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Integrating Optimal Solutions for Low-Cost Alternative Energy and CO_2 Integration Networks

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Among the different existing options for greenhouse emissions reduction, transforming the energy systems through implementing low CO_2 emissions technologies and managing the produced CO_2 emissions through capture, utilization, and storage (CCUS) are considered substantial for achieving the required reduction targets. Different decision support methodologies have been proposed to provide guidance for planning by determining the cheapest pathways that achieve the desired level of reduction. However, such approaches usually focus on one of the reduction pathways, thus, lacking the ability to investigate the synergies between all the available options. The objective of this work is to address the gap by providing a decision-support methodology that considers the available energy options, CO_2 management options, and their interactions to yield low-cost CO_2 reduction solutions for a given emissions reduction target. Previous literature provided optimization models for minimizing the costs of CO_2 reduction options whether through energy systems approach, or through CO_2 integration networks. This work builds on the findings of such studies to propose an integrated framework that incorporates the optimization results to minimize the cost of integrated CO_2 reduction systems considering simultaneously CCUS, energy systems, and further CO_2-reducing technologies. The proposed approach is illustrated through a case study which considers different CO_2 emitting sources, CO_2 utilization technologies, and renewable energy options. The application demonstrates the importance of considering the ultimate CO_2 reduction target in selecting the optimal pathways. It was shown that capturing CO_2 from power plants can result in savings for moderate reduction targets, however, high CO_2 reduction requires full implementation of renewable energy options to achieve significant savings. Such insights are valuable for planners and policy makers interested in achieving cost-efficient emissions mitigation. Hence, the method is applicable for analyzing decarbonization strategies on local, regional, and national scales.

1. Introduction

Minimizing the cost of climate action is key to efficiently achieve the required targets on time (Gkonis et al., 2020). This requires a comprehensive screening through the available emissions reduction pathways to select the optimal ones. Among the various available approaches for limiting the greenhouse gas emissions (mainly CO_2), renewable energy and CO_2 capture, utilization, and storage (CCUS) are key pillars to achieving the set abatement goals (IEA, 2021). Each of these pathways involves a set of technologies that constitute integrated systems which achieve CO_2 reduction targets at a cost. For the case of CCUS options, CO_2 needs to be captured to be then utilized or stored. This results in multiple options for: the sources from which CO_2 can be captured, the capture technologies, the CO_2 utilization pathways, and CO_2 storage sites, and consequently, multiple options for the integrated system which contains the CO_2 integration network (Tapia et al., 2018). Similar level of variety in the pathways can arise from the energy transition planning with the different energy options that need to be phased out and the various less-emitting technologies that can be implemented, given the effect of energy supply and demand dynamics (Limpens et al., 2019). Various optimization-based decision support methods have been developed to guide a cost-optimal energy transitions (Chang et al., 2021) and CO_2 integration network synthesis (Tapia et al., 2018). The different tools can screen the available options within each pathway to provide minimum-cost integrated systems as solutions for achieving a defined level of CO_2 reduction. However, the level of details addressed by each tool vary depending on the focus of the application.

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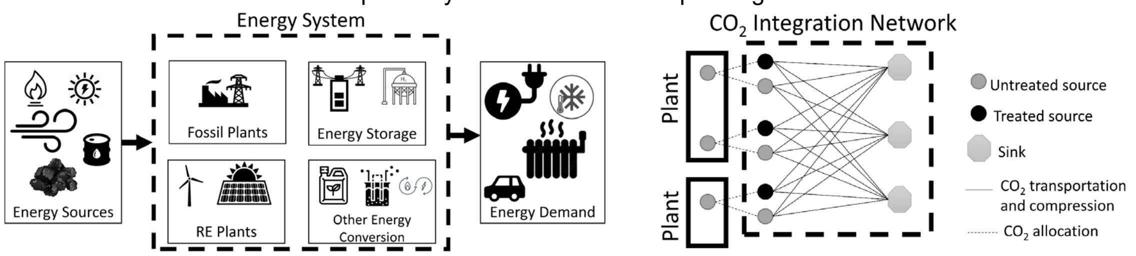
For example, energy transition optimization models consider the dynamic variation of renewable energy supply and demand to determine the optimal design of energy systems (Limpens et al., 2019). Many of such models consider capturing and storing CO_2 emissions, however, the option of utilizing the emissions is usually out of scope. On the other hand, cost-optimal CO_2 integration has considered various techno-economic parameters in CCUS planning, given the variations in purities, costs, and profits (Al-Mohannadi et al., 2020). However, such approaches follow steady state modelling assuming uniform production levels as the dynamics of energy supply and demand variations are out of scope. Hence, there is a missed opportunity of investigating the synergies between the different abatement pathways through integrating the solutions. Minimum marginal abatement cost (mini-MAC) curve has been proposed as a high-level cost-analysis method for integrated CO_2 reduction pathways which can represent renewable energy and CCUS options (Lameh et al., 2021). However, the representation is based on high-level estimations of the cost and reduction potential, which lacks the detail level of optimization models. Hence, there is a need for an integrated method that can demonstrate the integrated systems of CO_2 reduction while considering the details addressed by the optimization models. This work aims to address this gap by proposing a methodology to integrate the solutions obtained from different optimization models. Integrating the solutions allows the investigation of how the various pathways affect the total cost of CO_2 reduction. Such analysis is important for planners as it allows the comparison between the performances of the pathways based on their environmental and economic impacts. Moreover, the considered systems can be defined based on geographical areas, making the method suitable for guiding local, regional, and national decarbonization strategies which can be investigated further in the future. Two different approaches for integrating the solutions are proposed, and their performances are discussed in an illustrative case study. The cost curve is implemented to demonstrate the insights that can be generated from the optimization.

2. Methodology

The proposed methodology integrates solutions obtained from comprehensive optimization models. The aim is to provide integrated systems for CO_2 reduction, which include energy system transitions and CO_2 capture, utilization and sequestration, while considering the level of details addressed in each optimization model. Hence, the superstructure of the systems addressed by the methodology depends on the assumptions of the optimization models used to determine the integrated solutions. The case study presented in the Section 3 adopts EnergyScope (Limpens et al., 2019) as the optimization tool for the minimum-cost energy system transition, and the CO_2 integration model developed by (Al-Mohannadi et al., 2020) to represent cost-optimal CCUS networks. EnergyScope solves a linear programming model which determines the energy system portfolio with the minimum cost, corresponding to a set level of CO_2 reduction. The model considers the intermittency of renewable energy sources in designing energy transformation, production, and storage units so that a defined energy demand is reached. The variations in energy supply and demand are considered by inputting hourly distributions of energy production and energy demand for a whole year to the energy system optimization model. The sizing of the components and the scheduling are constrained by the availability of renewable resources and the demand they need to cover. The CO_2 integration model solves a mixed integer linear program to determine, for an existing set of CO_2-emitting sources, the cost-optimal CO_2 capture strategy and the best utilization and storage option as well as the CO_2 transportation lines that can achieve a set level of net CO_2 reduction. Figure 1 shows the scope of the systems addressed by each model. Both optimization models use as input a set of techno-economic parameters for the different technologies considered to determine the cost and emission level of the optimal systems and the corresponding constraints.



(a) (b)

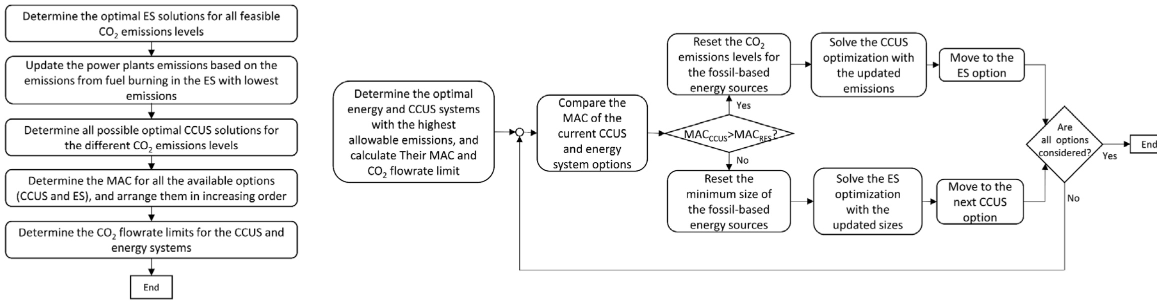
Figure 1 CO_2 reduction systems with the boundaries and components that define the scopes considered by the optimization models for energy system transition (a) and CO_2 integration network (b)

The integration between the solutions of both models is performed through representing their results on an integrated marginal abatement cost curve. The aim is to minimize the total cost of the integrated CO_2 reduction. The synergetic opportunities investigated in this work arise from the variety of CO_2 reduction options for fossil-based energy sources, and because different optimization models can consider different pathways for the same sources. The proposed method follows an iterative procedure because the capturable emissions from the energy system can be reduced either through energy transition or through CCUS. Hence, implementing either of the options would require the update of the level of emissions for the same source in both models. Figure 2 shows the algorithms implemented to obtain CO_2 reduction capacity and cost for each of the considered options. Both algorithms (Figure 2 (a) and (b)) start by identifying the different systems and their corresponding marginal abatement costs. The available systems are identified from the optimization models based on the costs of the available technologies by gradually increasing the CO_2 reduction level (changing the emissions constraint). For each CO_2 reduction level ($e_i^{CCUS}\ or\ e_i^{ES}$), the optimization problem is solved to determine the total cost. Increasing the CO_2 reduction level gradually results in a gradual increase in cost. The marginal abatement cost (MAC) for each option i ($CCUS_i$ or ES_i) is determined as a function of the additional cost required to achieve a higher CO_2 reduction potential with respect to the system with the closest (higher) emissions level, which is option i-1 ($CCUS_{i-1}$ or ES_{i-1}). Eq(1) and Eq(2) describe how the MAC for each option is determined:

$$MAC_i^{CCUS} = \frac{\mathrm{Cost}_i^{CCUS} - \mathrm{Cost}_{i-1}^{CCUS}}{Emissions_{i-1}^{CCUS} - Emissions_i^{CCUS}} \tag{1}$$

$$MAC_i^{ES} = \frac{\mathrm{Cost}_i^{ES} - \mathrm{Cost}_{i-1}^{ES}}{Emissions_{i-1}^{ES} - Emissions_i^{ES}} \tag{2}$$

Eq(1) and Eq(2) apply for both algorithms in Figure 2. Note that the denominations represent the CO_2 reduction potential for each CO_2 reduction option i, and this value is used to determine the CO_2 flowrate limit to represent the pathways on the integrated MAC curve. Knowing the MAC and the CO_2 reduction capacity for each of the considered options, the MAC curve of the integrated system can be constructed as shown in Figure 3. For a given level of CO_2 reduction target, the integrated CO_2 reduction system consists of the energy system and CCUS network closest to the target point.



(a) (b)

Figure 2 The algorithms developed to integrate the optimization solutions based on the full potential of energy systems (a) and based on the cheapest pathways (b)

The algorithms (Figure 2 (a) and (b)) differ in the prioritization criterion followed for determining the optimal solutions for fossil-based energy sources. The algorithm shown in Figure 2 (b) prioritizes the cheapest pathways whether they are through CCUS or through energy transition, as the aim is to minimize the total cost of CO_2 reduction. The prioritization is considered by resetting either the emissions level available for capture or the minimum sizes of fossil-based energy plants (Figure 2(b)). The other criterion followed in the algorithm shown in Figure 2 (a) aims to maximize the level of CO_2 reduction by ensuring that the energy transition pathways can be implemented to their full capacities. Given the limited capacities of CO_2 utilization and storage technologies and the variety of CO_2 emissions sources, this algorithm ensures the minimization of the emissions before planning the CO_2 integration network by investigating the ultimate CO_2 reduction capacity of the possible energy systems beforehand. The capturable emissions from the fossil-based energy sources are those that cannot be reduced by energy transformation. Both algorithms are applied in Section 3 and the corresponding results are compared and analyzed.

3. Case Study

The method is applied in this section to a hypothetical case to analyse the economics of integrated CO_2 reduction pathways from a system consisting of point sources. The technical, economic, and environmental data collected is used as input to the optimization models to obtain the results required to generate the abatement curves. The energy system analyzed in this work covers a demand defined on hourly basis (ERCOT, 2021b). Table 1 shows the techno-economic parameters considered for characterizing the power generation units. The variation of the renewable power sources (wind and solar) is considered on an hourly basis as well (ERCOT, 2021a). The hourly data is input into the EnergyScope model as time series distribution over one year. The fossil-fired power plants operate at 50 % efficiency with the following emissions level from fossil fuel combustion: 0.27 $kgCO_2/kWh_{th}$ for natural gas (NG) and 0.4 kg/kWh_{th} for coal (EIA, 2021). The annual capacity factors for the plants account for the difference between the capacity of the plant and the actual production rate, and they are considered as follows: 87 % for coal, 85 % for natural gas, 24 % for solar, and 36 % for wind. Moreover, two power storage options were considered in the planning of the low-emissions energy system: battery energy storage system (BESS) and power to gas/ gas to power (P2G/G2P). The installation costs of both options are 350 $/kWh and 3,340 $/kWh. Their operation and maintenance costs are 25 and 165, and the round-trip efficiencies are 90 % and 60 %. All techno-economic parameters are based on IRENA (2021), EIA (2020), and Limpens et al. (2019).

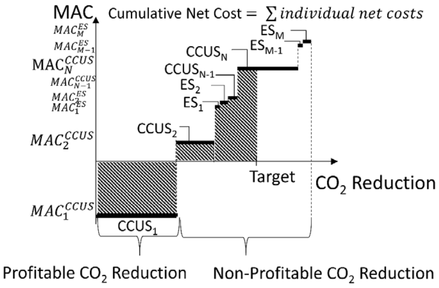


Figure 3 Integrated MAC curve

Table 1: Estimated capital and operation costs of the considered power production options

Power technology	Coal Power	Natural Gas Power	Solar PV	Wind
Capital Cost ($/kWp)	2,300	958	1,101	1,066
Operation Cost ($/kWp/y)	40.6	12.2	10	15

This case considers three major sources of emissions from the industrial sector, beside the emissions from the existing power system. The emissions from these sources can be captured and either utilized or stored in various CO_2 sinks. Table 2 and Table 3 show the data used to represent the sources and sinks to be able to design the CO_2 integration network. Note that the existing power system does not include any renewable power or power storage option. The existing natural gas and coal power plants cover all the power demand. The considered CO_2 sinks include direct utilization (Hepburn et al., 2019) of CO_2 (enhanced oil recovery-EOR), CO_2 storage GCCSI (2011), and emerging technologies that convert CO_2 to value added products such as fuels (Zang et al., 2021) and chemicals (Pérez-Fortes et al., 2016). The profitability of the CO_2 sinks is represented by the CO_2 breakeven cost, which reflects how much each process can afford to pay for the allocated CO_2. The negative values indicate non-profitability (net cost) as the processes need to be paid for the allocated CO_2. The capacity of each option represents the load constraint which is the maximum flow of CO_2 that the sink can take. Note that the secondary emissions from the sinks are 0 % for EOR and storage, 8 % for chemicals, and 40% for fuels. All the capture costs shown in Table 2 are determined based on Metz et al. (2005). These estimates consider post-combustion CO_2 capture by amine absorption (with 90% capture efficiency). The secondary emissions from this process are assumed to be 22 % of the captured CO_2. The total secondary emissions can vary between the sources and the sinks based on the compression and transportation requirements, and these are included in the CO_2 integration network optimization (Al-Mohannadi et al., 2020). Note that the pure CO_2 emissions include the sources in which CO_2 capture already exist as part of the process, hence, no extra costs or secondary emissions are associated with their allocation to the network.

Table 2: Emissions production rate and specific cost of CO_2 capture from the considered emissions sources

Source	Pure CO_2 emissions	Combustion	Cement Calcination	Coal Power	NG Power
Emissions (10^6 tCO_2/y)	3	20	2	12.4	15.9
Capture Cost ($/$tCO_2$)	0	31	55	25	27

Table 3: CO_2 processing capacity and CO_2 breakeven cost of the considered utilization and storage options

Sink	EOR	Storage	Chemicals	Fuels
Capacity (10^6 tCO_2/y)	1	15	4	17
CO_2 breakeven cost ($/$tCO_2$)	45	-20	-280	-440

Applying the method based on the two algorithms (Figure 2) allows the determination of the integrated cost curves showing the CCUS and energy transition pathways (Figure 4). The full potential of implementation of the energy system allows 100 % renewable energy contribution (using the available storage option). Based on the criterion of prioritizing the full potential of CO_2 reduction by energy systems transition, none of the emissions from the fossil-based energy sources is captured. This is shown in Figure 4 (a) where the considered CCUS options involved capturing the emissions only from the industrial sources. Note that even when prioritizing the full-potential implementation of renewable energy systems, the cost profile shows that for any level of CO_2 emissions reduction, both energy systems and CCUS options need to be considered as the costs of the various pathways vary within similar ranges. Both profiles in Figure 4 corresponding to both algorithms show that profitable opportunities for CO_2 reduction exist through phasing out coal energy and introducing natural gas power, and through utilizing CO_2 from the pure emissions in EOR. None of the emissions from the coal power plant were captured when prioritizing the cheapest pathways (Figure 4 (b)), because it was more profitable to phase out the power from coal. In both cases, increasing the CO_2 reduction target requires the implementation of more expensive pathways, resulting in a rise in the MAC of the required options. In the case where the cheapest pathways were prioritized and the capacities of the remaining options were updated (Figure 2 (b) and Figure 4(b)), capturing the emissions from the natural gas power plant is considered for moderate levels of CO_2 reduction as it is cheaper than implementing energy storage. This required an additional capacity in the considered sinks compared to the case in Figure 4(b) in which the power-related emissions were not captured. Consequently, high CO_2 reduction targets could not be achieved by energy transition as the production level of the NG power plant was fixed. Hence, the feasibility of the high reduction targets required the implementation of the expensive CO_2 sinks resulting in pathways with high MAC. The maximum MAC in this case reached 1,370 $/tCO_2$ which is high compared to the maximum MAC reached when prioritizing the full potential of renewable energy – 890 $/tCO_2$. The values obtained for the MAC for the pathways that involve the processing CO_2 in the sinks: chemicals and fuels are much higher than the CO_2 utilization costs reported by Hepburn et al. (2019). This is expected because the MAC accounts for the cost of capturing CO_2 from the sinks, as well as the environmental effects of the capture and utilization processes. Hence, the MAC increases significantly especially with the case of fuels that have low fixation efficiency (40 % secondary emissions). This shows the importance of considering both environmental and economic characteristics of the technologies to better represent their sustainable performance. This finding indicates a trade-off between prioritizing the cheapest pathways and prioritizing the full potential of renewables. To investigate this further, the total cost was plotted against the CO_2 reduction level (Figure 5). Both parts of Figure 5 show the same data plotted at different intervals and scales. For low to intermediate level of CO_2 reduction targets (Figure 5 (a)), prioritizing the cheapest pathways results in lower costs. In this case, capturing a fraction of the emissions from the natural gas power plant is cheaper than some of energy transition and CCUS options. This results in lower total cost for CO_2 abatement. However, prioritizing the maximum implementation of renewable energy results in higher achievable CO_2 reduction and lower costs at high reduction targets (Figure 5(b)). This is due to the limited capacity of the considered sinks which makes it necessary to invest in the expensive pathways to reach high level of CO_2 reduction. Hence, it is important to understand the long-term targets of CO_2 reduction before implementing the pathways.

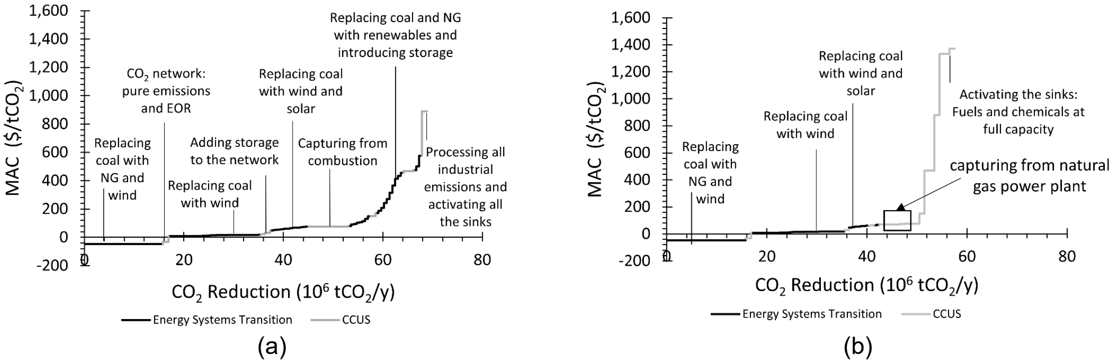


Figure 4 Estimated CO_2 abatement cost and CO_2 reduction potential as demonstrated on the integrated MAC curves generated based on the full potential of energy systems (a) and on prioritizing the cheapest options (b)

4. Conclusions

This work proposed an approach for integrating optimization solutions from different available models to determine a low-cost integrated system for CO_2 reduction. The consideration of different optimization models allows the novel method to consider different levels of details for planning CO_2 reduction systems, including time variability of energy supply and demand and elaborate allocation of CO_2 in the integration network. Moreover, the high-level representation of the solutions on an integrated mini-MAC curve allows a clear illustration of the insights determined from the optimization solutions. This facilitates the analysis and understanding of the environmental and economic impacts of the various considered options, which makes it suitable to explain the key results of the complicated optimization models. The method was applied in a case study where various technical, economic, and environmental parameters were used to characterize available power production and CO_2 processing options. The integration of the results from two optimization models showed that the criterion that results in the cheapest CO_2 reduction depends on the level of the targeted abatement; cost-optimal moderate CO_2 reduction level requires prioritization of cheapest options which results in capturing emissions from the natural gas power plant, and high CO_2 reduction level requires prioritizing the full potential of renewables which results in total energy transition without capturing the power plant's emissions. Future work will focus on applying the method for assessing country-level CO_2 abatement strategies. The method can be enhanced by developing an integrated optimization model that allows further investigation of the possible synergies between the different CO_2 reduction pathways.

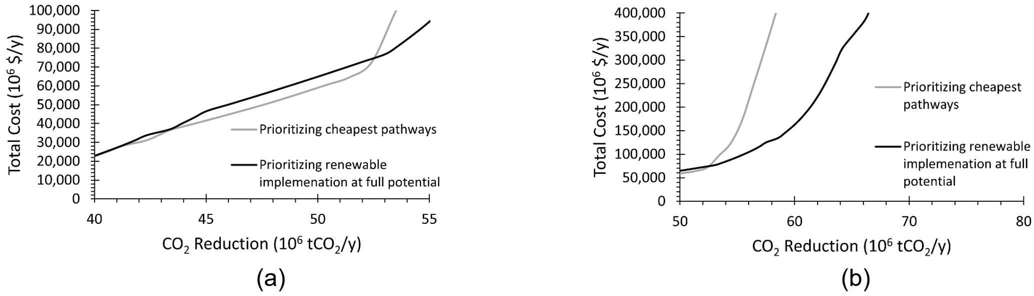


Figure 5 The total cost of CO_2 for moderate (a) and high (b) reduction targets

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