**Optimal design of supply chains for carbon capture, storage, and utilisation**

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**Highlights**

* Optimisation of a European carbon capture, transport, and storage network
* Aspects of societal risk and social acceptance can be included in the model
* Mechanisms for costs share and cooperation can foster implementation
* Challenges for carbon capture and utilisation are critically discussed

**1. Introduction**

The global anthropogenic emissions of greenhouse gasses (GHGs) experienced an exponential increase compared to pre-industrial levels and, among these, CO2 is the most abundant, with an overall emission that raised globally from 2 Gt/year in 1850 to over 35 Gt/year in 2010 [1]. Carbon capture and storage (CCS), and utilisation (CCUS) has been highlighted as one of the most promising options to decarbonise the energy sector, which still heavily relies on fossil fuel-fed facilities. When dealing with the strategic design of a European CCS infrastructure, it clearly emerges the necessity of employing quantitative mathematical tools to treat the combinatorial complexity of such large scale networks, in particular, mixed integer linear programming (MILP) for supply chain (SC) optimisation [2]. Addressing the problem of the design and optimisation of a CCS SC in the context of Europe, including the possibility to include carbon conversion and utilisation pathways, while considering uncertainty and consequent risk, aspects of societal risk and social acceptance from the public, along with the assessment of financial schemes for cooperation between stakeholders, are still major challenges for fostering an effective implementation of such a complex system.

**2. Methods**

The base case deterministic framework has been developed according to a MILP model that describes Europe in terms of emissions from large-stationary sources (i.e., coal and gas power plants). Regarding the capture facilities, either post-combustion, pre-combustion, or oxy-fuel combustion have been included as possible options, whereas both pipelines and ships have been described in techno-economic terms as potential transport means [3]. Then, a risk assessment has been incorporated within the modelling framework, accounting for the societal risk generated by a potential leakage in the transport system (quantified according to the seriousness of the hazard), coupled with the choice of installing risk mitigation options (e.g., concrete slabs, deep burying, marker tape, surveillance) [4]. The societal response to CCS have been further analysed through the concept of social acceptance, described through the amount of risk perceived by a population inhabiting within the region where an infrastructure is planned. The social response has been modelled as proportional to the project size, to the amount of population, and to the differential behaviour of the different European countries [5]. Furthermore, a set of constraints has been employed to balance the spread of installation and operation costs between countries, with the aim of fostering economic costs share and cooperation policies between different players. Finally, the effect of some utilisation pathways have been assessed in terms of economic and environmental benefits.

**3. Results and discussion**

The CCS models were optimised using the GAMS CPLEX solver on a 32GB RAM computer. Results from the deterministic framework demonstrated the good European potential for carbon sequestration and gave some indications on the total cost for CO2 capture, transport and sequestration. Capture costs were found to be the major contribution to total cost, while transport and sequestration costs were never higher than 10% of the investment required to set in motion and operate the whole network. The overall costs for a deterministic European CCS SC were estimated in the range of 27-38 €/t of CO2. The societal risk-constrained optimisation demonstrated the possibility to design a safe transport infrastructure with minor additional costs. Indeed, mitigation actions never represented more than 11% of total cost for installing and operating the transport network. However, no feasible solution could be found for a carbon reduction target higher than 50%, because of the unacceptable level of societal risk. When maximising social acceptance from the public (through minimising risk perception of CCS), results led to a massive exploitation of offshore sequestration solutions with a (possibly unacceptable) a total costs of about 50.88 €/t of sequestered, i.e. +34% with respect to the economic optimum, due to a more complex network configuration characterised by high transport (+434%) and sequestration (+853%) costs. A multi-objective optimisation analysis, however, allowed identifying a possible intermediate solution between the two conflicting objectives (i.e., economics against acceptance), capable of limiting risk perception, without excessively compromising the economic performance of the network. Regarding the model including costs share mechanisms between European countries, results showed that the additional European investment for cooperation (max. +2.6% with respect to a non-cooperative network) should not constitute a barrier towards the installation and operation of such more effective network designs. Finally, a preliminary analysis on CCUS indicated that some CO2 utilisation pathways for the production of chemicals (e.g., PPP, MeOH) can have a positive effect in decreasing costs of the overall supply chain.

**4. Conclusions**

In this work it has been developed a time-dependent, multi-echelon, spatially-explicit, large-scale, European digital optimisation tool, aiming at the strategic high-level definition of a CCS SC. These models will provide valuable insights into the optimal economic deployment of CCS technologies at a noteworthy scale that was never investigated before, and will be able to steer relevant research and policy into addressing correctly the problem of global warming through CCS.

**References**

1. IPCC, Climate Change-Synthesis Report, Geneva, 2014.
2. M. Bui, et al., Energy Environ. Sci. 11 (2018) 1062-1176.
3. F. d’Amore, F. Bezzo, Int. J. Greenh. Gas Control 65 (2017) 99-116.
4. F. d’Amore, P. Mocellin, C. Vianello, G. Maschio, F. Bezzo, Appl. Energy 223 (2018) 401-415.
5. F. Karimi, A. Toikka, Int. J. Greenh. Gas Control 70 (2018) 193-201.