Supplementary Information

Renewable-Integrated Flexible Carbon Capture: A Synergistic Path Forward to Clean Energy Future

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Contents

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S1 Optimization model parameters

Table S1 Financial parameters

Parameter	Description	Unit	Value
r^{disc}	Project annual discount rate	%	10
r^{tax}	Tax rate	%	15
t^{lf}	Project lifetime	years	25
t^{dp}	Project useful life	years	20
h^{op}	Number of operating hours	hrs/year	8760

Table S2 System design and operational parameters

Parameter	Description	Unit	Value
p_{cl}^{ref}	Nameplate capacity of coal power plant reference case	MW	600
S^{ref}	Reference case solvent flowrate [1]	$m^3\ h^{-1}$	7300
E_{cl}^{ref}	Reference case CO_2 emission intensity [1]	ton MWh^{-1}	0.76
p_{cl}^{max}	Nameplate capacity of coal power plant	MW	-
lf_{cl}^{min}	Minimum load factor of coal power plant	%	20
Δp_{cl}^{max}	Maximum ramping rate of coal power plant [2]	MWh^{-1}	$0.3\ p_{cl}^{max}$
η^{b}	Efficiency of electric boiler [3]	%	96
η^{te}	Thermal to electricity energy conversion factor for LP steam [4,5]	%	18.3
$cf_{m,\omega}$	Capacity factor of resource m for scenario ω	%	0 - 100
E_{cl}	Base-case CO_2 emission intensity of coal power plant	ton MWh^{-1}	-
γ_a	CO_2 removal rate of scrubber from flue gas	%	90
Δr_a^{max}	Maximum ramping rate of CO_2 scrubber	h^{-1}	1
Δr_d^{max}	Maximum ramping rate of CO_2 stripper	h^{-1}	1.25
η_{cl}^{max}	Maximum efficiency of coal power plant	%	44
p_{cl}^{0}	Maximum power input to the power plant	MW	$\frac{p_{cl}^{max}}{\eta_{cl}^{max}}$
μ_a	Efficiency penalty of CO_2 absorption	%	2
μ_d	Efficiency penalty of CO_2 desorption	%	4
μ_c	Efficiency penalty of CO_2 compression	%	2
S^{max}	Maximum solvent flowrate	$m^3\ h^{-1}$	$S^{ref}\ \frac{p_{cl}^{max} E_{cl}}{p_{cl}^{ref} E_{cl}^{ref}}$
r_a^{max}	Maximum CO_2 absorption rate in scrubber	-	1
r_d^{max}	Maximum CO_2 desorption rate in stripper	-	1.25
v_w^{ci}	Cut-in wind speed of wind turbine	$m\ s^{-1}$	1.5
v_w^{r}	Rated wind speed of wind turbine	$m\ s^{-1}$	12
v_w^{co}	Cut-off wind speed of wind turbine	$m\ s^{-1}$	25
$v_{w,\omega}$	Wind speed for scenario ω	$m\ s^{-1}$	-
H_ω	Global Horizontal Irradiance (GHI) for scenario ω	$W\ m^{-2}$	-
T_ω^{amb}	Ambient temperature for scenario ω	°C	-
H^{ref}	Reference solar irradiance	$W\ m^{-2}$	1000
$\eta^{arr}\eta^{dc/ac}\eta^{wir}$	Combined efficiency of solar PV arrays, inverter and wiring	%	93.75
V_0^{rich}	Initial volume in rich solvent storage tank	m^3	$\frac{sz^{tank}}{2}$
V_0^{lean}	Initial volume in lean solvent storage tank	m^3	$\frac{sz^{tank}}{2}$

Table S3 Cost parameters

Parameter	Description	Unit	Value
CO_w	Specific capital cost of wind energy	$ MW^{-1}	-
CO_{sp}	Specific capital cost of solar PV	$ MW^{-1}	-
CO_b	Specific capital cost of electric boiler [6]	$ MW^{-1}	88,000
CO^{tank}	Specific capital cost of solvent storage tank [7]	$ m^{-3}	300
N^{tank}	No. of solvent storage tanks	-	2
nh^{tank}	Maximum solvent storage duration	hr	2
sz^{tank}	Size of rich/lean solvent storage tanks	m^3	$nh^{tank} S^{max}$
CO^{capt}	Specific capital cost of capture system (2002 basis) [8]	$ MW^{-1}	810,000
I^{17}	Cost index for 2017	-	567.5
I^{02}	Cost index for 2002	-	395.6
π^s_ω	Spot market electricity price for scenario ω	$ MWh^{-1}	-
π^l	Long-term contract electricity price	$ MWh^{-1}	51.7
p^l	System power output as per contract commitment	MW	$\frac{2}{3} p^{max}_{cl}$
π^{csp}	CO_2 selling price	$ ton^{-1}	-
C^{gen}_{cl}	Specific power generation costs for coal power plant [9]	$ MWh^{-1}	31
C^{em}	Tax on CO_2 emissions	$ ton^{-1}	-
C^{ts}	Specific transportation and storage costs of captured CO_2 [5]	$ ton^{-1}	4.6
C^{ramp}	Specific ramping costs for coal power plant [10]	$ MW^{-1}	2

Table S4 Renewable energy and CO_2 emission cost parameters for current and future cases

Parameter	Unit	Current value	Future value
CO_w [11]	$ MW^{-1}	1,470,000	300,000
CO_{sp} [12]	$ MW^{-1}	1,470,000	300,000
C^{em}	$ ton^{-1}	10	80
π^{csp}	$ ton^{-1}	10	35

S2 Carbon capture model: Possible improvements

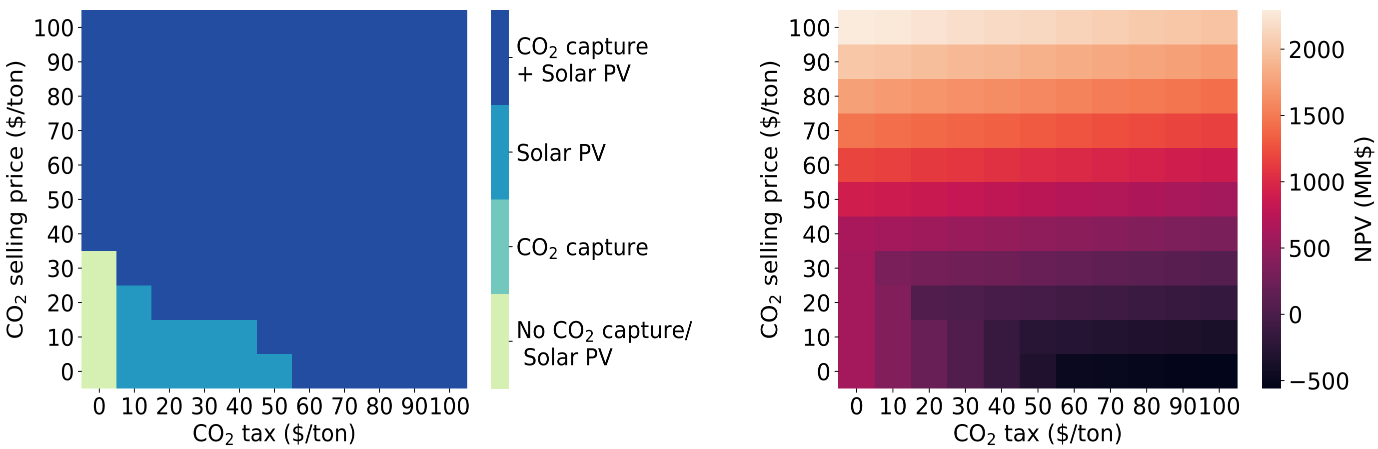
The CO_2 capture model considered in our analysis is based on the conventionally used chemical absorption process with MEA as the solvent. In the chemical absorption process, the rate of CO_2 absorption with solvent is a critical parameter. Although amines are the popular choice of solvents due to their high absorption rate of CO_2 and thermal stability, the use of amines for carbon capture results in significant equipment corrosion, high capital cost due to the large equipment size required and high make-up rate due to solvent degradation. Majority of the recent research on process improvements in solvent-based CO_2 capture focuses on alternative solvents or blended amines to address these challenges.[13–15] In addition, a major area of process improvement lies in reducing the high energy requirement of solvent regeneration. Research efforts in this area are directed towards optimizing the operating conditions and incorporating process modifications.[16] Significant reduction in energy consumption is possible through varying different operating parameters, for instance decreasing the lean solvent temperature, increasing the MEA concentration, increasing the solvent loading and increasing the operating pressure and temperature of the stripper.[17–19] Work on improvement of the process design includes the exploration of process intensification techniques such as heat integration opportunities to reduce the reboiler duty.[20,21] Other techniques include the use of an intensified separation unit such as a rotating packed bed as opposed to the conventional packed bed to reduce equipment size as well as increase the mass transfer rate.[22] As our analysis in this work is focused on the high-level nationwide scale, we consider the conventional process with MEA. This is because the technology is the closest to large-scale deployment in power plants despite its several drawbacks. However, introducing process modifications, optimizing the operating conditions and/or replacing the solvent-based on the aforementioned research work can potentially reduce the capture energy penalty. In the context of our integrated system, this would translate to increased cost savings for the power plant but reduce the role of the capture system to act as energy storage and counter renewable intermittency.

There are several alternative CO_2 capture processes, including membrane, adsorption and cryogenic processes, which can be also considered.[23,24] Membrane separation of CO_2 from flue gas can offer several advantages over the traditionally considered solvent-based absorption due to reduced equipment size, less energy requirement, and the absence of hazardous chemicals[25]. However, the application of membrane-based systems for large-scale post-combustion CO_2 capture from power plant flue gas is limited due to the compromise between permeability and selectivity. Furthermore, there exist low driving forces for membrane separation due to the low CO_2 concentration and pressure in flue gas.[26] Additional energy must be expended to increase the feed gas pressure, which adds to the cost. The analysis by Hasan et al.[23] suggests that although absorption is the cost-effective technology at low CO_2 concentrations, significant cost reduction is possible through membrane systems when the CO_2 concentration in feed gas is greater than 30%. Breakthroughs in new materials for membrane separation can potentially overcome some of the limitations and make the large-scale implementation for post-combustion capture attainable.

S3 Sensitivity analysis

To analyze how the integrated system design and profitability change with different levels of CO_2 tax as well as selling price, we perform a sensitivity study. This study is performed on a single power plant considering reference case nameplate capacity and CO_2 emission intensity, p_{cl}^{ref} = 600 MW and E_{cl}^{ref} = 0.76 ton MWh^{-1} respectively. The location selected for solar radiation data has an average annual capacity factor of 16.98%. A future cost of $0.3 per Watt for solar PV is considered. Both the CO_2 selling price and tax is varied between 0 and $100 per ton. When analyzing the variation of the optimal integrated system design and the profitability given by the net present value (NPV), we observe that for a CO_2 tax below $5 per ton and a CO_2 selling price below $35 per ton, there is not enough economic incentive to reduce emissions from the coal power plant and integrate either a CO_2 capture system or a solar PV farm (See Figure S1). As the CO_2 tax increases up to $55 per ton, the integration of solar PV is optimal as the sole emission reduction measure at low values of the CO_2 selling price. For the range of tax between $5 to $55 per ton, the CO_2 selling price threshold for the change from solar-only integration to both solar and CO_2 capture integration decreases for increasing levels of tax. All combinations of CO_2 tax above $55 per ton and CO_2 selling price above $35 per ton favor both CO_2 capture and solar PV integration with the coal plant.

Naturally, the NPV increases with the CO_2 selling price for a given value of CO_2 tax, but it decreases for increasing CO_2 tax (See Figure S1b). A loss of profit (i.e., negative NPV) may result if the CO_2 tax is higher than $35 per ton and the CO_2 selling price is below $15 per ton. Thus, although a high tax on emissions makes it imperative to invest in the integrated system, a minimum selling price of $15 per ton is required to ensure that the system is profitable.



(a) Optimal system design. **(b)** Optimal NPV.

Fig. S1 Sensitivity study of integrated system design and profitability to CO_2 selling price and CO_2 tax. We see three regions of integrated system design: (i) Integration is not optimal for low values of CO_2 selling price and CO_2 tax, (ii) a high tax and selling price provides economic incentive to integrate both a CO_2 capture system and solar PV farm, and (iii) solar PV integration is the sole emission reduction measure for intermediate values of tax and selling price. The resulting NPV shows an increasing trend for increasing CO_2 selling price and decreasing CO_2 tax. A minimum CO_2 selling price of $15 per ton is required for profitability at high tax scenarios.

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