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The separation of CO_2 from ambient air – A techno-economic assessment

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HIGHLIGHTS

- Amines/imines are most promising adsorbing agents to separate CO_2 from ambient air.
- Energy demand results in 3.65 GJ/t_{CO2} and a second law efficiency of up to 11.83%
- Costs of avoiding CO_2 emissions range from $ 824 (wind)-1333/t_{CO2} (natural gas)
- CO_2 separation from air is unable to economically compete with CCS.
- Separation from air will not play a vital role in the abatement of the CO_2 problem.

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ABSTRACT

This paper assesses the separation of CO_2 from ambient air from a technical and economic standpoint. Reducing CO_2 emissions and their sequestration from the atmosphere is vital to counteract ongoing climate change. The most promising technological options for CO_2 separation are first identified by reviewing the literature and comparing the most important technical and economic parameters. The results point to amines/imines as adsorbing agents to separate CO_2 from ambient air. A system layout is then designed and a technical analysis conducted by solving mass and energy balances for each component. An economic analysis is then performed by applying a specifically-developed model. The total energy demand of the system discussed here is calculated as 3.65 GJ/t_{CO2}. This high energy demand mainly derives from the system-specific implementation of two compressors that compress air/CO_2 and overcome the pressure losses. The second-law efficiency calculated ranges of 7.52–11.83 %, depending on the option of heat integration. The costs of avoiding CO_2 emissions vary between $ 824 and 1333/t_{CO2}, depending on the energy source applied. The results of this work present higher values for energy demand and costs compared to other values stated in literature. The reasons for this deviation are often insufficient and overoptimistic assumptions in other literature on the one hand, but also relate to the specific system design investigated in this paper on the other. Further case studies reveal that enormous land requirements and investments would be needed to reduce potential CO_2 quantities in the atmosphere to contemporary levels. A comparison between CO_2 removal from the atmosphere and carbon capture and storage technology for coal power plants shows that this technology is not yet able to economically compete with carbon capture and storage. Furthermore, the impact of CO_2 separation on the production costs of industrial commodities like cement and steel demonstrates that CO_2 removal from the atmosphere is not yet a viable alternative to solving the climate change problem. In the long-term, CO_2 separation from ambient air may still play an important role in the sequestration of CO_2 from diluted and dispersed sources, as the technology has the potential for significant further development and optimization.

1. Introduction

Climate change is an all-encompassing challenge facing humanity. The consequences of climate change include, amongst other things, an increase in mean temperature and sea level, the frequent occurrence of extreme weather events, changes in biodiversity and oceanic acidification. Climate change is result of the greenhouse effect: short-wavelength solar radiation enters the Earth's atmosphere and is partly reflected by surface. As the temperature of the radiation drops on its journey from the Sun to the Earth, its wavelength increases. The

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Nomenclature

List of abbreviations

CCS	carbon capture and storage
CCUS	carbon capture, utilization and storage
CNG	compressed natural gas
DNI	direct normal irradiation
LNG	liquid natural gas
MEA	monoethanolamine
PEI	polyethyleneimine
PtG	power-to-gas
PtL	power-to-liquids
PtX	power-to-x

List of symbols

Δ	delta [–]
A	surface [m^2]
A	annuity [$/a]
B_1, B_2	coefficients to account for additional costs [–]
c_p	specific heat capacity [J/mol/K]
c_A	abatement costs [$/$t_{CO2}$]
C_B	utilities costs [$/a]
c_{PC}	specific production costs [$/$t_{CO2}$]
C_{BM}	component costs [$] (for components that are not made of carbon steel for an operating pressure of 1 bar)
C^0_{BM}	component costs [$] (for components that are made of carbon steel for an operating pressure of 1 bar)
C_F	manufacturing costs [$/a]
C_G	overhead costs [$/a]
C_H	auxiliaries costs [$/a]
C_L	laboratory costs [$/a]
C_M	material costs [$/a]
C_p	staff manufacture costs [$/a]
C_p^0	acquisition costs [$]
C_{PC}	production costs [$/a]
C_R	commodities costs [$/a]
C_{SV}	taxes and insurances costs [$/a]
C_{UB}	supervision and bureau staff costs [$/a]
C_W	maintenance costs [$/a]
FCI	investment costs [$]
F_M, F_P, F_{BM}	coefficients to account for additional costs [–]
g	specific Gibbs energy [J/mol]
Δh_R	specific enthalpy of reaction [J/mol]
$\dot{H}$	enthalpy flow [W]
i	interest rate [%]
I_{2001}, I_{2012}	Chemical Engineering Cost Plant Index for 2001 and 2012 [–]
k	heat transmission coefficient [$W/m^2/K$]
K_1, K_2, K_3	component specific coefficients [–]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	polytropic exponent [–]
$\dot{n}$	molar flow rate [mol/s]
p	pressure [Pa]
q	thermal work [J/mol]
r	reaction rate [$mol/m^3/s$]
R	ideal gas constant (R = 8.314 J/mol/K)
t	deduction period [a]
T	temperature [°C or K]
V	volume [m^3]
w	specific work [J/mol]
x	sorbent loading [mmol/g]
X	sorbent working capacity [%]
y_i	concentration of component in the gas phase [–]
z_i	concentration of component in the liquid phase [–]
Z	capacity coefficient [–]
η	efficiency [–]
θ	ratio of heat recovery [–]
τ	abatement factor [–]
υ	stochiometric coefficient [–]

List of indices

0	standard conditions (1013 hPa, 0 °C)
ads	adsorption
cond	condensation
CO2	carbon dioxide
C2H4	ethylene
des	desorption
el	electric
em	emitted
evap	evaporation
F	fluid
g	gas phase
H2O	water/water vapor
HE	heat exchange
i	component i
in	inlet
j	variable j
k	count variable k
l	liquid phase
min	minimal
NG	natural gas
out	outlet
poly	polytropic
product	product
PEI	polyethyleneimine
rev	reversible
s	saturation
sep	separated
sorbent	sorbent
system	system
t	technical
th	thermal
waste	wasted
W	wall

infrared radiation reflected from the Earth's surface cannot completely pass through the "climate gas layer" in the troposphere, and so is reflected back to the Earth [1,2]. Therefore, the terrestrial temperature increases. The "climate gas layer" consists of water vapor as well as CO_2, methane and nitrous oxide etc. Alongside natural emissions of these climate gases, anthropogenic emissions have led to increased amounts of these gases in the troposphere, which are the highest in at least the last 800000 years [3]. Current measurements show approximately 1800 ppb of methane, 320 ppb of nitrous oxide and 407 ppm of CO_2 [3,4]. Although CO_2 has a global warming potential that is about 1/21 that of methane and about 1/310 that of nitrous oxide over 100 years [5], CO_2, with a current anthropogenic emission of about 38 Gt/a [3], is responsible for about 60% of anthropogenic climate change [6]. As forecast in Pham et al. [6], a CO_2 concentration of 570 ppm can be expected by 2100 as a result of population growth and improving economic conditions. As approximately 1000 ppm could be