Minimum marginal abatement cost curves (Mini-MAC) for CO₂ emissions reduction planning

Mohammad Lameh¹ · Dhabia M. Al-Mohannadi¹ · Patrick Linke¹

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Abstract

The economic impact of CO₂ emissions reduction requirements demands strategic planning to identify low-cost CO₂ mitigation pathways from combinations of the many available CO₂ emissions reduction options. Different tools have been developed to plan minimal cost CO₂ reduction pathways taking into consideration various options such as CO₂ capture, utilization, and sequestration (CCUS), shifting from fossil to renewable energy sources, as well as adopting sector-specific low emissions technologies. Current methods used to support strategic planning include high-level tools that cannot account for many possible options or fail to incorporate cost objective, and complex optimization approaches that are capable of identifying detailed low-cost solutions yet are demanding to use and often yield complex solutions in terms of processing schemes that are not easily understood by strategic planners. To address these limitations, a simple and clear methodology is proposed that allows to determine minimum cost CO₂ reduction pathways from the rich set of available options. The novel methodology employs an algebraic targeting technique that yields minimum marginal abatement cost (Mini-MAC) curves to clearly represent the low-cost CO₂ emissions reduction pathway available. The application of the methodology is illustrated with an example to develop minimum cost emissions reduction pathways considering CCUS, power shifting options, and negative emissions technologies. The benefits of the proposed Mini-MAC curves over alternative methods stem from their richness in terms of assessing CCUS, energy management options, and various integration options. Further, the clarity of the proposed Mini-MAC curves enables planners to easily understand available minimum cost pathways when developing strategies aimed at achieving low-cost CO₂ emissions reduction.

Graphical abstract

Keywords CO₂ mitigation · CO₂ capture · CO₂ utilization · CO₂ sequestration · Renewable energy · Marginal abatement cost · Minimum cost

List of symbols

S	The set of CO ₂ sources
d	The set of CO ₂ sink
E	The set of power generating options
η_{s_i}	CO ₂ capture efficiency at source s_i
F_{s_i}	CO ₂ flowrate allocated by source s_i to the CO ₂ network
F_{c-s_i}	CO ₂ flowrate of the original emissions stream fed into the capture process by source s_i
γ_{s_i}	Energy-related emissions factor for CO ₂ capture from source s_i
η_{d_j}	Net CO ₂ fixation efficiency in sink d_j
$F_{d_j}^{d_j}$	CO ₂ flow received by sink d_j
$F_{\text{fix-}ij}$	Net CO ₂ flowrate fixated through adding source s_i and sink d_j to the network
$C_{s_i}^{d_j}$	The specific cost of supplying CO ₂ emissions source s_i to the sink d_j
$\text{TCF}_{s_i}^{d_j}$	The total cost of supplying CO ₂ emissions source s_i to the sink d_j
R^{d_j}	The specific profit generated from the sink d_j
TP^{d_j}	The total profit generated from the sink d_j
$NC_{s_i}^{d_j}$	The net cost of adding source s_i and sink d_j to the network
$\text{MAC}_{s_i}^{d_j}$	The specific net cost of CO ₂ reduction associated with adding source s_i and sink d_j to the network
$F_{\text{prod-}s_i}$	The flowrate of CO ₂ generated by source s_i
$F_{\text{cap-}d_j}$	The flowrate of CO ₂ processed by the sink at full capacity
$F_{s_i}^{\text{max}}$	The upper limit of the flow that can be supplied by source s_i
$F_{d_j}^{\text{max}}$	The upper limit of the flow that can be processed by sink d_j
F_{max}^{ij}	The upper limit of the flow that can be incorporated in the network through adding source s_i and sink d_j
F_{max}^{ij}	The specific cost of power source E_i
ε_{E_i}	Specific CO ₂ emissions intensity of power source E_i
P^{ij}	The power that can be covered by E_j instead of E_i
$P_{E_i}^{\text{max}}$	The upper limit of the power that can be generated by power source E_i

Introduction

Carbon dioxide (CO₂) is the major greenhouse gas (GHG) constituting about 75% of the total GHG emissions (EPA 2014). Significant CO₂ emissions are produced from energy intensive industries such as power, cement, steel, and chemicals (Bui et al. 2018). In 2015, a total of 195 countries signed the Paris agreement committing to limit the global temperature rise to 2 °C by 2100 (Akerboom et al. 2020). To achieve

this goal, global GHG emissions are required to be reduced by 50–80% by 2050 (Fischelick et al. 2014), which poses a major challenge in light of expected rises in population and demands for energy and materials. Recent estimates suggest that the outlined plans and contributions will not collectively reach these emissions reduction targets (Rogelj et al. 2016). Despite the many commitments made over the past 50 years, the emissions rate has increased by 30×10^6 tCO₂/year (Lia et al. 2020). The failure is attributed mainly to economic and social burdens that prevent the implementation of emissions reduction projects (Foo and Tan 2016). Diverse sets of candidate energy technologies and CO₂ capture, utilization, and storage (CCUS) processes exist that can be implemented to achieve CO₂ reduction targets. The high cost of implementation of many such technologies is a major disincentive for industries and governments to reach the desired levels of emissions mitigation. The costs of stabilizing the emissions by 2030 have been estimated at USD 13×10^{12} , while the costs of shifting from fossil fuels to renewable energy have been estimated at around USD 44×10^{12} (Bullis 2014). Such high costs are beyond the economic carrying capacity of many nations and industries. To reduce these major economic burdens, strategic planning is required to synthesize the lowest cost pathways available to a nation, region, or industry from combinations of available technology options and systems configurations available.

A common tool employed to analyze CO₂ reduction options based on their economics is the marginal abatement cost (MAC) curve (Enkvist et al. 2007), which considers abatement costs and capacities. The curves represent different abatement options with varying specific costs and capacities on a cost vs capacity plot arranged from the most economically viable option to the least. MAC curves enable clear insights in terms of the selection of cost-efficient abatement options that help in prioritizing the investment into available options. In earlier works, such curves were termed conservation supply curves, and their later development for applications in CO₂ reduction strategy development led to the emergence of the term marginal abatement cost (MAC) curves (Ibrahim and Kennedy 2016). MAC is the specific cost associated with a certain level of emissions reduction and characterizes the economics of a CO₂ reduction technology. MAC 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 towards an emissions reduction goal. The curves have been used to support planners, strategy consultants and policy makers in understanding economics of the CO₂ reduction pathways (Ibrahim and Kennedy 2016). Published studies have employed MAC curves to provide global (Enkvist et al. 2007), regional (Luu et al. 2018) and national (Morthorst

1994) insights into economics of CO₂ emissions reduction options. Sector-specific MAC curves have also been developed to compare between CO₂ reduction technologies for major emitting sectors like CO₂ capture (Naims 2016), CO₂ utilization (Hepburn et al. 2019), cement (Hasanbeigi et al. 2010), power, chemicals, and steel (Naucr and Enkvist 2009). These studies used the MAC curves as illustration tools to compare between technologies, and not as planning tool that guides CO₂ reduction. Naims (2016) presented capture cost curves arranging different CO₂ sources based on the required capture cost, while Hepburn et al. (2019) used the curve to represent different CO₂ utilization options based on their economic performance. While the MAC curves developed in such studies provide clear insights into possible low-cost CO₂ reduction pathways, the current method of MAC analysis has significant limitations in terms of its ability to consider system integration options. For instance, CCUS options are typically considered as general, lumped options with no regard to the cost variability between the different emissions sources, capture, utilization, and storage options. Both studies considered one side of the CO₂ supply chain when CCUS is applied, disregarding the actual cost of CO₂ reduction which might be affected by the secondary emissions associated with capture or utilization processes. Hence, current MAC curves are of limited use as an analysis tool that gives quick insights on the optimal solution for carbon reduction planning.

Methodologies for the synthesis and analysis of CO₂ reduction pathways have also been extensively researched in the fields of process systems engineering and process integration (Manan et al. 2017). An important strategy in process integration techniques is to identify maximum achievable targets that can be used to benchmark optimal designs. Optimal designs can then be generated through identifying the possible alternatives and selecting the options that result in achieving the targets (Linnhoff and Eastwood 1988). The objectives can be environmental such as maximizing CO₂ storage and utilization capacity or minimizing CO₂ emissions, or economic by minimizing the cost of CO₂ reduction, or both objectives can be considered in the planning. Targeting is performed through high-level graphical or algebraic pinch analysis tools that provide insights on the optimal achievable goals under the considered constraints (Klemes et al. 2018). The design is performed through mathematical programming approaches that provide integrated systems as optimal solutions. Foo and Tan (2016) reviewed pinch analysis and mathematical programming techniques developed to support CO₂ emissions planning. Tapia et al. (2018) focused on the techniques developed for decision making in CCUS planning. Early applications of Process Integration methodologies go back to the development of pinch analysis for heat integration (Linnhoff et al. 1979). Smith and Delaby (1991)

related the emissions from a single process to the developed energy targets. Dhole and Linnhoff (1993) developed the Total Site Analysis which considers heat integration between different processes. The Total Site targeting was later applied with the objective of CO₂ emissions minimization (Klemes et al. 1997). Tan and Foo (2007) presented Carbon Emissions Pinch Analysis which identifies the minimum number of zero-emissions energy sources required to meet a set level of CO₂ reduction while meeting the demand. Some studies adopted the forementioned techniques to develop targeting methodologies for the CCUS planning problem. Ilyas et al. (2012) proposed a pinch methodology for optimizing CO₂ capture and storage (CCS) for power sector, while considering renewable energy. Diamante et al. (2013) adopted the graphical pinch analysis to optimize source–sink matching in planning CCS implementation. Thengane et al. (2019) applied a pinch-based methodology to maximize the flowrate of captured CO₂ for utilization and storage. Lameh et al. (2020) presented a graphical technique to assess the profitability of CCUS strategies using CO₂ source and sink profiles. The problem of minimizing the cost of CO₂ reduction considering variety of CO₂ reduction options has been addressed only at the design level through optimization models. Turk et al. (1987) proposed an integer programming model for allocating CO₂ to EOR. Weihs and Wiley (2012) explored cost-optimal CO₂ transmission networks. Hasan et al. (2014) developed a mixed integer linear programming model to optimize the cost of large-scale CO₂ supply chain. Al-Mohannadi and Linke (2016) developed an optimization model for planning CO₂ integration considering different CO₂ utilization and storage options. The model was then developed to incorporate multiperiod planning (Al-Mohannadi et al. 2016). Recently, a two-step decomposition approach has been developed (Al-Mohannadi et al. 2020) to avoid the nonlinearity, and the model has been applied to multiperiod planning of CCUS and renewable energy projects. Hassiba et al. (2017) optimized the cost of CO₂ reduction through energy, power, and CO₂ integration. The problem of minimizing the cost of CO₂ reduction has also been considered in planning utilization, monetization, and integration of resources. Al-Mohannadi and Linke (2020) optimized the monetization of natural gas while considering CCUS options and heat integration for CO₂ reduction. Ahmed et al. (2020) minimized the cost of material and energy conversion clusters, while considering CO₂ reduction through CCUS and renewable electricity. The mathematical programming approach requires complicated and time-consuming procedures involving detailed modeling and optimization, which require computational power and may result in equally significant solutions needing further analysis. Having an integrated system as the 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.

The reviewed literature shows that although the MAC curves provide clear insights into CO₂ reduction planning, they lack the ability to consider the integrated system. On the other hand, Process Integration approaches consider the integrated system, but that is done at the design level through optimization. This results in complex solutions that may not allow the complete understanding of the different options and the obtained solutions. Hence, a high-level analysis technique is required which consider the economics of CO₂ integration, while addressing the technical details of the considered processes. Such technique should provide quick insights on the available options to allow a high-level understanding of the system. This work addresses the gap through introducing a two-step analysis approach that systematically identifies cost-efficient CO₂ reduction routes. The method provides quick insights into the economics of CO₂ reduction through screening and evaluating the possible options based on the main techno-economic factors describing the technologies. The first step of the analysis applies an algebraic methodology to screen the CO₂ reduction options and their integration. In the second step, the identified solutions are utilized to construct minimum marginal abatement cost curves (Mini-MAC), which allow the visualization and understanding of the CO₂ reduction planning and the economic impact of the different options. The following section presents the formal problem statement, followed by the detailed description of the proposed methodology. The tool is then applied to a case study in which CO₂ reduction is planned considering CCUS and power shifting options. Significant insights are provided through the analysis of the obtained results.

Problem statement

The approach considers a set of CO₂-emitting sources of known flow and quality, which emissions can be reduced through processing in different CO₂ utilization and storage options, or through avoidance through shifting to cleaner energy sources for example. The proposed method follows an algebraic analysis approach to determine the minimum cost associated with a net CO₂ reduction and the optimal pathways to implement among the existing options.

The formal problem statement can be stated as follows: given is a set of CO₂ sources S ($S = [s_1, s_2, \dots, s_m], m \in \mathbb{N}$), a set of CO₂ processing options (sink) d ($d = [d_1, d_2, \dots, d_n], n \in \mathbb{N}$), and a set of power generation options E ($E = [E_1, E_2, \dots, E_p], p \in \mathbb{N}$) including existing and alternative power options. The algorithm should determine which sources to capture from, which sinks to implement, which power

options to phase out and which power options to introduce with the objective of minimizing the total cost while meeting a set CO₂ emissions reduction target. The economic impact of CO₂ mitigation can then be investigated based on the available options.

Different economic and technical parameters characterizing the various processes considered are required to be able to solve the problem. The parameters required to understand the system are costs, revenues, emissions flowrates, efficiencies and capacities. These would allow the determination of the cost considered per CO₂ reduced for the different possible available options and the CO₂ reduction capacities. The results of the algebraic technique are then used to construct the minimum marginal abatement cost curves (Mini-MAC), illustrating the major parameters of cost-efficient emissions mitigation planning: the cost and the capacity of the different options.

Algebraic targeting method

The methodology is first developed to address the problem of emissions mitigation through CCUS pathways. The described technique is an analysis algorithm which allows the identification of optimal carbon network design with minimum cost for the given sets of the existing CO₂ stationary sources and the possible CO₂ utilization and sequestration options. The method can determine the optimal cost for a set level of CO₂ reduction, or the maximum CO₂ reduction level for a set cost. The general methodology followed starts by identifying different technical and economic parameters for the implemented technologies (capture, utilization, and storage technologies). The data are used in the developed algorithm to rank the pathways from cheapest to most expensive, and to identify the corresponding costs and CO₂ reduction capacities. An updated MAC curve can then be constructed from the obtained results, with each CCUS option represented as a source–sink pair accounting for the entire supply chain of the carbon network. Constructing the MAC curve allows the incorporation of further CO₂ reduction technologies into the solution, giving a holistic view on cost-efficient pathways for CO₂ reduction.

CO₂ leakage from the carbon network

The produced CO₂ stream from a source requires processing so that it can be utilized or stored in a corresponding sink. Secondary CO₂ emissions can be generated from processing the captured CO₂ streams due to inefficiencies and power requirements. It is important to consider the CO₂ leakage from the system in order to calculate the net CO₂ reduced. To quantify the CO₂ secondary emissions generated after

the implementation of CCUS, the following parameters are defined as follows:

- The CO₂ capture efficiency at source (η_{s_i}): the fraction of the allocated CO₂ flowrate from the source (F_{s_i}) to the carbon network over the CO₂ flow of the original emissions stream fed into the capture process F_{c-s_i} ($\eta_{s_i} = F_{s_i} / F_{c-s_i}$). η_{s_i} depends on the capture process technology implemented.
- The energy-related emissions factor (γ_{s_i}): the fraction of the flowrate of the secondary emissions associated with the power and energy requirements for processing the source's stream (capture, compression, and heating/cooling) to the flowrate of the captured and allocated CO₂ (F_{s_i}). γ_{s_i} depends on the energy intensity of the capture process and on the source of the energy.
- The net CO₂ fixation efficiency in the sink η_{d_j} : the fraction of the CO₂ flow received by a sink (F^{d_j}) that is fixated either by sequestration or by fixation in a product. η_{d_j} accounts for the CO₂ leakage from the sink's process as well as the emissions associated with its power requirements.

Both η_{s_i} and γ_{s_i} are demonstrated on the flow diagram of CO₂ capture and processing from the source's side shown in Fig. 1.

Sink's efficiency η_{d_j} is demonstrated on the flow diagram of CO₂ processing in the sink presented in Fig. 2.

CCUS network refers to the system composed of the different CO₂ sources and sinks, and the CO₂ exchanged between them. Creating or expanding the carbon network is done by increasing both the supply and demand of CO₂ flow throughout the network. The supply is expanded through increasing the supply flowrate (F_{s_i}) of an existing source or through adding other sources. To match the increase in

Fig. 2 Flow diagram of CO₂ processing in the sink

supply and to avoid accumulation, demand is increased either through expanding the capacity (F_{d_j}) of an already existing sink or through adding another sink. The flow diagram of incorporating a source s_i and a sink d_j exchanging CO₂ at flowrate F^{ij} is shown in Fig. 3.

The net flowrate of the CO₂ fixated through expanding the CCUS network by adding a source s_i and a sink d_j becomes: $F_{fix-ij} = (\eta_{d_j} - \gamma_{s_i}) F^{ij}$. This accounts for the difference between the total flowrate fixated in the sink and the flowrate of the secondary emissions caused by processing on the supply side. The total reduction in CO₂ emissions from implementing the carbon network can be calculated by summing up all the fixated flows from the implemented source–sink couples.

Marginal abatement cost

The marginal abatement cost is the cost associated with a certain level of CO₂ reduction. It characterizes all CO₂ reduction pathways and allows a direct comparison between the options based on their economics relative to their

Fig. 1 Flow diagram of CO₂ emissions processing from the source's side

Fig. 3 Flow diagram of the carbon network expansion

environmental impact. As mentioned earlier, the method proposed identifies the layout of the minimum cost CO₂ network for a certain level of CO₂ reduction. The network is composed of different connections between the existing sources and the available sinks, and each of these possible connections is considered as an option for establishing or expanding the network. Each of these options can be identified by the corresponding marginal abatement cost.

The considered options are composed of CO₂ supply component and CO₂ demand component, and the economics on both sides of the CO₂ supply chain need to be considered in calculating the MAC. Let $C_{s_i}^{d_j}$ be the specific cost (relative to the allocated CO₂, i.e., in USD/tCO₂-allocated) required for supplying the CO₂ emissions stream from the source s_i to the sink d_j at the required specifications for processing in the sink. The supply cost includes the annualized capital and operating costs of carbon capture, compression, and transportation (piping). These costs depend on the properties of the emissions stream from the source (composition, pressure, temperature), and the requirements of sink to be able to process the exchanged CO₂. The costs can be determined through performing techno-economic analysis, which is not included in this study. Such studies have been extensively conducted throughout literature (Metz et al. 2005). The describe method uses such predetermined costs. The specific cost of carbon supply is considered as an input to the proposed methodology. The total cashflow $TCF_{s_i}^{d_j}$ required for supplying CO₂ can then be determined: $TCF_{s_i}^{d_j} = F^{ij} \times C_{s_i}^{d_j}$.

The sinks take the CO₂ stream at the set specifications as a feedstock which is either stored or utilized to produce products with added value. The production of such products can be profitable, resulting in a net profit which depends on the process implemented. The specific profit generated from the sink d_j (R^{d_j}) for processing the allocated CO₂ is used to characterize the economics of the CO₂ demand component

in the carbon network. It can also be determined from an economic analysis on the process implemented, but it will be considered as an input to the proposed methodology. The total profit flow TP^{d_j} generated from processing CO₂ in the sink can be described as follows: $TP^{d_j} = F^{ij} \times R^{d_j}$. Note that R^{d_j} can be negative indicating that the process implemented in the sink is not profitable (like storage), and the cost is equal to the absolute value of R^{d_j} .

The profit generated from CO₂ utilization in the sink can offset the costs required for carbon supply. Hence, the net cost ($NC_{s_i}^{d_j}$) of adding a source s_i with a sink d_j into the carbon network is the difference between the total cost of carbon supply ($TCF_{s_i}^{d_j}$) and the total profit from the sink (TP^{d_j}): $NC_{s_i}^{d_j} = F^{ij} \times (C_{s_i}^{d_j} - R^{d_j})$. The marginal abatement cost can then be determined for each of the considered options of source–sink pairs by dividing the net cost by the net flowrate of reduced CO₂:

$$MAC_{s_i}^{d_j} = \frac{F^{ij} \times (C_{s_i}^{d_j} - R^{d_j})}{F^{ij} \times (\eta_{d_j} - \gamma_{s_i})} = \frac{C_{s_i}^{d_j} - R^{d_j}}{\eta_{d_j} - \gamma_{s_i}} \quad (1)$$

Targeting algorithm

The MAC of a source–sink couple depends on both the source and the sink; hence, it is important to take both simultaneously in the arrangement as mentioned earlier. Figure 4 illustrates the steps followed in the proposed method.

The introduced 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 MAC. Such analysis will make the solution comparable with other carbon reduction

Fig. 4 Flowchart of the algebraic methodology for planning the carbon network

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.

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 Sect. 3.2.

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 options. The flowrates of CO₂ available for allocation from the sources F_{s_i} and the capacities of the sinks F_{d_j} are determined. The CO₂ flowrates available by the sources are limited by the flowrate of the emissions produced and the capture

efficiency of the applied technology ($F_{s_i}^{\max} = F_{\text{prod-}s_i} \times \eta_{s_i}$). The maximum flowrate that can be allocated to the sink is limited by technical, economic, and social factors that set the capacity of the potential sink ($F_{d_j}^{\max} = F_{\text{cap-}d_j}$).

The exchanged CO₂ flowrate is determined 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.

$$F_{\max}^{ij} = \arg \min \left(F_{s_i}^{\max}, F_{d_j}^{\max} \right) \quad (2)$$

The allocation capacity of the first pair is equal to the minimum between the capturable CO₂ 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 exchanged 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 other sources and sinks (excluded from the pair at the current iteration) are not changed. The following equations summarize the updates performed for the availability and capacity of the flows for the source and the sink.

$$F_{s_i}^{\max} = F_{s_i}^{\max} - F_{\max}^{ij} \quad (3)$$

$$F_{d_j}^{\max} = F_{d_j}^{\max} - F_{\max}^{ij} \quad (4)$$

The iteration ends by updating the maximum flowrates. It is repeated for the remaining source–sink pairs until either the sources allocate all the possible CO₂ available or until all the sinks reach maximum capacity. The result is a carbon network designed based on prioritizing the source–sink pairs with the least carbon removal cost. All the flowrates of the exchanged CO₂ streams ($F^{ij} \forall i, j$) are determined, and they are used in calculating the resulting CO₂ reduction and the net cost required for each option according to definitions present in Sects. 3.1 and 3.2.

Constructing the Mini-MAC curves and developing the target

The Mini-MAC curve can be constructed from the results of the calculations presented previously, considering CCUS planning as a two-sided problem. For each of the considered source–sink pairs, $F_{\max}^{ij}$ correspond to the capacity of the CO₂ stream that can be exchanged, from which the capacity of CO₂ reduction $F_{\text{fix-}ij}^{\max}$ can be determined. Hence, each option can be represented as a segment on the MAC versus F_{fix} plot as shown in Fig. 5. Note that the area under the plot representing the source–sink pair is the net cost required for introducing the corresponding source and sink into the carbon network ($NC_{s_i}^{d_j} = F_{\text{fix-}ij} \times MAC_{s_i}^{d_j}$). Note that for some options, the profit generated from the sink exceeds the cost required for capturing the CO₂ stream from the source. This would result in a negative MAC and a negative NC indicating that such option is profitable, and it will be accompanied by net profit.

For the set of options which is determined from the described algorithm (Sect. 3.3), each option is represented as shown previously, and they are arranged in increasing order of MAC. Figure 6 shows a representation of the Mini-MAC curve with multiple CCUS options of

Fig. 5 The representation of a CCUS option on the Mini-MAC curve

Fig. 6 The representation of the different CCUS options on the Mini-MAC curve

source–sink pairs. The cumulative net cost corresponding to a set CO₂ reduction target is the summation of the net costs of all the connections represented by the segments to the left of the target. It is the total area under the plot. The plot is split into two regions: profitable CO₂ reduction and a non-profitable CO₂ reduction. In case there are profitable options from CO₂ reduction through CCUS, the maximum profit that can be implemented is equal to the area between the segments and the F_{fix} -axis in the profitable region. The corresponding CO₂ reduction is equal

to the flowrate at the point separating the profitable and non-profitable regions.

Incorporating other CO₂ reduction options into the planning

The MAC is a common property that can characterize all CO₂ reduction pathways. Developing the Mini-MAC curve for the different CCUS options allows the comparison between CCUS and other carbon reduction technologies. Consequently, the described tool can be used for a holistic planning for cost-optimal CO₂ reduction strategies.

Every CO₂ reduction option has a fixation capacity and a specific MAC. Both these properties can be used to represent the option on the Mini-MAC curve as shown for the CCUS option in Fig. 5. The developed algorithm can be used to plan the implementation of options where the capacities are dependent on each other (like in the presented case of CCUS). This issue may apply to planning power shifting from CO₂-emitting power sources to power sources with less CO₂ emissions. In this case, the same algorithm can be applied through identifying the different options and their corresponding MAC, arranging them, and determining the capacities under the limits of power generation constraint rather than the source–sink capacity constraint. The formal problem statement can be represented as follows: for a set of existing CO₂-emitting power

operating and capital costs C_{E_j} (USD/kWh) and has specific emissions ε_{E_j} (tCO₂/kWh) such that $\varepsilon_{E_j} < \varepsilon_{E_i}$. P^{ij} is the power that can be covered by E_j instead of E_i . The described systems can be shown in Fig. 7. Examples of such options can be coal to gas shifting, oil to gas, fossils to renewables...

Comparing the costs and the flowrate of CO₂ emissions between the two systems, the formulas for the MAC and for the fixated CO₂ flowrate can be determined as follows:

$$\text{MAC}_{E_i}^{E_j} = \frac{C_{E_j} - C_{E_i}}{\varepsilon_{E_i} - \varepsilon_{E_j}} \quad (5)$$

$$F_{\text{fix-}ij} = (\varepsilon_{E_i} - \varepsilon_{E_j}) \times P^{ij} \quad (6)$$

After calculating the MAC for all possible shifting options, the algorithm shown previously can be applied, starting by arranging the options in increasing order of MAC and determining the power shifting capacity for each option. Each option considers a pair of power sources: existing and potential. The existing power source E_i generates power P_{E_i} which is the maximum power that can be replaced ($P_{E_i}^{\text{max}} = P_{E_i}$). The potential power source may have a cap on the power generation due to geographic, technical, economic, or social factors. Let P^{Ej} be the maximum power that can be generated by a potential power source E_j , hence: $P_{E_j}^{\text{max}} = P^{Ej}$.

Fig. 7 Power shifting option from a polluting power source to power source with less emissions

sources and a set of potential power sources with less CO₂ emissions, there is a need to identify which of the existing sources to phase out and which of the potential sources to implement so that a determined CO₂ reduction target is achieved at minimum cost.

The MAC of a power shifting option can be determined as follows.

Consider an existing power source E_i which requires operating cost C_{E_i} (USD/kWh) and has specific emissions ε_{E_i} (tCO₂/kWh). A fraction of the power generated by E_i can be replaced by a potential power source E_j which requires

The iterations start with the first power shifting option to choose the corresponding power P^{ij} allocated for each pair. Similar to the CCUS planning, the aim is to maximize the power shifting in the cheapest options. The maximum power P_{max}^{ij} that is generated by the existing source E_i and can be alternatively produced by the potential source E_j is equal to the minimum between what E_i is producing and what E_j can produce: $P_{\text{max}}^{ij} = \arg \min (P_{E_i}^{\text{max}}, P_{E_j}^{\text{max}})$.

After determining the power shift in each pair, the remaining power produced by E_i and the remaining capacity of E_j are updated.

$$P_{E_i}^{\max} = P_{E_i}^{\max} - P_{\max}^{ij} \quad (7)$$

$$F_{E_j}^{\max} = F_{E_j}^{\max} - F_{\max}^{ij} \quad (8)$$

This procedure is repeated for all iterations until either the total power generated from all the existing sources is covered by the alternative options or when all the alternative options supply power at their full capacities. After determining the power coverage by each of the options, the corresponding reduced CO₂ flowrate can be determined, and each of the considered options can be represented on the MAC curve. Note that the existing power sources are considered in both the CCUS options and the power shifting options, and their capacities are affected by the implementation of carbon capture as well as the less polluting energy options. Hence, it is important to consider all the options simultaneously when determining the capacities and applying the algorithm accordingly.

Illustrative examples

The presented method is applied to a system consisting of different CO₂ stationary sources. Different CO₂ sinks are considered as pathways for implementing CCUS as the CO₂ reduction technology. The scope is then extended to include shifting from the existing power sources to alternative power options with less CO₂ emissions. Finally, negative emissions technologies (NETs) are incorporated in the demonstration through considering direct air CO₂ capture and storage (DACCS), afforestation, and bioenergy with CO₂ capture and storage (BECCS).

Example 1: CCUS planning

The considered sources include: an ammonia plant, a steel plant, a coal-fired power plant, a natural gas fired power plant, and natural gas fired industrial heating. Tables 1 and 2 summarize the data collected for the considered sources and sinks. CO₂ capture is assumed to take place through an amine absorption unit with a capture efficiency $\eta_s = 90\%$.

The CO₂ stream from the ammonia is pure and does not require capture. The CO₂ supply costs for the different CO₂ sources are obtained based on Naims (2016), Al-Mohannadi and Linke (2016), and Al-Mohannadi et al. (2017). The supply cost includes the cost of capture, compression, and transportation. The energy-related emissions are obtained from Von der Assen et al. (2016), and they include the emissions associated with supplying energy to the capture and compression. Each power plant generates 500 MW of electricity, and their total level of emissions are calculated accordingly, assuming 39% efficiency of the coal power plant and 52% efficiency for the natural gas power plant (EIA 2016). The considered set of sources produce 13.14×10^6 tCO₂/y out of which 11.9×10^6 tCO₂/y can be captured.

The sinks considered in this example as the utilization and sequestration options include enhanced oil recovery (EOR), methanol production through dry reforming coupled with solar-powered electrolysis (MEOH), Greenhouse, and underground CO₂ sequestration. The profits generated from the sink options as well as their efficiencies are determined from Al-Mohannadi et al. (2017). All sinks require pure CO₂ streams supplied through CO₂ capture. The economic parameters considered for the sources and the sinks are the annualized capital costs, the operating costs, and the generated profits. The annualization assumes 8760 operating hours per year with a lifetime of 20 years.

All possible combinations between the considered sources and sinks are determined, leading to 20 different options as pathways for CO₂ reduction through CCUS. The different options are present in Table 3, along with the

Table 2 Data collected for sinks

Sink	Capacity F_d (10 ⁶ tCO ₂ /y)	Profit generated R_d (USD/tCO ₂)	Fixation efficiency η_d (tCO ₂ -reduced/tCO ₂ -allocated)
EOR	2	30	1
MEOH	1	20	0.99
Greenhouse	1	5	0.5
Storage	7	− 10	1

Table 1 Data collected of the sources

Source	CO ₂ emissions F_{prod} (10 ⁶ tCO ₂ /y)	CO ₂ available for allocation F_s (10 ⁶ tCO ₂ /y)	CO ₂ Supply cost C_s (USD/tCO ₂)	Energy-related emissions γ_s (tCO ₂ -emitted/tCO ₂ -captured)
Ammonia	1.00	1.00	3	0.00
Steel	1.30	1.17	32	0.13
Power plant (coal)	4.14	3.73	38	0.27
Industrial combustion	5.00	4.50	46	0.10
Power plant (NG)—1 GW	1.69	1.52	46	0.13

results obtained from applying the algorithm described in Sect. 3.3 to the collected data.

The arrangement of the source–sink options indicates that minimizing the net cost of CO₂ reduction through the CO₂ integration network should consider both the source and the sink simultaneously. Consider the greenhouse and storage sink options from the demonstrated example. When coupled with a source that has low supply cost such as ammonia, greenhouse is a more profitable option than storage ($MAC_{ammonia}^{greenhouse} = -\text{USD}4/\text{tCO}_2$ while $MAC_{ammonia}^{storage} = \text{USD}13/\text{tCO}_2$). However, when the source requires higher supply cost (e.g., steel), then coupling it with greenhouse results in a higher cost than coupling it with storage ($MAC_{steel}^{greenhouse} = \text{USD}72/\text{tCO}_2$ while $MAC_{steel}^{storage} = \text{USD}31/\text{tCO}_2$). That is due to the dependence of the MAC on both the economic and environmental characteristics of the sources and the sinks. The priority is given to the sources with low supply cost and low secondary emissions factor, and to sinks with high profits and high fixation efficiencies. If the economic and the environmental factors contradict, as in the case for greenhouse and storage (greenhouse generate more profit but it is less efficient than storage), then the decision depends on the net cost ($C_{s_i}^{d_j} - R^{d_j}$) and fixation efficiency ($\eta_{d_j} - \gamma_{s_i}$) of the source–sink couple. The expensive options (high $C_{s_i}^{d_j}$ or low R^{d_j}) are then prioritized over cheaper ones only if they

have much higher removal efficiency to justify the higher investment.

The maximum CO₂ flowrate that can be allocated in the CO₂ network through adding a source and a sink is determined based on the described algorithm (Sect. 3.3), being constrained by the emissions availability from the source and the capacity of the sink. The null values of the flowrates in Table 3 indicate that either the source has allocated all its emissions, or the sink has reached its capacity from participating in more profitable options prioritized by the algorithm. The net reduced flowrate from incorporating the source–sink pair into the CO₂ integration network and the corresponding net cost are calculated as shown previously (Sects. 3.1, 3.2) depending on the allocated flowrate, the environmental factors (efficiency and secondary emissions), and the MAC.

The MAC and the net reduced CO₂ flowrate F_{net} can be used to construct the Mini-MAC curve as described in Sect. 3.4. The Mini-MAC curve corresponding to the described system is shown in Fig. 8. The profile shows the optimal pathways for generating a CO₂ integration network leading to a reduction of up to $9.3 \times 10^6 \text{ tCO}_2/\text{y}$ (around 71% of the total generated emissions). The profiles show that for the considered system of sources and sinks, greenhouse is the least favorable sink option, although it is a profitable utilization pathway. This is due to its low fixation efficiency as mentioned earlier. Such analysis verifies the findings of the optimization models developed by Al-Mohannadi and

Table 3 Results generated from applying the algorithm to the system considering only the CCUS options

Source	– Sink	MAC (USD/tCO ₂)	$F_{ij-\text{max}}$ (10 ⁶ tCO ₂ /y)	F_{net} (10 ⁶ tCO ₂ /y)	NC (USD 10 ⁶ /y)
EOR	– Ammonia	– 27.00	1.00	1.00	– 27.00
MEOH	– Ammonia	– 17.17	0.00	0.00	0.00
Greenhouse	– Ammonia	– 4.00	0.00	0.00	0.00
EOR	– Steel	2.29	1.00	0.87	2.00
EOR	– Power plant (coal)	8.90	0.00	0.00	0.00
Storage	– Ammonia	13.00	0.00	0.00	0.00
MEOH	– Steel	13.87	0.17	0.15	2.04
EOR	– Industrial combustion	18.46	0.00	0.00	0.00
EOR	– Power plant (NG)	18.46	0.00	0.00	0.00
MEOH	– Power plant (coal)	20.26	0.83	0.74	14.94
MEOH	– Industrial combustion	30.34	0.00	0.00	0.00
MEOH	– Power plant (NG)	30.34	0.00	0.00	0.00
Storage	– Steel	31	0.00	0.00	0.00
Storage	– Power plant (coal)	53.42	2.90	2.61	139.21
Storage	– Industrial Combustion	64.60	4.10	3.55	229.59
Storage	– Power plant (NG)	64.60	0.00	0.00	0.00
Greenhouse	– Steel	72.01	0.00	0.00	0.00
Greenhouse	– Power plant (coal)	82.80	0.00	0.00	0.00
Greenhouse	– Industrial combustion	111.74	0.40	0.15	16.41
Greenhouse	– Power plant (NG)	111.74	0.60	0.22	24.59

Linke (2016) and Al-Mohannadi et al. (2017) where the optimization did not activate the sinks with lowest efficiencies even though they were more profitable than other considered sinks.

The analysis shows that there is a profitable opportunity for reducing CO₂ from the ammonia plant through the implementation of EOR. In this scenario, no capture costs are required as the ammonia process provides a high-purity CO₂ stream, and the cost of supply is attributed to the piping and compression which can reach up to USD 3×10^6 /y depending on the amount of CO₂ allocated. This allocation can lead to a reduction of up to 1×10^6 tCO₂/y, generating profits up to USD 27×10^6 /y in profits. Any further reduction would require capturing CO₂ from other sources and adding less profitable sinks (than EOR) to the network. This would increase the net cost of CO₂ reduction resulting in options where the capture cost outweighs the profits generated by the sinks. Beyond CO₂ reduction of 1×10^6 tCO₂/y, the net cost of the network starts increasing, reaching USD 0/y at CO₂ abatement flowrate of 2.91×10^6 tCO₂/y. This means that up to 22% of the emitted CO₂ from the considered sources can be reduced through CCUS without the need for external cashflow to cover the costs. Implementing all the available options to reduce 71% of the total emissions requires a cumulative net cost of USD 402×10^6 /y, with an average cost of USD 43.2/tCO₂.

Example 2: CCUS and energy mix planning

The scope of the problem considered in Example 1 is expanded to include energy shifting options besides the

Fig. 8 Mini-MAC curve considering only the CCUS options

Table 4 Data collected for existing power sources

Existing energy sources	Power rating (MW)	Total operating cost C_{Ei} (USD/MWh)	Emissions ϵ_{Ei} (tCO ₂ /MWh)
Coal power plant	500	9.41	0.95
Gas power plant	500	4.76	0.39

considered sinks as CO₂ reduction pathways. The same system of sources and sinks is considered, alongside the renewable energy options: solar power and wind power. An option of fuel shifting from coal to natural gas is considered as well. Tables 4 and 5 summarize the data required for the existing power sources and the alternative power options. The operating and capital costs of the different energy sources are based on the values reported by EIA (2016). The emissions factors are based on EIA (2020), taking into consideration the efficiencies of the gas and coal power plants (52% and 39%, respectively) mentioned in Example 1. The power capacities of the alternative power options are based on typical values of such plants (EIA 2016). The capacities of the renewable energy options are governed by technical, geographical, and social factors such as land availability and weather conditions. The capital costs are considered only for the alternative power options, and they are annualized assuming 8760 operating h/y over 20 years. The operating costs include the fixed costs (fuel, labor...) and maintenance.

The considered alternative energy sources would generate five different options for CO₂ reduction through energy shifting. Table 6 shows the different options and the corresponding MACs. The data indicate that shifting to alternative energy options is cheaper than capturing the emissions from the power plants. According to the profile presented in Fig. 8, the optimal planning of the CO₂ integration network couples the coal power plant with MEOH and storage with MAC between USD 20/tCO₂ and USD 50/tCO₂. The natural gas power plant is coupled with storage at a price of USD 65/tCO₂. Hence, the costs of the different power shifting options are less than those for the CCUS options involving the power sources.

Another insight indicated by data present in Table 6 is the prioritization given to phasing out coal-fired power generation. This is expected due to the high emissions intensity of the considered coal power plant. For a given investment cost needed for the implementation of renewable energy options

Table 5 Data collected for the alternative power options

Alternative energy	Power capacity (MW)	Total cost C_{Ej} (USD/MWh)	Emissions ϵ_{Ej} (tCO ₂ /MWh)
Solar	300	16.95	0
Wind	150	15.25	0
Gas	500	11.06	0.39

at a given scale, higher CO₂ flowrate would be reduced when phasing out the coal relative to that when phasing natural gas. This have led to a lower MAC for energy shifting from coal which explains the prioritization.

The algorithm is applied to the holistic problem considering all the possible CO₂ reduction pathways described in Examples 1 and 2. The generated results with the nonzero flows/allocation are shown in Table 7. The results show that for the described system, the costs of the various CCUS options are between—USD 27/tCO₂ and USD 64.6/tCO₂ and those for the power shifting options are between USD 2.95/tCO₂ and USD 31.58/tCO₂. This means that choosing the cost-efficient pathway should consider both CCUS and power shifting options, depending on the reduction target. Note that the maximum allocated flowrate for the CCUS options is determined based on the described algorithm (Sect. 3.3), with the flow availability from the power plants updated considering the power shifting options as well. For example, fuel switching from coal to gas would lead to a decrease in the flow available from the coal combustion and to an increase in the flow available from the gas combustion depending on the power rating. The same idea applies for switching from natural gas or coal to renewable energy options where the emissions generated from the fuel fired

power plants drop, which means that the maximum CO₂ flowrate that can be allocated in the CCUS network from the power sources decreases.

The net reduced CO₂ flowrate and the net cost for each option are calculated as shown in Sects. 3.1 and 3.5. The Mini-MAC curve is then constructed and represented in Fig. 9. The confirms that the CCUS and power shifting options contribute to the cost-efficient solution depending on the CO₂ reduction target. For a reduction target below 1.88 MtCO₂/y (14% of the considered emissions), CO₂ should be captured from ammonia and steel, and allocated to EOR. Beyond that, and up to CO₂ reduction of 6.71 MtCO₂/y (51% of the considered emissions), a mix between CCUS and power shifting should be implemented. This solution corresponds to implementing CO₂ capture from ammonia, steel, and industrial combustion, and adding methanol production to EOR as the utilization options. Moreover, complete replacement for coal and partial replacement for natural gas through introducing renewable energy sources need to be implemented. Beyond the 51% reduction, the CCUS network to be expanded through capturing the remaining emissions and introducing storage. The updated profile has the same profitability margin as the one developed in Example 1, since none of the energy shifting options is profitable. However, introducing the energy shifting options increase the margin of zero-cost CO₂ reduction from 2.91×10^6 tCO₂/y to 5.04×10^6 tCO₂/y. The rise in zero-cost CO₂ reduction flowrate is because shifting from coal to gas is cheaper some CCUS options included in the zero-cost CO₂ reduction target in Example 1 (MEOH-Steel and MEOH-Power Plant (coal)). Introducing the power shifting options to the solution increases the CO₂ reduction capacity from 9.3×10^6 tCO₂/y to 11.3×10^6 tCO₂/y, since the emissions can be fixated without the need of the greenhouse sink option with low efficiency and high MAC. Since the power

Table 6 The MAC of the possible energy shifting options

Energy shifting option		Alternative energy	MAC (USD/tCO ₂)
Coal power plant	to	Gas	2.95
Coal power plant	to	Wind	6.17
Coal power plant	to	Solar	7.97
Gas power plant	to	Wind	27.16
Gas power plant	to	Solar	31.58

Table 7 The solution of the algorithm applied to the holistic problem

Sink/energy	Source	MAC (USD/tCO ₂)	$F_{ij-\max}$ (10 ⁶ tCO ₂ /y)/ $P_{ij-\max}$ (GWh/y)	F_{net} (10 ⁶ tCO ₂ /y)	NC (USD 10 ⁶ /y)
EOR	Ammonia	– 27.00	1.00	1.00	– 27.00
EOR	Steel	2.29	1.00	0.87	2.00
Gas*	Power plant (Coal)	2.95	4.38**	2.45	7.23
MEOH	Steel	13.87	0.17	0.15	2.04
Wind*	Power plant (NG)	27.16	1.314**	0.51	13.78
MEOH	Industrial combustion	30.34	0.83	0.71	21.58
Solar*	Power plant (NG)	31.58	2.628**	1.01	32.05
Storage	Industrial combustion	64.60	3.67	3.18	205.52
Storage	Power plant (NG)	64.60	1.67	1.45	93.78

*Power shifting CO₂ reduction options

**Power $P_{ij-\max}$ (GWh/y)

Fig. 9 Mini-MAC curve generated for the holistic problem

shifting options are cheaper than the average cost of CO₂ reduction obtained in Example 1 of the considered CCUS options (USD 43.2/tCO₂), the total cost of maximum CO₂ reduction dropped to USD 351 × 10⁶/y through introducing renewable energy, with an average cost of USD 31/tCO₂.

An interesting insight developed from the profile presented in Fig. 9 is the suggestion of shifting all the coal energy to gas energy, due to the low cost of gas power compared to renewable energy. Moreover, the profile suggests to shift from gas to wind and solar if higher CO₂ reduction is required. Hence, the method suggests that to be able to reach a reduction target of 6.71 MtCO₂/y, besides the corresponding CCUS network, a gas power plant should be introduced to phase out coal, and the existing gas power should shift to solar and wind. An alternative option that can be cheaper for high CO₂ reduction targets is to phase out the coal to introduce solar and wind directly. This alternative would reduce the capital cost of the new gas power plant since there is no need to build a gas power plant and then phase out gas power.

For the presented example, the renewable energy sources can generate up to 450 MW of power. The coal power plant generates 500 MW. Hence, a gas power plant with a power rating of 50 MW can be introduced to cover the remaining coal power. The resulting Mini-MAC curve from such planning is shown in Fig. 10. Shifting from coal to wind or solar is cheaper than shifting from gas power. However, the maximum CO₂ flowrate that can be fixated through shifting from coal to gas (cheapest power shifting option) decreases. These changes led to a change in the net cost represented by the area between the profile and the horizontal axis. Nonetheless, the maximum limit for CO₂ reduction is not changed because achieving the maximum CO₂ reduction target would require the implementation of the same CCUS options, with a similar power mix of 450 MW from renewables and 55 MW from natural gas.

The alternative option for CO₂ reduction planning would result in saving the unnecessary cost of introducing and

Fig. 10 Mini-MAC curve generated for the alternative design of the holistic problem

phasing out natural gas, leading to a lower net cost for the CO₂ reduction targets that require the implementation of renewable energy. This can be shown in Fig. 11 where the net costs are plotted against the net CO₂ reduction flow-rate for the three cases that has been presented. Choosing the best alternative depends on the CO₂ emissions reduction target. The cost resulting from following the algorithm solution is lower than the cost resulting from the alternative planning until the net CO₂ reduction reach 5 × 10⁶ tCO₂/y. Beyond that, the cost profiles shift, and the alternative planning become cheaper. For any of the cases, phasing out coal power is a priority for optimal CO₂ reduction. If low level of CO₂ reduction is required (less than 5 × 10⁶ tCO₂/y), gas power should be introduced to minimize the total cost. For high level of CO₂ reduction, a mix between all the power options should be introduced for a cheaper CO₂ reduction. The alternative planning would result in saving USD 24.8 × 10⁶/y for the high CO₂ reduction targets, which is the cost of installing the unnecessary natural gas power plant. The average cost of the maximum CO₂ reduction would then drop to USD 28.75/tCO₂ for the maximum CO₂ reduction (11.3 × 10⁶ tCO₂/y).

Example 3: Negative emissions technologies (NETs)

A main advantage of the Mini-MAC curves, besides the powerful visualization and insights, is the ability to include all CO₂ reducing technologies, not only CCUS or power shifting. This is illustrated in this section, through extending the scope to include NETs. NETs are several traditional (like forestation/ afforestation) and emerging (like direct air capture) options that can remove CO₂ from the atmosphere. They have gained attention with the rising belief that net zero global emissions require major large-scale implementation of such technologies (Haszeldine et al. 2018). In this example, three different negative emissions pathways are examined: bioenergy coupled with CO₂ capture and storage

Fig. 11 The net cost of CO₂ reduction resulted from the planning according the three cases

(BECCS), afforestation, and direct air capture coupled with CO₂ capture and storage (DACCS). BECCS involves planting trees and crops which absorb CO₂ from the atmosphere through photosynthesis and use them to generate bioenergy through either burning them directly or transforming them to fuels. The generated emissions from such processes are captured and stored, so that a net CO₂ reduction is achieved. Afforestation includes restoring land through planting trees which also can absorb CO₂ from the atmosphere through photosynthesis. Finally, direct air capture involves using chemical reactions to absorb CO₂ from the atmosphere. The extracted CO₂ is then stored which results in a net CO₂ reduction. The data were collected for these pathways based on the values reported by McLaren (2012) and de Coninck et al. (2018), and it is present in Table 8. The costs used correspond to the lowest within the ranges reported, and the capacities are assumed based on the global potential for CO₂ reduction of these technologies relative to the emissions considered in this example. It is assumed that these technologies do not emit secondary CO₂ (power is covered through renewable energy for example), and the pathways involving CO₂ storage do not affect the storage capacity mentioned in Example 1 for the CCUS options.

The Mini-MAC curve which includes the NETs is shown in Fig. 12. Same insights can be derived as in the previous examples. The choice of the pathways depends on the CO₂ reduction target. The cheapest among the NETs is the afforestation, which is prioritized over the CCUS options involving capturing CO₂ from natural gas combustion. BECCS comes next among the NETs, being less expensive than storing CO₂ after capture from natural gas combustion. The most expensive option considered is the DACCS, which raised upper limit of the cost range to USD 100/tCO₂. The inclusion of the NETs in the system did not affect the profitable or zero-cost CO₂ reduction targets. This is because these targets are achieved with cheaper options, and the NET options are not activated for CO₂ reduction targets less than

Table 8 Data collected for the NET options

NET Option	MAC (USD/tCO ₂)	CO ₂ reduction capacity (MtCO ₂ /y)
Afforestation	20	0.6
BECCS	45	0.9
DACCS	100	3

6 MtCO₂/y. However, the NETs increased the maximum net CO₂ reduction that can be achieved, as it reaches 15.84 MtCO₂/y. This target is higher than the amount of CO₂ generated by the considered system (13.14 MtCO₂/y). Hence, implementing all the considered options would not only reduce the amount of CO₂ emitted, but it would also result in a negative emissions system. Since the costs of DACCS and BECCS are higher than the average cost of the maximum CO₂ reduction without the NETs (USD 28.75/tCO₂), the introduction of NETs led to an increase in the average CO₂ reduction cost associated with the maximum achievable CO₂ reduction. The average cost is USD 42.8/tCO₂. The average cost depends on the ultimate CO₂ reduction target. The comparison between the results obtained from the three examples shows that it is important for CO₂ reduction planning to consider all the possible options, which yields the integrated system that achieves the CO₂ reduction target at the least cost possible.

Conclusions

This work has presented an analysis methodology that is simple relative to other design and optimization methodologies used to address the problem of economic optimization of CO₂ reduction. The method consists of two steps.

Fig. 12 Mini-MAC curve generated for holistic problem including CCUS, power shifting, and NET options

First, an algebraic analysis approach determines the minimum abatement cost of CO₂ reduction pathways based on different technical and economic factors. The total cost of CO₂ reduction is minimized through prioritizing the cheapest CO₂ reduction pathways. The results of the algebraic analysis together with the capacities for CO₂ reduction are then used to construct minimum marginal abatement cost curves (Mini-MAC). These resulting Mini-MAC curves are powerful tools to illustrate cost-optimal solution pathways for CO₂ emissions reduction planning. The proposed method is expected to benefit designers and policy makers by enabling the quick identification of cost-optimal solutions and communicating results in easily comprehensible graphical representations, i.e., the Mini-MAC curves, to audiences of diverse backgrounds. The methodology is generally applicable to handle diverse CO₂ reduction options to solve the general CO₂ emissions reduction problem by considering different possible pathways. For instance, power shifting options for CO₂ reduction have been then incorporated to give several insights into the planning of CO₂ reduction pathways across CCUS and renewable energy options. The developed Mini-MAC curves allow the quick identification of optimal CO₂ reduction pathways and provide an understanding of the corresponding economics (net costs and profits) for given level of CO₂ emissions reduction. The CO₂ reduction target with maximum profit and the CO₂ reduction target with zero cost can be identified from the graphical analysis of the proposed Mini-MAC curves. Additionally, the proposed Mini-MAC curves can be used to benchmark the strategic design and carbon policy. Future work will aim at applying the developed methodology to country case studies and to technology road mapping.

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Authors and Affiliations

Mohammad Lameh¹ · Dhabia M. Al-Mohannadi¹ · Patrick Linke¹

✉ Patrick Linke
patrick.linke@tamu.edu

¹ Department of Chemical Engineering, Texas A&M University At Qatar, PO Box 23874, Doha, Qatar