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Economic optimisation of European supply chains for CO_2 capture, transport and sequestration, including societal risk analysis and risk mitigation measures

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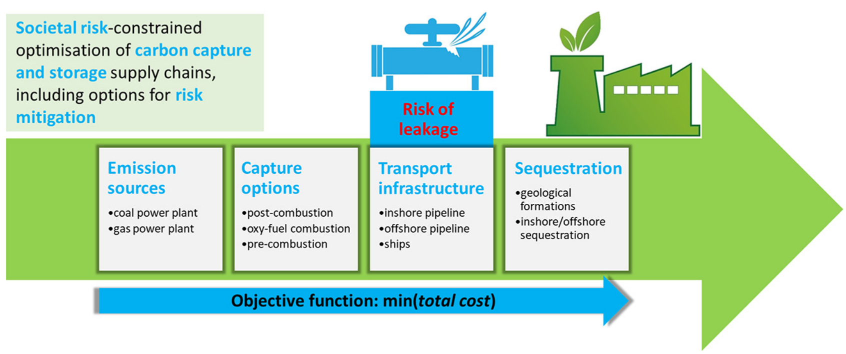
HIGHLIGHTS

- A model for optimising the European carbon capture and sequestration (CCS) is proposed.
- Societal risk analysis is incorporated within the CCS model.
- Risk mitigation measures are included as options for local risk reduction.
- Scenarios assessing different risk definitions and policies are implemented.
- Societal risk does not affect CCS costs significantly, but limits the sequestration potential.

GRAPHICAL ABSTRACT



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ABSTRACT

European large stationary sources are currently emitting more than 1.4 Gt of CO_2 every year. A significant decrease in greenhouse gases emissions cannot be achieved without carbon capture and sequestration (CCS) technologies. However, although being practiced for over 30 years, CO_2 transportation is intrinsically characterised by the risk of leakage. This study proposes to assess and tackle this issue within the CCS design problem, by proposing a spatially explicit mixed integer linear programming approach for the economic optimisation of a European supply chain for carbon capture, transport and geological storage, where societal risk assessment is formally incorporated within the modelling framework. Post-combustion, oxy-fuel combustion and pre-combustion are considered as technological options for CO_2 capture, whereas both pipelines (inshore and offshore) and ships are taken into account as transport means. Both inland-inshore and offshore injection options are available for carbon geological sequestration. Risk mitigation measures are considered in the design of the transport network. The overall supply chain is economically optimised for different minimum carbon reduction scenarios. Results demonstrate that accounting for societal risk may impact the overall carbon sequestration capacity, and that the proposed approach may represent a valuable tool to support policy makers in their strategic decisions.

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Nomenclature

Acronyms

CCS carbon dioxide capture and storage
IDLH immediately dangerous to life or death
LC50 lethal concentration 50%
MILP mixed integer linear programming
MIP mixed integer programming
SC supply chain

Sets

g European region{1, 2, …, 123, 134}
h hazardous incident{*i*, *ii*, *iii*, *iv*}
k capture technology $\{post_{coal}^{comb}, post_{gas}^{comb}, oxy_{coal}^{fuel}, pre^{comb}\}$
l transport mode{*inshore pipeline*, *offshore pipeline*, *ship*}
m mitigation option{*none*, *marker tape*, *concrete slabs*, *deep burying*, *surveillance*}
p transport capacity{1, 2, 3, 4, 5, 6, 7}

Parameters

A area of the hole
α European minimum carbon quota to be captured [%]
$b(x)$ half-width of the section [m]
CCR^{seq} capital cost rate for injection well
C_d release hole of discharge [0.61]
d_g average injection well depth in region g [km]
γ viscosity correction factor [1.00]
$\gamma_{g,k}$ ratio of coal- and gas- fired power plants in region g for capture technology k to be employed
f^{ship} cost factor for ship transport [€/t of CO_2/km]
g_c gravitational constant [m/s^2]
int^{cost} cost for intra-connection within cell g [€/t of CO_2/km]
LD_g size of cell g [km]
$LD_{g,g'}$ matrix of distances between region g and g' [km]
L_h liquid release distance of hazard h [km]
μ average failure rate [faults/year]
m_1 cost parameter for injection well [€]
m_2 cost parameter for injection well [€]
$MF_{m,l}$ mitigation factor of measure m on mode l [%]
η_k capture efficiency for technology k [%]
off_g additional cost of offshore injection well
OM^{seq} maintenance rate for injection well
P_{atm} atmospheric pressure [kPa]
Pd_g population density in region g [people/km^2]
$\overline{Pd}_{g,g'}$ average population density between region g and g' [people/km^2]
$Pf_{h,l}$ probability of hazard h on mode l [events/km]
P_g population in region g [people]
$P_{g'}$ population in region g' [people]
$Pmax_g$ amount of anthropogenic CO_2 that is generated in region g [t of CO_2]
Q_p transported capacity discretisation according to set p [t of CO_2]
$\rho_{l,CO2}$ liquid density of CO_2
SR_g^{max} maximum societal risk in region g [events]
$S_y(x)$ lateral dispersion parameter [m]
$S_z(x)$ vertical dispersion parameter [m]
$Stot_{max}^{CO2}$ maximum capacity of each injection well [t of CO_2]
$terrain_g$ Terrain factor in region g
UCC_k unitary capture cost for technology k [€/t of CO_2]
$UMC_{m,l}$ unitary mitigation cost for measure m through mode l [€/km]
$UTC_{p,l}$ unitary transport cost for size p through mode l [€/t of CO_2/km]

Continuous variables

$\alpha^{stability}$ stability factor
$c(x, y, z)$ vapour concentration at ground level [ppm]
$c_c(x)$ centreline ground-level concentration of CO_2 [ppm]
$Ctot_{k,g}^{CO2}$ carbon capture through k in region g at time period t [t of CO_2]
$\dot{m}_{CO2}$ discharged flowrate of CO_2
N_g^{seq} number of injection wells in region g
P operative pressure of the pipeline [kPa]
P_t failure probability based on Poisson distribution of rare events
$Ptot_{k,g}^{CO2}$ processed CO_2 through technology k in region g [t of CO_2]
$Q_{g,l,g'}^{CO2}$ carbon flowrate transported from g through l to g' [t of CO_2]
$Q_{p,g,l,g'}^{CO2}$ carbon flowrate of size p transported from g through l to g' [t of CO_2]
Ri Richardson dimensionless number
R_t reliability based on Poisson distribution of rare events
$Sh_{h,g,g'}^{inter}$ surface affected by hazard h between region g and g' [km^2]
$Sh_{h,g}^{intra}$ surface affected by hazard h in region g [km^2]
SR_g total societal risk in region g [events]
SR_g^{inter} societal risk in region g produced by inter-connection systems [events]
$SR_{g'}^{inter}$ societal risk in region g' produced by inter-connection systems [events]
SR_g^{intra} societal risk in region g produced by intra-connection systems [events]
$SR_{p,g,l,g'}^{inter}$ local societal risk produced by flowrate p transported from g through l to g' [people·events]
$SR_{g,l}^{intra}$ local societal risk for intra-connection within region g through mode l [people·events]
$Stot_g^{CO2}$ carbon sequestered in region g [t of CO_2]
TCC global total capture cost [€]
TSC global total sequestration cost [€]
TTC global total transport cost [€]
TTC^{dist} scale effect of transport distance on total transport cost [€]
TTC^{intra} effect of intra-connection cost on total transport cost [€]
TTC^{m} total cost for installing mitigation measures [€]
TTC_{inter}^{m} total cost for mitigation on inter-connection systems [€]
TTC_{intra}^{m} total cost for mitigation on intra-connection systems [€]
TTC^{size} scale effect of transport size on total transport cost [€]

Binary variables

$\delta_{m,p,g,l,g'}^{inter}$ 1 if mitigation m is applied on flowrate p from region g through l to g', 0 otherwise
$\delta_{m,g,l}^{intra}$ 1 if mitigation m is applied on intra-connection within region g through l, 0 otherwise
$\lambda_{p,g,l,g'}$ 1 if flowrate p is transported from region g through l to g', 0 otherwise
Y_g 1 if a capture infrastructure is installed in region g, 0 otherwise