Cost Analysis for CO₂ Reduction Pathways

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It has been widely acknowledged that addressing the issue of climate change should focus on reducing, and ideally eliminating, the influx of CO₂ to the atmosphere. This has led to the emergence of various CO₂-reducing technologies, which differ in their economic and environmental performances. Considering only one side of the problem may be misleading, so this work introduces a novel high-level cost analysis methodology which assesses the different CO₂ reduction options based on CO₂ marginal abatement cost - MAC (an indicator that integrates environmental and economic performances). The study contributes to the existing literature by accounting for the impact of the temporal variations in power demand and renewable energy sources on the MAC of the considered options. The proposed approach is demonstrated through an analysis that explores integrated pathways for CO₂ reduction through CCUS technologies and renewable energy technologies. Energy storage is considered for the intermittent renewable energy options. The results for the different scenarios are combined on a Mini-MAC curve, a recently developed cost analysis tool for planning CO₂ reduction pathways, in which significant insights on the economics of the CO₂ reduction are demonstrated and analyzed.

1. Introduction

Climate change is a major challenge that requires urgent actions towards reducing greenhouse gas emissions to limit the rise in global temperature. This would require reducing the global CO₂ emissions to net zero (IEA, 2021), which in turn requires a wide scale implementation of CO₂ reducing technologies. Different options exist for CO₂ reduction among which renewable energy systems (RES) and CO₂ capture, utilization, and storage (CCUS) are considered as key pillars (IEA, 2021). The performance of such pathways is assessed from the environmental point of view through life cycle assessment analyses - LCAs (Thonemann and Pizzol, 2019) or from a technological/economic perspective through techno-economic analyses - TEAs (Hepburn et al., 2019). It is important to consider both the techno-economic and environmental performances when planning for CO₂ reduction in order to avoid falling in common pitfalls of prioritizing options that perform well in one criterion but fail in another (example: profitable CO₂ utilization pathways that produce more CO₂ as secondary emissions than they utilize). One method of integrating LCAs and TEAs is by considering the marginal abatement cost (MAC) of CO₂ reduction, which is the cost associated with a certain life cycle CO₂ reduction level (Zimmermann et al., 2020). Optimization approaches have been developed to guide a detailed implementation of cost-optimal CO₂ reduction pathways while considering the total cost of a net CO₂ reduction target (Al-Mohannadi et al., 2020). However, it is important to have a higher-level planning perspective to be able to assess and understand the solutions obtained from optimization. To address this gap, Lameh et al. (2021) developed a methodology for assessing and analyzing CO₂ reduction options through developing minimum marginal abatement cost (mini-MAC) curves which represent integrated systems consisting of various CO₂ reduction options. The approach uses high level parameters (costs and secondary emissions) to represent the different options based on their MAC and CO₂ reduction potential. The mini-MAC method assumes linearity of cost with CO₂ reduction for a given option, which may not apply when accounting for the temporal variations of energy supply and demand. The dynamics of the varying renewable energy sources and the fluctuating demand can play a major role in designing energy systems (Limpens et al., 2019). To our knowledge, there is no high-level cost analysis approach that can demonstrate the economic and environmental performances of CO₂ reduction strategies while considering the temporal variations in energy.
supply and demand and the effect of that on the design, sizing, and costs of the integrated system. Hence the contribution of this work is in proposing a high-level method for representing integrated systems while accounting for intermittencies and temporal variations of energy supply, demand, and storage. The proposed method is a two-step approach which identifies the proper sizes of the energy system components and the corresponding costs, considering the availability of resources and the demand. The mini-MAC profile of the integrated system is then developed based on the determined costs. The approach is represented through a case study based on the current situation of CO₂ emissions and energy resources availability in Qatar.

2. Methodology

This work considers the possibility of CO₂ reduction from a set of CO₂-emitting point sources by either implementing renewable energy (RE) options or by capturing and utilizing/storing the emissions. The aim is to understand the CO₂ reduction potential and the costs associated with the different achievable CO₂ reduction levels involving the implementation of the economically efficient pathways. This requires an integration between the environmental and the techno-economic performances of the considered options to determine the cost associated with the resulting CO₂ abatement. The proposed methodology is a two-step approach which starts by the identification of the minimum MAC (mini-MAC) of the different options while accounting for the dynamic variations in the supply of renewable energy, followed by the representation of the efficient options on a combined mini-MAC curve to analyze the performance of the integrated system. Figure 1 defines the scope followed for the considered technologies.

![Flow diagrams showing the scope of the considered (a) RES and (b) CCUS pathways](image)

Figure 1: Flow diagrams showing the scope of the considered (a) RES and (b) CCUS pathways

The first step of the approach is conducting an analysis for the individual options to determine their CO₂ reduction capacity and the MAC. For the renewable energy systems, the cost and the level of CO₂ reduction depend on the sizes of the RE generation and the RE storage units (Figure 1a). The energy security is ensured by assuming that the demand for power is always covered either by the RES (directly through the generated power or indirectly through discharging the stored energy) or by the backup fuel plant. This is done by performing the energy balance on each time step of the considered period, considering the RE generation and storage constraints which depend on the capacities of the RES components. In the case study shown in Section 3, hourly data throughout a typical year for the solar energy supply and for the demand for electricity is input into the method based on which the calculations are performed. The mini-MAC for the RES options corresponding to a certain level of CO₂ reduction is determined by varying the capacities of the RE generation and storage components, calculating their annualized costs, and calculating the power needed from the backup fuel-to-power plant and the corresponding CO₂ emissions. Eq(1) shows definition of the MAC for RES options. The mini-MAC profile is obtained by plotting the MAC against the CO₂ reduction level (Figure 2a).

\[
MAC_{\text{RES}} = \frac{\text{total annualised cost of the energy system}}{\text{flowrate of CO}_2 \text{ before implementing RES} - \text{flowrate of CO}_2 \text{ after implementing RES}}
\]

Considering the CCUS options, the mini-MAC is determined as described in Lameh et al. (2020), depending on the capture cost, the economics of the sink (CO₂ utilization or storage), and the secondary emissions. However, most technoeconomic studies of CO₂ utilization technologies do not consider the raw materials (other than CO₂) as part of the scope, but rather assume a price neglecting the environmental impact of attaining the feedstocks (Zimmermann et al., 2020). H₂ is a major feedstock when it comes to CO₂ utilization, as various processes depend on H₂ and CO₂ (like methanol, synthesized natural gas, Fischer Tropsch fuels, DME…). In this work, green H₂ is assumed to be generated through water electrolysis with the energy supplied from renewable sources (Figure 1b). This pathway is chosen since the aim is to reduce CO₂ through CCUS and green H₂ ensures that this goal is achieved. Hence, the cost of H₂ depends on the sizes of the electrolysis unit, the RE generation unit, and H₂ storage unit. Due to the temporal variations in the renewable
energy sources, the sizing of the different components would depend on the time-based profile of renewable energy generation. The RE generation unit is sized so that H\textsubscript{2} supply to the utilization process, whether directly from the electrolyzer or from the storage, meets the H\textsubscript{2} requirements of the process throughout the operating period. The electrolyzer and the storage units are sized based on the maximum achieved operational loads. The price of H\textsubscript{2} can be determined based on the cost of the components, the price of H\textsubscript{2}O required, and the profits from selling pure O\textsubscript{2}. The economics of the sink process are characterized by the CO\textsubscript{2} breakeven cost which can be calculated as shown in Eq(2). After that, the MAC of the different CCUS options can be determined as presented by Eq(3).

$$CO_2 \text{ breakeven cost} = \frac{\text{profit from selling the product} - \text{cost of utilization process} - \text{cost of } H_2}{\text{flow rate of utilized } CO_2}$$  \tag{2}$$

$$MAC_{CCUS} = \frac{\text{cost of } CO_2 \text{ capture} - \text{CO}_2 \text{ breakeven cost of utilization (or storage)}}{\text{CO}_2 \text{ fixation efficiency in the sink} - \text{secondary } CO_2 \text{ emissions from capture}}$$  \tag{3}$$

Figure 2: Mini-MAC of (a) the RES options, (b) the CCUS options, and (c) the integrated system

The MAC and CO\textsubscript{2} reduction potential of the different CCUS options corresponding to the various combinations between the sources and the sinks are determined as shown by Lameh et al. (2021) (Figure 2b). The second step of this approach is combining the mini-MAC profiles for the CCUS and RES options to analyze the cost and the CO\textsubscript{2} reduction potential of the integrated system (Figure 2c). Knowing the abatement costs of all the options, the different pathways are represented on a mini-MAC curve in increasing cost order to prioritize the cheapest options. CO\textsubscript{2} reduction via CCUS is constrained by the availability of the captured emissions and the capacity of the considered utilization and storage options. CO\textsubscript{2} reduction via RE options is constrained by the capacity of the RE technologies and the power demand. Analyzing the integrated mini-MAC curve allows the identification of the layout of the integrated system with reduced CO\textsubscript{2} emissions (Figure 3).

Figure 3: The integrated system with low CO\textsubscript{2} emissions as determined from the integrated mini-MAC curve

3. Case study

The described methodology is applied to a system consisting of CO\textsubscript{2} emitting sources which data (Table 1) is obtained based on the case of Qatar. The high purity sources include the processes in which CO\textsubscript{2} is captured and emitted in high concentrations, and the corresponding emissions flow rate is based on the operation of GTL and LNG plants (Alfadala and El-Halwagi, 2017). Qatar is a major natural gas (NG) producer, and NG combustion is the main source of energy for industrial heating and power production. The emissions flow rate for the NG combustion is based on the heat requirements of the different industrial plants operating in Qatar. The emissions flow rate from the NG power plant is based on the power demand covered by the existing power plants (Kahramaa, 2018). CO\textsubscript{2} capture costs and secondary emissions are based on Metz et al. (2005), Leeson et al. (2017), and von der Assen et al. (2016). The data for the considered sinks is obtained from
different techno-economic studies for the utilization of CO₂ with H₂ to produce methanol (Pérez-Fortes et al., 2016), synthesized natural gas – SNG (Chauvy et al., 2021), and Fischer Tropsch fuels – FT fuels (Zang et al., 2021). The costs of the processes, the direct and indirect CO₂ emissions, and the CO₂ and H₂ requirements are obtained from the mentioned studies. Solar energy is considered as the RE option where power is generated through photovoltaic (PV) modules. The hourly solar power generation data (kWh/kWp) is determined from the PVGIS model (PVGIS, 2016) assuming 14% losses in the system. The costs of the PV-module, the electrolyzer, and the H₂ storage are determined based on IRENA (2020) and Nordin and Rahman (2019). The sizing of the PV system, the electrolyzer, and the H₂ storage for each of the considered sinks is performed as discussed in section 2, and the CO₂ breakeven costs are determined accordingly (Eq(2)). The costs of enhanced oil recovery (EOR) and CO₂ storage are based on Hepburn et al. (2019) and GCCSI (2011). The data used for the different sinks processes is shown in Table 2.

### Table 1: Data collected for the CO₂ sources

<table>
<thead>
<tr>
<th>Sources</th>
<th>Emissions Flowrate (tCO₂/y)</th>
<th>Capture Cost ($/tCO₂-captured)</th>
<th>Secondary CO₂ (tCO₂/tCO₂-captured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Purity Sources</td>
<td>8.3</td>
<td>4.7</td>
<td>0.06</td>
</tr>
<tr>
<td>NG Combustion</td>
<td>54.1</td>
<td>34.6</td>
<td>0.24</td>
</tr>
<tr>
<td>NG Power Plant</td>
<td>25.4</td>
<td>34.6</td>
<td>0.24</td>
</tr>
<tr>
<td>Cement</td>
<td>2.21</td>
<td>60</td>
<td>0.24</td>
</tr>
</tbody>
</table>

### Table 2: Data collected for CO₂ utilization and storage options

<table>
<thead>
<tr>
<th>Sinks</th>
<th>H₂ Intake (tH₂/tpProduct)</th>
<th>CO₂ Intake (tCO₂/tpProduct)</th>
<th>CO₂ Breakeven Cost ($/tCO₂)</th>
<th>Capacity (tCO₂/y)</th>
<th>Fixation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOR</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
<td>0.75</td>
<td>100 %</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.2</td>
<td>1.46</td>
<td>-380</td>
<td>1.46</td>
<td>91 %</td>
</tr>
<tr>
<td>Methane</td>
<td>0.45</td>
<td>2.41</td>
<td>-852</td>
<td>10</td>
<td>98 %</td>
</tr>
<tr>
<td>FT Fuels</td>
<td>0.635</td>
<td>6.8</td>
<td>-394</td>
<td>6.82</td>
<td>43 %</td>
</tr>
<tr>
<td>Storage</td>
<td>NA</td>
<td>NA</td>
<td>-20</td>
<td>10</td>
<td>100 %</td>
</tr>
</tbody>
</table>

For designing the RES, solar energy is considered through PV modules and lithium-ion battery energy storage system (BESS). The hourly profile of the power load throughout a conventional year is determined based on Kahramaa (2018). The solar power generation is determined from the PVGIS model (PVGIS, 2016) based on the location of Qatar and assuming 14% losses in the system. The capital cost of PV is 715 $/kWp and the operation and maintenance (O&M) costs are assumed to be 10 $/kWp/y (IRENA, 2020). The BESS has a capital cost of 400 $/kWh, an O&M cost of 4 $/kWh/y, and 2,000 full life cycles (Mongird et al., 2020). The first step of the methodology is applied for the collected data to obtain the CO₂ break even costs (Table 2) and the mini-MAC profiles for the different RES and CCUS pathways. Figure 4 shows the separate profiles of the mini-MAC obtained for the RES and CCUS options.

![Figure 4: The minimum marginal abatement cost (mini-MAC) curves for (a) RES and (b) CCUS options](image)

The results show a slight opportunity of profiting from CO₂ reduction through utilization of high purity emissions in EOR. The profitable CO₂ reduction is around 0.71 MtCO₂/y. Such profit can be used to fund the storage of CO₂ from high purity sources resulting in a cost-neutral CO₂ reduction of 1.85 MtCO₂/y. The implementation of PV is competitive compared to CO₂ capture and storage from NG combustion, having similar MAC and CO₂ reduction potential. However, the cost of RES rises when BESS is required to cover further electricity demand. Nonetheless, the RES option remains much cheaper than the expensive utilization options of CO₂ (methanol, SNG, and FT fuels).
The mini-MAC profile of the integrated CO₂ reduction system is shown in Figure 5a. The integrated profile is obtained by combining the MAC and CO₂ reduction potential of both RES and CCUS options, ensuring that the cheapest options are prioritized. Analyzing the profile allows the determination of the cost of CO₂ reduction (Figure 5b) and the design of the system (the capturing sources, the implemented sinks, and the implemented power options) which achieves a set CO₂ reduction target (Figure 6). The results show that up to 19.5% of the considered CO₂ emissions (17.5 MtCO₂/y) can be reduced through implementing solar power from PV (without the need for storage), and allocating CO₂ from high purity sources and natural gas combustion to EOR and storage. Such pathways result in an average CO₂ reduction cost of 45 $/tCO₂. Further CO₂ reduction requires the implementation of more expensive options such as electricity storage and CO₂ utilization to produce chemicals and fuels. Solar energy has the potential of replacing natural gas power through combining PV with BESS. The required capacities of PV and BESS are 34 GWp and 132 GWh. The integrated system with CCUS (considering EOR and storage) can reduce up to 33.8 MtCO₂/y at an average cost of 261 $/tCO₂. The implementation of all the considered options requires full replacement of natural gas power, capturing CO₂ from high purity sources and natural gas combustion, and operating all the sinks at their full capacities. This allows achieving a CO₂ reduction target of 48.3% of the considered emissions at a high average cost reaching 488 $/tCO₂. The high costs associated with the introduction of BESS and CO₂ utilization (methanol, SNG, FT-fuels) are attributed to the high costs of energy storage and H₂ production and storage. Hence, major breakthroughs are required to reduce the costs of these technologies to make the economic reduction of CO₂ possible at reasonable prices.

Figure 5: (a) Integrated mini-MAC profile and (b) the cost of CO₂ reduction

4. Conclusion

This work proposed a novel high-level cost analysis method for CO₂ reduction pathways that is able to account for the effect of the intermittency of the renewable energy sources and the temporal variations in the demand for power on the economic and environmental performances of RES and CCUS options. The method was applied to a case study to demonstrate the significant insights that can be determined. It was shown that for the case of Qatar, solar power and CO₂ capture, utilization in EOR, and sequestration can play a key role in an economic CO₂ reduction. Such pathways can reduce up to 17.5 MtCO₂/y with an average cost of 45 $/tCO₂. Further CO₂ reduction can be achieved by introducing battery storage (up to 33.8 MtCO₂/y) and CO₂ utilization for chemicals production (up to 43.5 MtCO₂/y); however, the average cost of CO₂ reduction would rise significantly to 261 $/tCO₂ and to 488 $/tCO₂. Future work will further analyse the sensitivity of the CO₂ reduction price relative to the expected reductions in costs associated with the improvement of the existing technologies.

Figure 6: Different designs for the CO₂ reduction system corresponding to different levels of CO₂ reduction
References


GCCSI, 2011, The costs of CO2 storage: post-demonstration CCS in the EU, Global CCS Institute, Brussels, Belgium.


Kahramaa, 2018, Kahramaa Annual Statistics Report 2018, Qatar General Electricity and Water Corporation, Doha, Qatar


Leeson D., Mac Dowell N., Shah N., Petit C., Fennell P., 2017, 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, 61, 71-84.


Thonemann N., Pizzol M., 2019, Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry, Energy and Environmental Science, 12(7), 2253-2263.

