1 - \gamma_{\text{s}})])] \times (1 - \text{IT}) \quad (8)$$

$$\text{Source's Profit (without CCUS)} = (\text{CF} - \text{CT} \times \text{F}_{\text{emit}}) \times (1 - \text{IT}) \quad (9)$$

The condition on the carbon price for the source to participate in the carbon network can be derived from the condition on the profits (Source's Profit with CCUS > Source's Profit without CCUS). The constraint on the carbon price presented in Eq.10.

$$CP > C_{si} - CT \times (1 - \gamma_{si}) \quad (10)$$

Eq.10 shows that for each source there exist a minimum carbon price below which the source will not participate in the carbon network. This cost will be referred to as CP_{si}, equal to the right-hand side of the Eq.16, and characterizes the decision of each source si.

A sink would participate in the carbon network if the carbon price allows at least the generation of profit from processing the CO_2 allocated (Sink's Profit > 0). A specific breakeven carbon price (in $/t$CO_2$ for example) is commonly reported in the literature to characterize the economics of the CO_2 utilization and sequestration technologies (sinks), and this price is equal to the net cashflow generated from operating the sink's process (i.e. break even CO_2 price = R_d = (Sink's Revenues – Sink's Costs)/$F_{alloc\text{-}d}$).

Hence, the sink's profit can be calculated as follows:

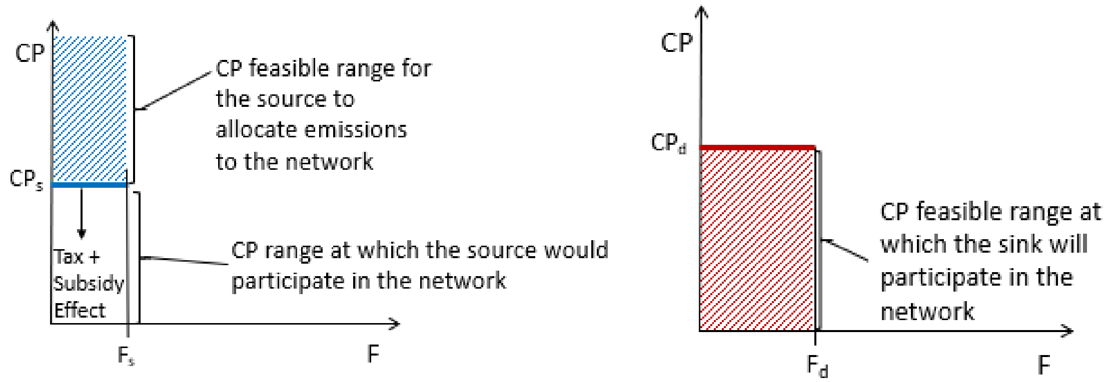
$$Sink's\ Profit = [R_d - CP] \times Falloc \times (1 - IT) \quad (11)$$

The condition for the sink to participate in the carbon network (Sinks Profit > 0) can be used to derive an expression describing the maximum carbon price the sink is willing to pay for the allocated CO_2. The constraint on the carbon price CP that allows the sink's participation in the network is:

$$CP < R_{dj} \tag{12}$$

Eq.12 shows that for each sink there exist a maximum carbon price above which the sink will not participate in the carbon network. This price will be referred to as CP_{dj}, equal to the right-hand side of the Eq.12, and characterizes the decision of each sink d_j.

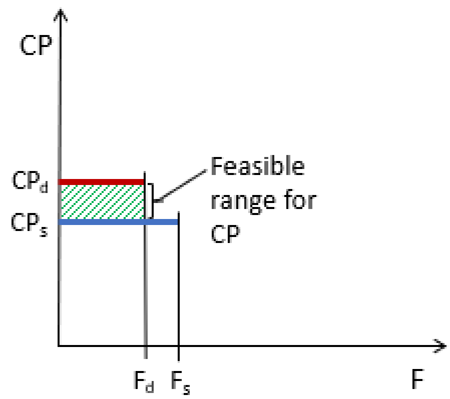
As mentioned earlier, the carbon price is determined through the carbon market dynamics. It depends on the flow available for allocation, the price at which the sources are willing to sell and the price at which the sinks are willing to buy. All these characteristics can be represented graphically on the carbon price curve. The curve is similar to the tool developed in Chapter IV (the graphical technique), representing the source through its minimum selling price CP_{si} and its flow availability F_{si} (Figure 22a), and representing the sink through its maximum buying price CP_{dj} and its capacity F_{dj} (Figure 22b). Both Figure 22a and Figure 22b show the feasible ranges for CP at which the source or the sink will be willing to participate in the carbon network.

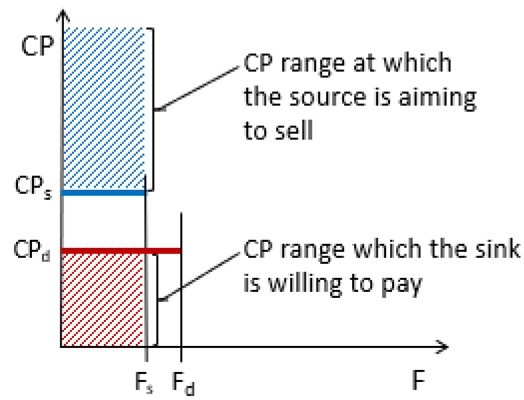


(a) **(b)**

Figure 22 The representation of the source (a) and the sink (b) on the carbon price curve

The integration of both sources and sinks into the carbon network can be represented graphically as shown in Figure 23. Two configurations can be generated upon the integration: either CP_d is greater than CP_s (Figure 23a) or CP_s is greater than CP_d (Figure 23b). If CP_d is greater than CP_s, then this indicates a possibility for carbon network that ensures the win-win situation for both the source and the sink. Otherwise, the sink won't afford the minimum price that the source is asking, and the network will not exist.



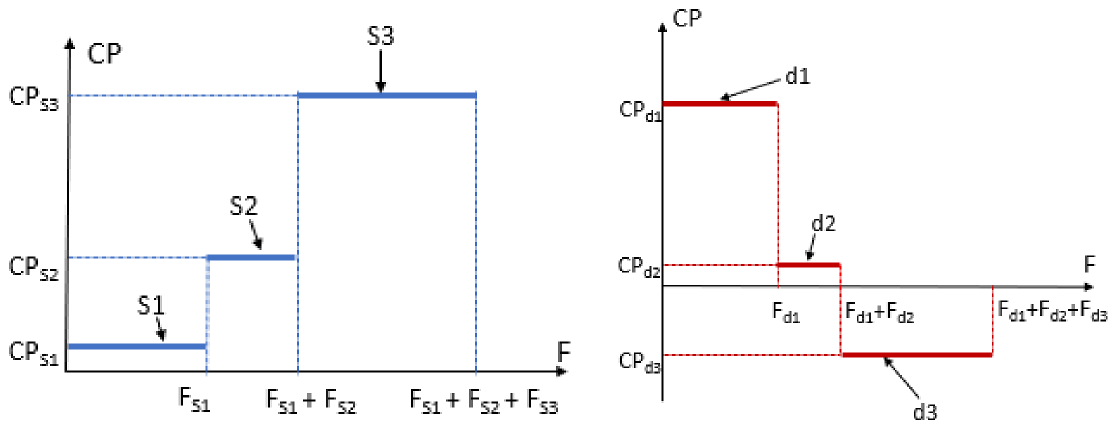


(a) **(b)**

Figure 23 The representation of the source-sink integration on the carbon price curve showing a feasible carbon network (a) and an infeasible carbon network (b)

Note that Eq.10, shows that the minimum carbon price for the source to participate in the network is dependent on the carbon policy applied. If no carbon policy is implemented (CT = 0), CP_s would be equal to the total capture and compression costs. The source's representation on the carbon price curve would be similar to the source's presentation on the carbon capture profile in the graphical technique developed in Chapter IV. CP_s decreases with increasing carbon tax rate. This is translated graphically by downward transition of the source's segment, which mean that if the carbon tax rate is high enough, an infeasible carbon network can become feasible. The government sets the carbon policy to achieve a required carbon reduction. On the other hand, increasing the carbon tax may have recessive impact on the economy as the industries will be losing a fraction of their income which may affect the global competitiveness of the locally produced products. As a result, businesses may close, and unemployment may increase. Hence a balance is required to avoid any economic consequences.

When multiple sources and multiple sinks exist, the same representation holds for each source and each sink. The sources, constituting the supply side of the carbon network, will follow the law of supply and their segments will be arranged in the increasing order of CP_{si} (Figure 24a). The sinks, constituting the demand side of the carbon network, will follow the law of demand, and their segments will be represented in the decreasing order of CP_{dj} (Figure 24b).



(a) **(b)**

Figure 24 The representation of multiple sources (a) and multiple (b) sinks on the carbon price curve

The carbon network can be represented graphically as shown in Figure 25. The representation of the sources' and the sinks' profiles give an insight on the scale of the feasible carbon network and the participating sources and sinks. The carbon market equilibrium is defined as the point at which the position of the two profiles with respect to each other shifts: the sink's profile drops below the source's profile. This point divides the graph into two sections: before the carbon market equilibrium is achieved, there is a feasible region for the network to take place where the supply flowrate is equal to the demanded flowrate at a possible carbon price. In this region, there exist a carbon price at which all the sources can afford to sell, and all the sinks can afford to buy, and beyond that region none of the sources or the sinks can hold up to the competition. Hence after the equilibrium point, it is assumed that none of the sources or the sinks would be willing to participate the carbon price set by the dynamics between sources and sinks before the equilibrium.

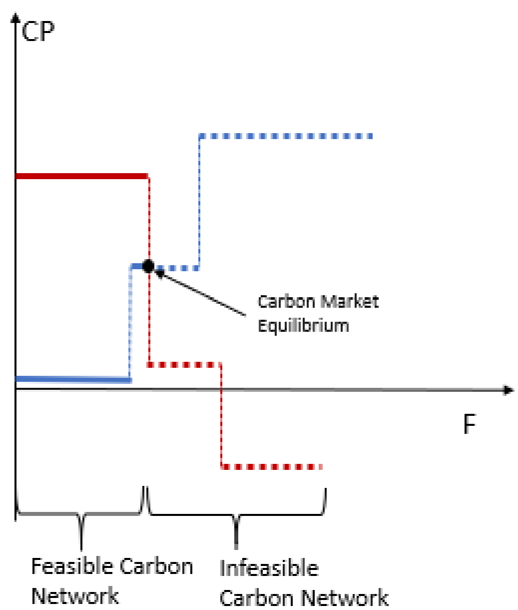


Figure 25 The graphical representation of the carbon network with multiple sources and multiple sinks

It is common in economics to determine the price of a product from the supply-demand equilibrium presented on the price curve. However, the generated carbon price curve differs from the traditional curve used; it is not continuous, and every segment represent a different stakeholder. Each source aims to sell at the maximum possible carbon price and each sink tries to buy at the lowest possible carbon price. The competition between the sources to sell at a profitable CP and between sinks to buy at affordable CP defines the market dynamics which control the carbon price in the network. As mentioned earlier, before the carbon market equilibrium, their exist a carbon price CP which satisfies all the sources and all the sinks which segments are to the left of the equilibrium. This condition is shown by the following inequality:

$$max\ (CP_{sb}) < CP < min\ (CP_{db})\ \forall s_b\ \&\ \forall d_b\ before\ the\ equilibrium \quad (20)$$

Note that $max\ (CP_{sb})$ corresponds to the selling carbon price for the source at the equilibrium and $min\ (CP_{db})$ corresponds to the buying carbon price sink at the equilibrium. Since the sinks to the left of the carbon market equilibrium are more profitable than the sinks to the right, they may afford to participate in the carbon network at higher carbon prices to win the competition and generate profit from the allocated CO_2. This condition can be translated into the following inequality:

$$max\ (CP_{da}) < CP\ \forall d_a\ after\ the\ equilibrium \quad (21)$$

In Eq.21, $max\ (CP_{da})$ is carbon price corresponding to the sink right after the equilibrium. Similarly, the sources to the left of the carbon market equilibrium require less capture costs and can sell at lower carbon price to ensure the participation in an economically favorable carbon network. This condition can be shown by the following constraint:

$$min\ (CP_{sa}) > CP\ \forall s_a\ after\ the\ equilibrium \quad (21)$$

In Eq.22, *min* (CP_{sa}) is carbon price corresponding to the source right after the equilibrium. The system of the inequalities represented in Eq. 20, Eq.21, and Eq.22 can be solved graphically to determine the possible value or range for the CP at which the CO_2 exchange to and from the network takes place. Figure 26 shows the graphical solution for CP at different configurations of sources and sinks right before and right after the equilibrium profile.

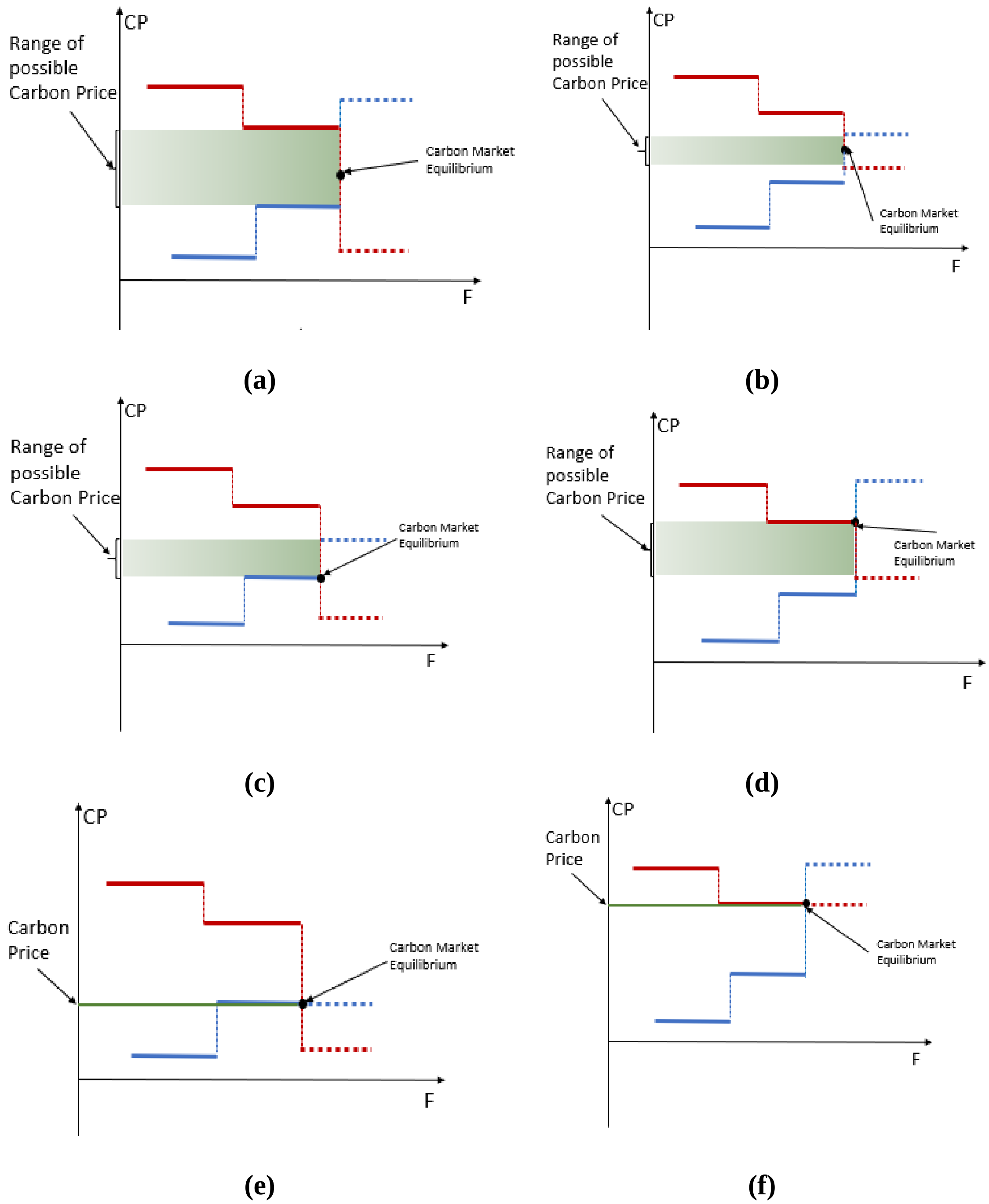


Figure 26 The graphical solution of the carbon price for different source-sink configurations at carbon market equilibrium

After setting the carbon policy parameters (carbon tax rate) and determining the market layout and carbon price as described earlier, the net profits of each source, each sink, and the government can be calculated. The generated profits can be compared with the profits without the implementation of the carbon policy to assess its economic impact of the policy on the different players.

Case Study

Consider a system composed of different plants: GTL, cement, methanol, aluminum, and a natural gas fired power plant. Each of the plants has one source of emissions except for GTL which produces pure CO_2 from capturing the effluent of the reformer and a diluted CO_2 stream from its utilities. The technical and economic properties of the different sources are represented in Table 6.

Table 6 Source's data for the case study on carbon policy

Source	**CO_2 Produced (10^6 tCO_2/y)**	**Ci ($/$tCO_2$)**	**γ_i (tCO_2-produced/tCO_2-captured)**
GTL - Concentrated	4.12	2.5	0.03
Cement	1.38	32.5	0.27
GTL - Diluted	11.38	36.5	0.26
Methanol	0.64	36.5	0.26
Aluminum	3.30	36.5	0.29
Power Plant	3.8	40.1	0.13

The total emissions level of the considered sources is 24.62×10^6 tCO_2/y. Amine absorption is considered as the capture process with 90% capture efficiency. The considered sinks are summarized in Table 7 with their technical and economic properties. Beside CCUS, solar energy can be used to generate up to 50% of the power plant's capacity to reduce CO_2 emissions at a marginal abatement cost of 31 $/$tCO_2$-reduced.

Table 7 Sink's data for the case study on carbon policy

Sink (d_i)	**F_{di} (10^6 tCO_2/y)**	**R_{di} ($/$tCO_2$)**	**η_{di}**
Enhanced Oil Recovery (EOR)	5	30	100%
Methanol B	2	20	99%
Storage	18	-10	100%

The algebraic approach described in Chapter V was applied to the presented data in order to obtain the marginal abatement cost curve of the system. The MAC curve represents the optimal pathways to reduce CO_2 from the described sources (Figure 27)

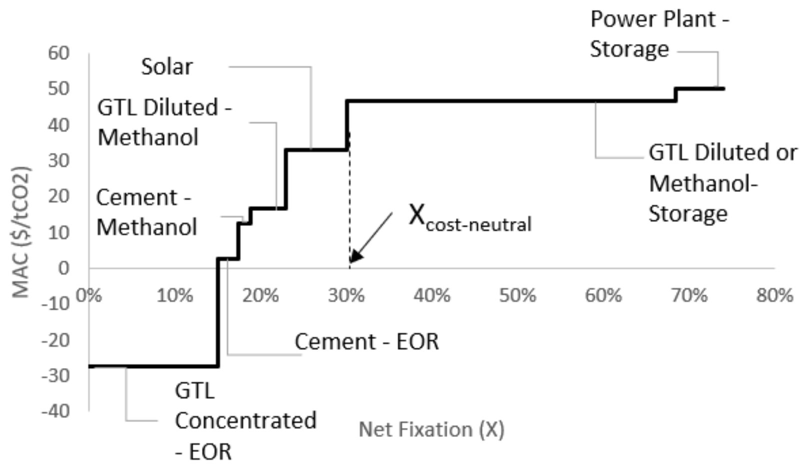


Figure 27 MAC curve for the case study on carbon policy

The algebraic targeting showed that the profitability pinch of the carbon network is achieved at a CO_2 allocation flowrate of 4.12 $\times 10^6$ tCO_2/y, resulting in 15.1% carbon reduction and 113 $\times 10^6$ \$/y net profit. The cost-neutral carbon reduction target was found to be 31% of the total emissions considered, achieved through allocating 7.38 $\times 10^6$ tCO_2/y into the carbon network, and operating the solar energy system at its maximum capacity.

Figure 28 shows the carbon price curve generated for the described system without the implementation of any carbon policy. The "combustion segment" represents the CO_2 sources that are the utility generation units in the methanol and GTL plant which have the same economic properties. When no policy is applied, a carbon network can be generated corresponding the "profitability pinch" target which in this case is characterized by an allocation flowrate of 4.12 $\times 10^6$ tCO_2/y. In other words, 15.1% of the total emissions can be reduced without applying any carbon policy.

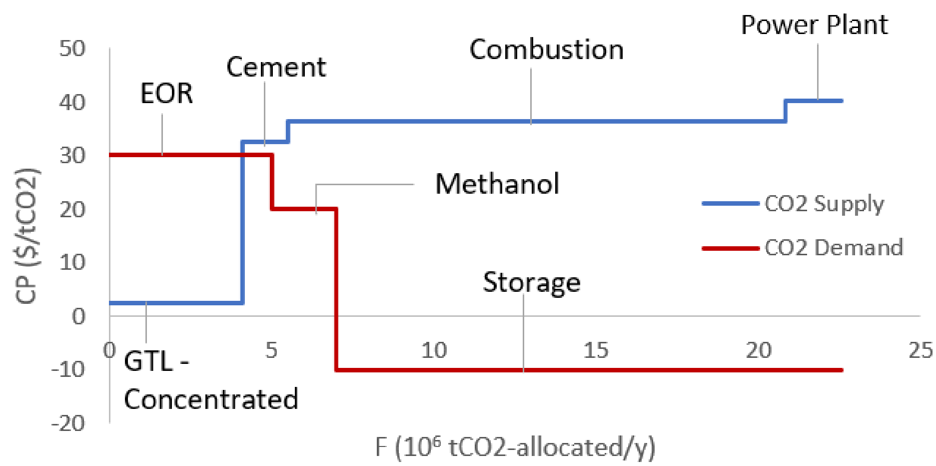


Figure 28 Carbon price curve without applying any carbon policy

The cost-neutral carbon reduction target can ideally be implemented without any economic impact on any of the different stakeholders, as the total profit of the system would be zero and no costs should be paid to achieve such target. Due to the different interactions among the various stakeholders in the system, carbon policy is necessary to achieve a net carbon reduction exceeding that associated with the profitability pinch. The targeting developed has shown that the carbon reduction can reach up to 31% while being profitable. A carbon tax policy that allows the cost neutral carbon reduction target to be achieved was investigated.

Varying the carbon tax rate CT, a net fixation of 30% was achieved for CT = 33$/t$CO_2$. The effect of the new carbon tax on the CO_2 market is shown on the carbon price curve in Figure 29. As mentioned earlier, the carbon tax's effect is shown by the downward shifting of the supply curve. Since the sources would still have to pay carbon tax for the secondary emissions from the capture process, the impact of the tax differs among the sources depending on the corresponding secondary emissions factor γ_i. This will result in a change in the arrangement of the sources where sources with high capture cost but relatively low γ_i may ask for lower carbon price than sources with lower capture cost but higher γ_i. This is the case for the power plant where its rank among the sources in the CCUS network dropped from the 6th to the 3rd in terms of carbon pricing. Graphically, it is shown that the feasible carbon network under the proposed carbon tax will be constituted of GTL-concentrated, cement, and power plant from the supply side, and from EOR and methanol on the demand side, with a carbon exchange flowrate of 7×10^6 tCO_2/y. Solar energy will be implemented at its maximum capacity.

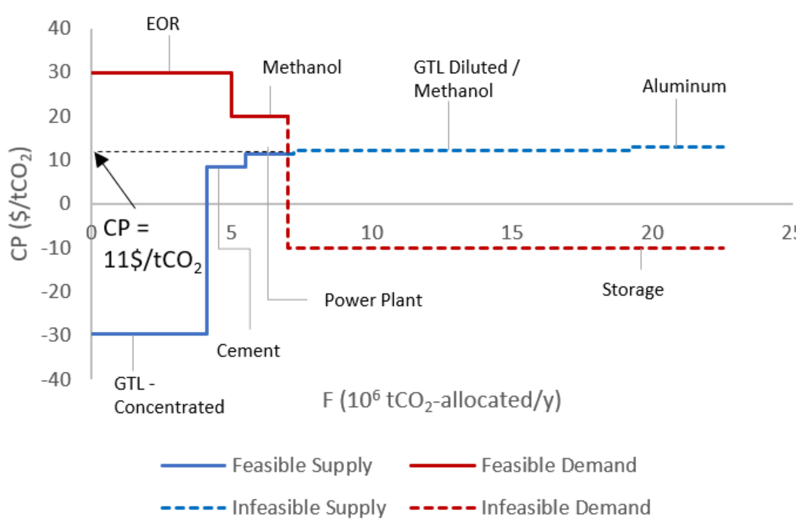


Figure 29 Carbon price curve of the system with carbon tax rate CT = 33 \$/tCO$_2$

In the optimal network obtained from the targeting for a CO_2 reduction of 30%, power plant did not participate. Hence, the carbon tax resulted in a deviation from the optimal solution. As a result, carbon network generated under the carbon tax policy implemented as describe in this Chapter would result in a 5 $\times 10^6$ \$/y deviation from the optimal solution.

The case study performed shows a possible application of the targeting techniques to assess the design of carbon policies. Future work will focus on addressing the problem of designing carbon policy and assessing its performance under the different interactions in the context of the developed targets. Consequently, the carbon network design strategies can be implemented in a political framework that ensures the feasibility of the carbon reduction targets.

CHAPTER VII

CONCLUSION AND FUTURE WORK RECOMENDATIONS

This work has presented a novel targeting technique that is simple relative to the other design methodologies used to address the problem of economic optimization of carbon reduction. It can serve as a benchmark to assess process design and carbon policy design in the future. A graphical approach was developed to address the problem of CCUS cost targeting. The method was developed further through an algebraic approach that accounts for the secondary emissions of the capture and utilization processes to determine the MAC and allow the comparison between the different carbon reduction strategies. The methods were applied to a case study and different planning criteria were investigated: minimizing carbon network cost, minimizing carbon network footprint, and minimizing MAC of the carbon network. It was found that the environmental criteria lead to higher costs and lower targets, and the MAC provides a balance between the economic and environmental impacts. Power shifting options to reduce CO_2 emissions were then added to the picture and the costs of carbon abatement options in different geographic regions were investigated, and it was found that the impact of the different options varies depending on the accessibility to energy and carbon utilization/sequestration options. An outlook on carbon policy was provided through developing a model that describes the different interactions and the carbon market dynamics under carbon tax. It was found that applying the carbon tax to reach the cost-neutral carbon reduction did not result in the optimal solution.

Recommendations:

1. Developing the targeting technique to consider the effect of mixing streams on the cost of carbon capture.
2. Further carbon reduction pathways can be considered such as energy integration.
3. Accounting for the different uncertainties that can affect the costs and capacities of the considered pathways.
4. Developing a tool to design optimal carbon policies in context of the developed targets.

REFERENCES

1. Rockström, J., et al., *A safe operating space for humanity.* nature, 2009. **461**(7263): p. 472.

2. Friedlingstein, P., et al., *Global carbon budget 2019.* 2019.

3. Bui, M., et al., *Carbon capture and storage (CCS): the way forward.* Energy & Environmental Science, 2018. **11**(5): p. 1062-1176.

4. Leeson, D., et al., *A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources.* International Journal of Greenhouse Gas Control, 2017. **61**: p. 71-84.

5. Allwood, J.M., J.M. Cullen, and R.L. Milford, *Options for achieving a 50% cut in industrial carbon emissions by 2050*. 2010, ACS Publications.

6. Fan, Y., et al., *Analyzing impact factors of CO2 emissions using the STIRPAT model.* Environmental Impact Assessment Review, 2006. **26**(4): p. 377-395.

7. Fischedick, M., et al., *Industry In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report.* 2014.

8. Rogelj, J., et al., *Paris Agreement climate proposals need a boost to keep warming well below 2 C.* Nature, 2016. **534**(7609): p. 631-639.

9. Fais, B., N. Sabio, and N. Strachan, *The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets.* Applied Energy, 2016. **162**: p. 699-712.

10. Tapia, J.F.D., et al., *A review of optimization and decision-making models for the planning of CO2 capture, utilization and storage (CCUS) systems.* Sustainable Production and Consumption, 2018. **13**: p. 1-15.

11. Foo, D.C. and R.R. Tan, *A review on process integration techniques for carbon emissions and environmental footprint problems.* Process Safety and Environmental Protection, 2016. **103**: p. 291-307.

12. Sinha, R.K. and N.D. Chaturvedi, *A review on carbon emission reduction in industries and planning emission limits.* Renewable and Sustainable Energy Reviews, 2019. **114**: p. 109304.

13. Grimaud, A. and L. Rouge, *Carbon sequestration, economic policies and growth.* Resource and Energy Economics, 2014. **36**(2): p. 307-331.

14. Galeotti, M., S. Salini, and E. Verdolini, *Measuring environmental policy stringency: Approaches, validity, and impact on environmental innovation and energy efficiency.* Energy Policy, 2020. **136**: p. 111052.

15. Lia, G., A. Zakari, and V. Tawiah, *Does environmental diplomacy reduce CO2 emissions? A panel group means analysis.* Science of The Total Environment, 2020: p. 137790.

16. El-Halwagi, M.M., *Pollution prevention through process integration: systematic design tools*. 1997: Elsevier.

17. Linnhoff, B. and J.R. Flower, *Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks.* AIChE Journal, 1978. **24**(4): p. 633-642.

18. El-Halwagi, M.M., *Sustainable design through process integration: fundamentals and applications to industrial pollution prevention, resource conservation, and profitability enhancement*. 2017: Butterworth-Heinemann.

19. Manan, Z.A., et al., *Advances in Process Integration research for CO2 emission reduction–A review.* Journal of cleaner production, 2017. **167**: p. 1-13.

20. Dhole, V.R. and B. Linnhoff, *Total site targets for fuel, co-generation, emissions, and cooling.* Computers & chemical engineering, 1993. **17**: p. S101-S109.

21. Tan, R.R. and D.C. Foo, *Pinch analysis approach to carbon-constrained energy sector planning.* Energy, 2007. **32**(8): p. 1422-1429.

22. Tan, R.R., K.B. Aviso, and D.C. Foo, *Carbon emissions pinch analysis of economic systems.* Journal of cleaner production, 2018. **182**: p. 863-871.

23. Turk, G.A., et al., *CO2 transport: A new application of the assignment problem.* Energy, 1987. **12**(2): p. 123-130.

24. Tan, R.R., et al., *Crisp and fuzzy integer programming models for optimal carbon sequestration retrofit in the power sector.* Chemical Engineering Research and Design, 2010. **88**(12): p. 1580-1588.

25. Tan, R.R., D.K.S. Ng, and D.C.Y. Foo, *Pinch analysis approach to carbon-constrained planningfor sustainable power generation.* Journal of Cleaner Production, 2009. **17**(10): p. 940-944.

26. Diamante, J.A.R., et al., *A graphical approach for pinch-based source–sink matching and sensitivity analysis in carbon capture and storage systems.* Industrial & Engineering Chemistry Research, 2013. **52**(22): p. 7211-7222.

27. Ilyas, M., Y. Lim, and C. Han, *Pinch based approach to estimate CO 2 capture and storage retrofit and compensatory renewable power for South Korean electricity sector.* Korean Journal of Chemical Engineering, 2012. **29**(9): p. 1163-1170.

28. Ooi, R.E., et al., *Planning of carbon capture and storage with pinch analysis techniques.* Chemical Engineering Research and Design, 2013. **91**(12): p. 2721-2731.

29. Nawi, W.N.R.M., et al., *Pinch analysis targeting for CO 2 total site planning.* Clean Technologies and Environmental Policy, 2016. **18**(7): p. 2227-2240.

30. Tan, R.R., et al., *Optimal source–sink matching in carbon capture and storage systems with time, injection rate, and capacity constraints.* Environmental Progress & Sustainable Energy, 2013. **32**(2): p. 411-416.

31. He, Y.-J., et al., *Optimal source–sink matching in carbon capture and storage systems under uncertainty.* Industrial & Engineering Chemistry Research, 2014. **53**(2): p. 778-785.

32. Hasan, M.F., et al., *Nationwide, regional, and statewide CO2 capture, utilization, and sequestration supply chain network optimization.* Industrial & Engineering Chemistry Research, 2014. **53**(18): p. 7489-7506.

33. Al-Mohannadi, D.M. and P. Linke, *On the systematic carbon integration of industrial parks for climate footprint reduction.* Journal of cleaner production, 2016. **112**: p. 4053-4064.

34. Al-Mohannadi, D.M., et al., *Multi-period carbon integration.* Journal of Cleaner Production, 2016. **136**: p. 150-158.

35. Hassiba, R.J., D.M. Al-Mohannadi, and P. Linke, *Carbon dioxide and heat integration of industrial parks.* Journal of cleaner production, 2017. **155**: p. 47-56.

36. Al-Mohannadi, D.M., et al., *On the synthesis of carbon constrained natural gas monetization networks.* Journal of Cleaner Production, 2017. **168**: p. 735-745.

37. Ghali, M.R., J.-M. Frayret, and C. Ahabchane, *Agent-based model of self-organized industrial symbiosis.* Journal of Cleaner Production, 2017. **161**: p. 452-465.

38. Rizk, Y., M. Awad, and E.W. Tunstel, *Decision making in multiagent systems: A survey.* IEEE Transactions on Cognitive and Developmental Systems, 2018. **10**(3): p. 514-529.

39. Axtell, R.L., C.J. Andrews, and M.J. Small, *Agent-based modeling and industrial ecology.* Journal of Industrial Ecology, 2001. **5**(4): p. 10-14.

40. Boix, M., et al., *Optimization methods applied to the design of eco-industrial parks: a literature review.* Journal of Cleaner Production, 2015. **87**: p. 303-317.

41. Bichraoui, N., B. Guillaume, and A. Halog, *Agent-based modelling simulation for the development of an industrial symbiosis-preliminary results.* Procedia Environmental Sciences, 2013. **17**: p. 195-204.

42. Mantese, G.C. and D.C. Amaral, *Agent-based simulation to evaluate and categorize industrial symbiosis indicators.* Journal of cleaner production, 2018. **186**: p. 450-464.

43. Romero, E. and M.C. Ruiz, *Framework for applying a complex adaptive system approach to model the operation of eco-industrial parks.* Journal of Industrial Ecology, 2013. **17**(5): p. 731-741.

44. Albino, V., L. Fraccascia, and I. Giannoccaro, *Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: an agent-based simulation study.* Journal of Cleaner Production, 2016. **112**: p. 4353-4366.

45. Fraccascia, L., I. Giannoccaro, and V. Albino, *Efficacy of landfill tax and subsidy policies for the emergence of industrial symbiosis networks: An agent-based simulation study.* Sustainability, 2017. **9**(4): p. 521.

46. Tang, L., et al., *Carbon emissions trading scheme exploration in China: A multi-agent-based model.* Energy Policy, 2015. **81**: p. 152-169.

47. Yazdanpanah, V. and D.M. Yazan, *Industrial symbiotic relations as cooperative games.* arXiv preprint arXiv:1802.01167, 2018.

48. Yazdanpanah, V., D.M. Yazan, and H. Zijm. *Industrial symbiotic networks as coordinated games*. in *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems*. 2018. International Foundation for Autonomous Agents and Multiagent Systems.

49. Tan, R.R., et al., *An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration.* Chemical Engineering Research and Design, 2016. **106**: p. 43-58.

50. Ramos, M., *Bilevel optimization of Eco-Industrial parks for the design of sustainable resource networks*. 2016.

51. Aguilar, K.D.T., et al. *Carbon dioxide reduction incentive for eco-industrial parks using bilevel fuzzy programming*. in *2017IEEE 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)*. 2017. IEEE.

52. Gao, J. and F. You, *Game theory approach to optimal design of shale gas supply chains with consideration of economics and life cycle greenhouse gas emissions.* AIChE Journal, 2017. **63**(7): p. 2671-2693.

53. Ibrahim, N. and C. Kennedy, *A methodology for constructing marginal abatement cost curves for climate action in cities.* Energies, 2016. **9**(4): p. 227.

54. Morthorst, P.E., *Constructing CO2 reduction cost curves The case of Denmark.* Energy Policy, 1994. **22**(11): p. 964-970.

55. Enkvist, P., T. Nauclér, and J. Rosander, *A cost curve for greenhouse gas reduction.* McKinsey Quarterly, 2007. **1**: p. 34.

56. Nauclér, T. and P.-A. Enkvist, *Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve.* McKinsey & Company, 2009. **192**(3).

57. Dahowski, R., et al., *A preliminary cost curve assessment of carbon dioxide capture and storage potential in China.* Energy Procedia, 2009. **1**(1): p. 2849-2856.

58. Dahowski, R., et al., *Building the cost curves for CO2 storage: North America.* IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 2005.

59. GHG, I., *Building the cost curves for CO2 storage: European sector.* Cheltenham: International Energy Agency Greenhouse Gas R&D Programme, 2005.

60. Naims, H., *Economics of carbon dioxide capture and utilization—a supply and demand perspective.* Environmental Science and Pollution Research, 2016. **23**(22): p. 22226-22241.

61. Hepburn, C., et al., *The technological and economic prospects for CO_2 utilization and removal.* Nature, 2019. **575**(7781): p. 87-97.

62. von der Assen, N., et al., *Selecting CO2 sources for CO2 utilization by environmental-merit-order curves.* Environmental science & technology, 2016. **50**(3): p. 1093-1101.

63. EIA, U., *Capital cost estimates for utility scale electricity generating plants.* US Department of Energy, Energy Information Administration. Parts on PHP and batteries http://www. eia. gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption. pdf, 2016.

64. Yamaguchi, K., et al., *Scenario analysis of hypothetical site conditions for geological CO2 sequestration in Japan.* Energy Procedia, 2011. **4**: p. 4052-4058.

65. GlobalPetrpPrices. *Norway electricity prices, September 2019 | GlobalPetrolPrices.com*. 2020.

66. Salahuddin, M. and J. Gow, *Effects of energy consumption and economic growth on environmental quality: evidence from Qatar.* Environmental Science and Pollution Research, 2019. **26**(18): p. 18124-18142.

67. UCSUSA. *Each Country's Share of CO_2 Emissions*. 2019.

68. Alfadala, H.E. and M.M. El-Halwagi, *Qatar's chemical industry: Monetizing natural gas.* Chemical Engineering Progress, 2017. **113**(2): p. 38-41.

69. QatarSteel. *Qatar Steel » Reducing Emissions old*. 2020.

70. IEA. *Qatar - Countries & Regions - IEA*. 2019.

71. UNFCCC. *Greenhouse Gas Inventory Data*. 2018.

72. EIA, U., *Capital cost estimates for utility scale electricity generating plants.* US Department of Energy, Energy Information Administration. Parts on PHP and batteries www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf, 2016.

73. Tsukimori, O. *TABLE-Japan's electricity cost estimates by power source in 2030-METI*. 2015.

74. Momoko, A., et al., *Economic and energy outlook of Japan through FY2018.* Institute of Energy Economics, Japan, 2017.

75. Kato, E. and A. Kurosawa, *Evaluation of Japanese energy system toward 2050 with TIMES-Japan–deep decarbonization pathways.* Energy Procedia, 2019. **158**: p. 4141-4146.