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Developing Minimum Cost Targets for Carbon Reduction in Different Geographical Regions

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The increased concentrations of greenhouse gases, especially CO_2, in the atmosphere has raised concern toward the environmental impact of global warming. Consequently, global industrial and political commitments have been established to reduce greenhouse gas emissions. Carbon reduction can be achieved either by increasing the efficiency of the existing processes, using renewable sources of power instead of burning fossil fuels, or through implementing carbon capture, utilization, and/or sequestration technologies. Unfortunately, the implementation of carbon reduction projects is minor compared to the existing opportunities. For projects to be implemented, it is very important to establish their economic feasibility. Given the different access to renewable energy, utilization, and storage options, CO_2 emissions reduction would exhibit very different economics depending on the location. The implementation of carbon reduction technologies should be performed in a strategic approach that yields minimal investment and operating costs. This work incorporates different options for renewable energy sources, carbon utilization, and/or carbon sequestration. The aim is to plan an optimal arrangement of these technologies for implementation in different geographic locations such as Norway, Japan, and Qatar. Process Integration techniques used to optimize the operation of chemical processes have been developed to support decisions and organize the planning of carbon reduction projects. Carbon abatement cost curves have been applied as a policy and decision support tool allowing easy comparison between different technologies and pathways. This work tries to find the minimum cost of mitigating emissions through applying Process Integration principles on the different geographical regions and constructing the corresponding cost curves. The results will allow understanding the opportunities for carbon reduction under the economic constraints.

1. Introduction

The rising concentrations of CO_2 in the atmosphere and the associated consequences on the environment through global warming have driven global scientific and political efforts to reduce CO_2 emissions. These efforts have led to the emergence of various pathways for mitigating emissions. Options include restricting CO_2 production from the sources via processes enhancement, the use of cleaner power sources, through treating, storing, or utilizing emissions. Countries often choose a variety of CO_2 reduction options to define their carbon reduction strategies and commitments toward the climate change problem. However, these commitments, in many cases, fail to reach the targets as the emissions levels keep increasing. In the past 50 y, 500 recognized agreements were signed by different countries, however, the emissions rate increased by 30 × 10^6 t/y between 1980 and 2014 (Lia et al., 2020). 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 (Galeotti et al., 2020). The costs vary between countries depending on the availability of options like renewable energy or carbon capture, utilization, and sequestration (CCUS). Consequently, countries allocation of funds to implement or incentivize the existing industries to adapt mitigation methods differ, which leads to variations in the total cost and capacity of carbon reduction implementation.
This work 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. Various tools have been developed to assist the management of economically favorable mitigation routes.

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Marginal Abatement Cost (MAC) curves have been developed to support the establishment of policy tools that guide carbon reduction (Atkins et al., 2018). MAC curves have been applied to individual sectors to represent the costs and capacities of different carbon reduction strategies and compare them (Ibrahim and Kennedy, 2016). The application of MAC curves in the field of CCUS has been performed to assess the economic performance of either carbon capture taking only sources into account (Naims, 2016), or carbon utilization considering the state-of-art carbon sink technologies (Hepburn et al., 2019). No study has been conducted in which MAC curves are developed considering both sides of the allocation.
Recent developments in the field of Process Integration (PI) have led to the implementation of PI techniques for optimal planning of carbon reduction (Manan et al., 2017). Pinch Analysis methods and Mathematical Programming have been implemented as decision support tools for planning CCUS projects taking into account the whole carbon supply chain from the sources to the sinks (Tapia et al., 2018). This work follows the principles of Process Integration, taking into consideration the optimal arrangement between sources and sinks to obtain the cost of carbon network based on its capacity and represent the options with the renewable energy alternatives in MAC curve for each of the countries under study.

2. Approach

This paper considers a set of industrial sectors already existing in each of the countries as the point sources. For a given level of carbon reduction, a mix between the different alternative energy and carbon utilization and storage options with minimum carbon removal cost is proposed. Carbon utilization and storage options are considered as CO_2 sinks. Figure 1 illustrates the methodology framework followed in this study. Each country is taken as a system where the existing sources can capture and allocate CO_2 to potential sinks. The sinks use the CO_2 to produce value-added products and generate profit. Already existing power plants can act as normal sources capturing and allocating CO_2, and can also reduce CO_2 through adopting alternative energy sources with a lower carbon footprint.

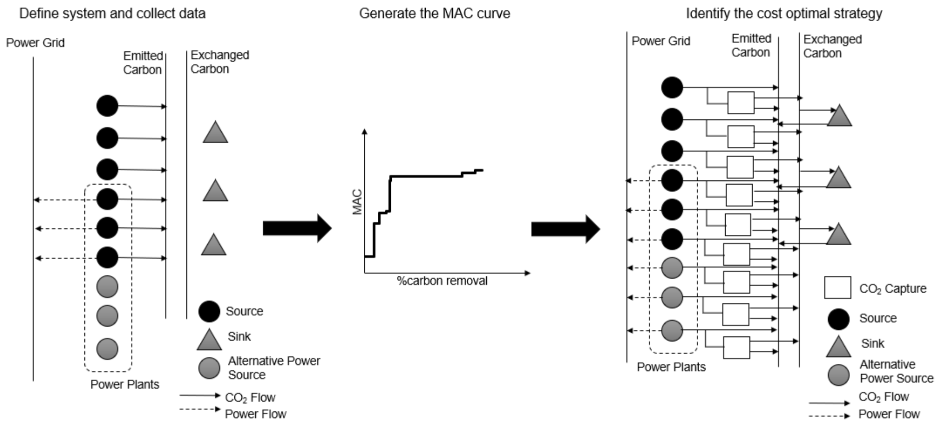

Figure 1: The framework of the approach followed for a single country

The total cost depends on the scale of carbon capture from the sources, carbon utilization in the sinks and the alternative energy options are operated, as well as the costs of these processes. Secondary emissions generated from the energy requirements of carbon capture and compression, fixation inefficiencies of the sinks, and operation of alternative energy sources are considered in calculating the net carbon removal of the proposed system. Carbon capture and compression specific cost (C in \$/tCO_2-captured) and energy requirements (represented in terms of secondary emissions from energy requirements γ in t CO_2-produced / t CO_2-captured) vary between the sources depending on the purity of CO_2 in the emissions streams. Each of the utilization and storage options is defined by the revenue generated from producing value-added products (R in \$/tCO_2-allocated) and net carbon removal efficiency (η in t CO_2-removed / t CO_2-allocated). The MAC of adding a source i and a sink j to the carbon network can be calculated as shown in Eq(1):

$$MAC_{CCUSij} = \frac{C_i - R_j}{\eta_j - \gamma_i} \tag{1}$$

The MAC of implementing alternative energy sources can be calculated as shown in Eq(2) considering the cost of operation (CE_i in \$/kWh) of the already existing power generation technology E_i. The total cost (CA_j in \$/kWh) of implementing the alternative technology E_j, as well carbon emissions of both technologies (ε_i and ε_j in t CO_2/kWh).

$$MAC_{Eij} = \frac{CA_j - CE_i}{\varepsilon_i - \varepsilon_j} \quad (2)$$

MAC was calculated for all possible combinations of sources and sinks as well as alternative energy options under study. The options were arranged in an increasing order of MAC to prioritize the cheapest pathways. The carbon removal limit was determined for each of the options taking into account the availability of carbon captured from each source, CO_2 capacity of each sink, the power generation capacity of each alternative power source, as well as the total power requirements of the country. The capacity of carbon removal from a CCUS option through capturing CO_2 from source i and adding a sink j to the carbon network is equal to the capacity of carbon allocated multiplied $(\eta_j - \gamma_i)$. The capacity of carbon removal through replacing an existing power source E_i by and alternative power source E_j is equal to the minimum power generation capacity between the two sources multiplied by the $(\varepsilon_i - \varepsilon_j)$. The MAC curves for the three countries are constructed according to the presented procedure, and the cost-optimal strategies for given levels of carbon reduction can be identified.

3. Country Cost Profiles

The study investigates the cost of carbon reduction through implementing optimal pathways in different geographic locations: Norway, Qatar, 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 allow the utilization of CO_2 in enhanced oil recovery (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 (Yamaguchi et al., 2011), 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 (GlobalPetrpPrices, 2020). 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 (Salahuddin and Gow, 2019). Power in Qatar is currently generated from natural gas-fired power plants. Japan contributed by around 3 % of the total world CO_2 emissions in 2016 (UCSUSA, 2019), 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.

Table 1: Qatar's emissions sources and the corresponding parameters

Source	CO_2 Produced (10^6 t CO_2/y)	C_i ($/t CO_2)	γ_i (t CO_2-produced/t CO_2-captured)
GTL C U	7.43	2.5	0.04
Natural Gas Processing	2.6	2.5	0.04
Steel	3.47	30.5	0.13
Cement	3.79	32.5	0.27
Fuel Combustion	42.22	36.54	0.1
Power Plant (NG)	18.06	40.17	0.13

Qatar's emissions level from the oil and gas industry were determined based on production rates retrieved from Alfadala and El-Halwagi (2017) and emissions factors from Al-Mohannadi et al. (2017). Emissions data from the steel industry were obtained from QatarSteel (2020), and emission from power generation was obtained from (IEA, 2019). Capture and compression cost data (C_i) were obtained from Al-Mohannadi et al. (2017) 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 et al. (2016).
Emissions rates from the sources in Norway and Japan were obtained from the database of the United Nations Framework Convention on Climate Change (UNFCCC, 2018). 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 be supply energy for the introduced processes. The cumulative contribution of the sources considered to the total emissions of each of the countries is as follows: 85 % for Qatar, 60 % for Norway, and 65 % for Japan.

Table 2: 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	45.6
Refineries	0.84	45.6
Aluminum	1.94	48

Table 3: 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	2.46	4.4	0.04
Steel	5.72	61.4	0.13
Cement and Lime	31.98	63.4	0.27
Power - Coal	211	66.2	0.1
Power - Oil	39	66.2	0.12
Fuel Combustion	286	67.4	0.1
Power - NG	168	71.1	0.13
Refineries	35.8	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. (2017), and their values are: 30 \$/t CO_2 for EOR, 20 \$/t CO_2 for methanol, and -10 \$/t CO_2 for sequestration, and they are 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 50 % of total demand, with the price estimated from EIA (2016). Since Qatar is a major producer of natural gas, the operating cost of the existing power plants was neglected. 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 (Tsukimori, 2015). The operating costs of the existing power plants were assumed to be the prices of imported fossil fuels, which were obtained from Momoko et al. (2017). The capacities for the alternate energy sources were determined from Kato and Kurosawa (2019).

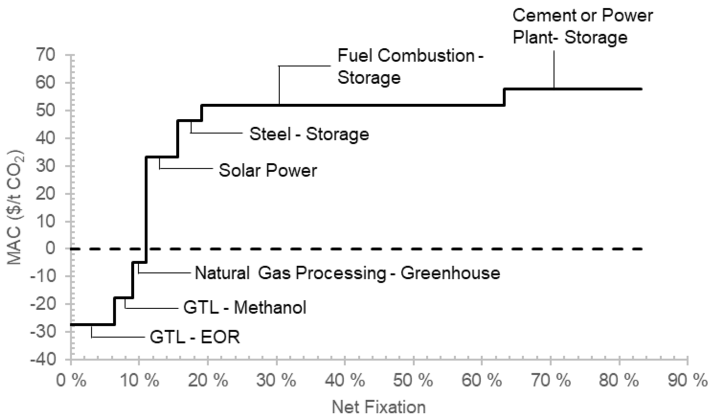

Figure 2: Qatar's abatement cost profile

Figures 2, 3, and 4 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 as a carbon utilization option to reduce emissions by 8 % in Norway. 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 is cheaper than carbon sequestration in Qatar, and it needs to be prioritized directly after the profitable CCU options.

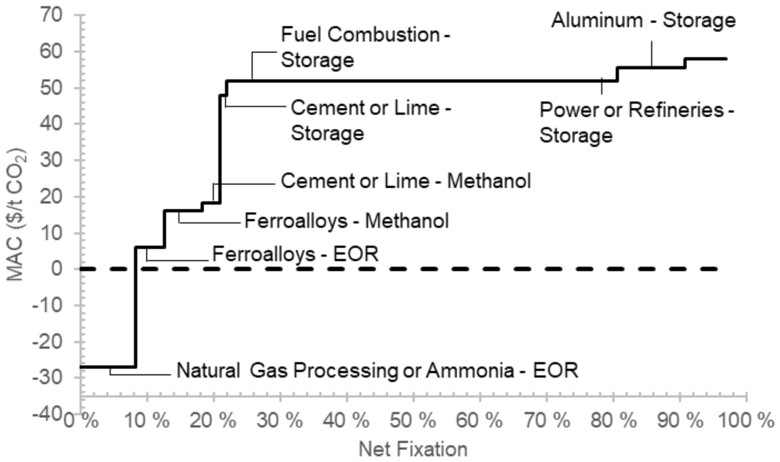

Figure 3: Norway's abatement cost profile

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.

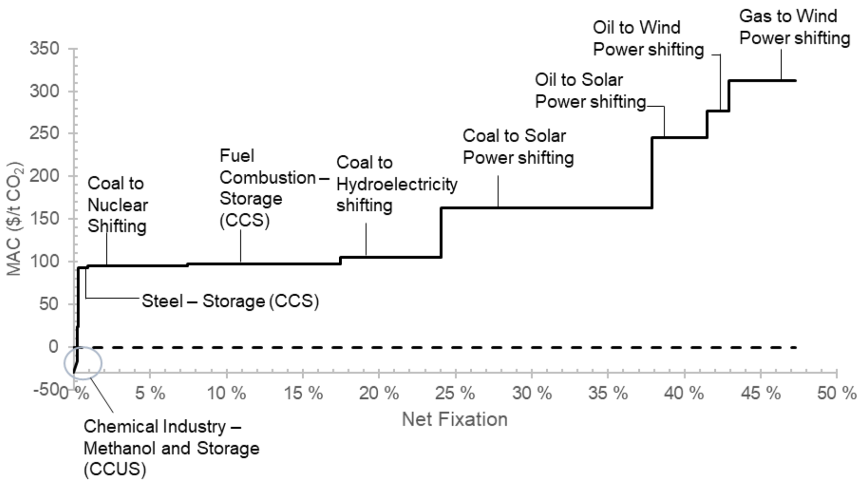

Figure 4: Japan's abatement cost profile

4. Conclusion

Optimal carbon reduction pathways through implementing CCUS and clean energy technologies were investigated for three different geographic regions. The costs and the emissions from carbon capture, utilization, and energy sources were used in constructing MAC curve for the optimal arrangement of the options. The results showed variability between the optimal strategies for carbon reduction as well as the cost and capacity of the investigated options. Adopting carbon utilization in EOR, methanol production, and greenhouses in Qatar can reduce emissions from stationary sources by 11 % while generating 180 × 10^6 \$/y profit. Solar energy application in Qatar is less expensive than CCS. In Norway, utilizing CO_2 in EOR can yield a profit of 53 × 10^6 \$/y while reducing the emissions from point sources by 8 %. Carbon reduction in Japan is more expensive due to the lack of accessibility to cheap energy, which makes it a priority to reduce energy demand.

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