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Modelling large-scale CCS development in Europe – linking techno-economic modelling to transport infrastructure

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Abstract

This paper studies the potential lay-out of CCS infrastructure in Europe, by combining techno-economic modelling of Europe's electricity sector with a detailed modelling and analysis of a CO_2 transport infrastructure. First, the electricity sector is described using the *Chalmers Electricity Investment Model*, which, for each EU member state, yields the technology mix – including CCS - until the year 2050. The model gives the lowest system cost under a given CO2 emission reduction target. Thus, the model gives the annual flows of CO_2 being captured by country and fuel. Secondly, these flows are used as input to *InfraCCS*, a cost optimization tool for bulk CO_2 pipelines. Finally, the results from *InfraCCS* are applied – along with Chalmers databases on power plants and CO_2 storage sites – to design the development *over time* of a detailed CO_2 transport network across Europe considering the spatial distribution of power plants and storage locations. Two scenarios are studied: with and without *onshore* aquifer storage. The work shows that the spatial distribution of capture plants over time along with individual reservoir storage capacity and injectivity are key factors determining routing and timing of the pipeline network. The results of this work imply that uncertainties in timing for installation of capture equipment in combination with uncertainties related to accurate data on storage capacity and injectivity on reservoir level risk to seriously limit the build-up of large-scale pan-European CO_2 transportation networks. The study gives that transport cost will more than double if aquifer storage is restricted to offshore reservoirs. Thus, it is found that the total investments for the pan-European pipeline system is € 31 billion when storage in onshore aquifers is allowed and € 72 billion if aquifer storage is restricted to offshore reservoirs with corresponding specific cost of € 5.1 to € 12.2 per ton CO_2 transported.

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Keywords: Energy system modelling; CCS; timing; infrastructure; optimisation; injectivity.

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1. Introduction

The EU Commission has proposed that the EU should reduce GHG emissions by 80 to 95% below 1990 levels by 2050, i.e. in reality implying a near 100% reduction in CO_2 emissions from the stationary energy sector. However, the Commission has also recognised the continued importance of fossil fuels in order to have a diversified energy mix and thereby achieving a high degree of supply security and that continued use of fossil fuels will have to be combined with CCS (Carbon Capture and Storage) if long-term GHG emission reduction objectives are to be reached [1].

This study combines techno-economic modeling of the power and heat sector in Europe yielding annually captured CO_2 by country and by fuel, with a cost optimisation model for large-scale CO_2 pipeline transportation network in two scenarios up to 2050. In a second step the large-scale bulk CO_2 transportation network is developed into a detailed collection, transmission and distribution network, applying Chalmers databases of CO_2 sources and storage sites. Information on storage locations, storage capacity and injectivity has been applied as input to the network analysis. Thus, this study analyses the build-up of large-scale pan-European CO_2 transportation networks. Several such studies exist, like for instance the CO_2-Europipe project [2], the ARUP study [3] and Element Energy [4]. These studies have all provided valuable insights into the build-up of large-scale CO_2 transportation networks across Europe or the North Sea region. Yet, what has been lacking is analysis considering *the spatial distribution of capture plants over time*. The aim of the present work is to develop a methodology to introduce CCS over time utilising Chalmers databases of power plants and CO_2 storage sites in combination with modeling of the electricity generation system, i.e. to introduce capture plants and the ramp-up system requirements over time and thereby also identifying major challenges to large-scale pan-European CO_2 networks. Furthermore, this study analyses two cases; with and without onshore storage giving a first estimate of the economic implications of rejecting onshore storage on a country-by country level.

2. Methodology

The techno-economic model used in this work, the ELectricity INvestment Model (ELIN) [5], applies Chalmers Power Plant database which contains data on existing power plants in EU plus Norway and Switzerland to find the technology and fuel mix in the electricity generation system from the present up to the year 2050. The model yields the economic optimum fuel mix based on minimizing the net present value of the sum of annual costs of generating electricity in the MSs investigated (excluding taxes and subsidies) over the time period studied. The driving force to reduce CO_2 emissions is included through an endogenous price on CO_2 emissions, which is calculated in the model as the marginal cost of abatement through an exogenous emission cap given in the scenario investigated. In the scenario of this work (see the “Policy” scenario in [5] for details), the CO_2 constraints to 2020 reflects the higher ambition by EC as strived for while negotiating international treaties, i.e. an overall target of reducing GHG by 30% relative 1990 emissions. This implies that the reduction in CO_2 required within the power generation sector should be 40% [5]. Post 2020 the annual CO_2 emission cap is reduced linearly to meet the 85% emission reduction by 2050. Electricity from renewable energy sources (RES) is according to current 20% EU target for 2020, here assumed as a common target for the region studied and interpreted for the electricity system to 30% RES by 2020 [5]. Post 2020, RES is assumed to grow up to 45% by 2050. There are re-investments in nuclear in existing plants, but not in Germany and Belgium for which current political decisions are assumed to remain. Finally, the assumed efficiency improvements and demand management lead to only a modest increase in demand for electricity (0.5% on average per year). One result from the modelling is the amount of installed CCS based electricity generation capacity and the captured volumes of CO_2 on an annual basis by fuel and by country from 2020 onwards (when CCS is assumed commercially available). The ELIN model includes estimates of the total CCS cost, i.e. cost of capture, transport and storage, differentiated between EU member states based on a previous evaluation of transport and storage costs. Thus, the present work refines the transport cost used by the ELIN model and gives a detailed routing of pipelines both with respect to geographical allocation and ramp-up over time.

The CCS capacities and corresponding amounts of captured CO_2 as obtained from the modeling, are linked to the InfraCCS model [6], which is an optimisation model providing the bulk CO_2 transport network at European scale which gives the lowest cost for the period 2015-2050 (although in this work CCS is not assumed commercially available until 2020 as indicated above). Storage sites and their capacities used by InfraCCS are obtained from the EU GeoCapacity project [7], applying the 'conservative' set of estimates on storage capacities apart from in three countries; Germany, Italy and Poland where more recent data have been applied [8-11]. One important feature of the InfraCCS optimisation model is that the model jointly optimises the deployment across the full time horizon, i.e. the sizing and construction decisions for pipelines in different years are considered simultaneously. Thus, the model may e.g. decide to build a large underutilised pipeline in 2020, in anticipation of additional future flows that will arrive only around 2030. Indeed, such a decision may be cheaper than building many smaller parallel pipelines over time. In summary, the InfraCCS model optimises the timing of various investments in order to be able to accommodate the time-varying flows of CO_2 at the lowest possible cost.

The bulk pipeline system provided by InfraCCS is then used as input to an analysis of a detailed CO_2 collection and distribution network applying Chalmers databases of CO_2-sources and sinks. As mentioned above, modeling of the electricity sector gives annual CCS based capacity additions by country and fuel. Starting from the bulk network developed by InfraCCS and utilizing Chalmers databases of power plants and CO_2 storage sites, the pipeline system is being expanded to comprise collection and distribution systems. Each capture plant is assumed to have a capacity of 1 GW and to replace an existing plant based on age so that CCS based capacity and CO_2-volume by fuel for each country and in each year correspond to the CCS based capacity and CO_2-volume provided by ELIN modelling results. This method yields the spatial distribution of capture plants over time. However, all pipeline segments in the expanded network have been sized with regard to peak flow through that particular segment.

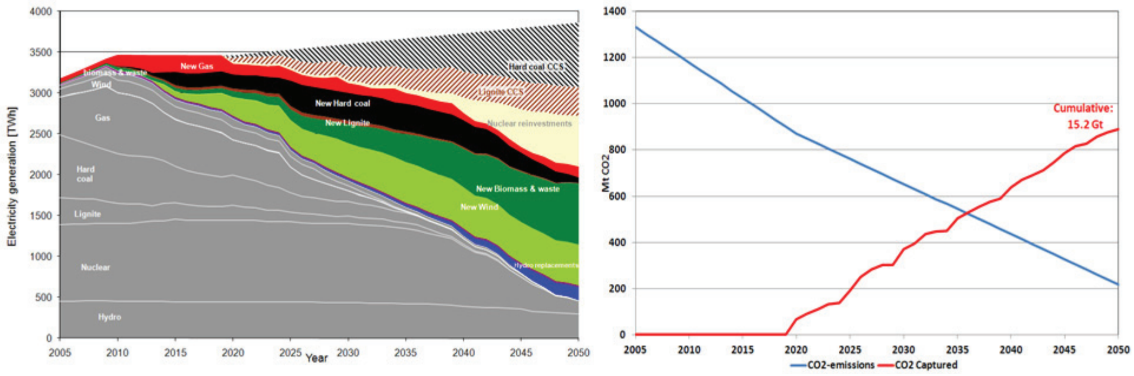
Chalmers CO_2 storage database contains reservoir specific information on some 1,800 aquifers, gas and oil fields in Europe [12]. Storage capacity on individual reservoir level has been adjusted in order to correspond to the conservative capacity provided by the GeoCapacity project apart from, as mentioned above, in Germany, Italy and Poland. Following [6], we make the assumption that the ratio between storage capacity of a reservoir and its maximum injection rate should be comparable to the R/P ratio of the petroleum sector, i.e. we make what should be a reasonable assumption that injection of a fluid into a reservoir is technically comparable to the extraction of a fluid from the reservoir. According to [13], the global R/P ratio of oil was 45.7 years in 2009. We therefore assume a minimum time of 45 years required to fill up any reservoir, which is in line with [14] and very similar to the approach used in [15] to model large reservoirs: the latter authors use the same type of restriction, but with 40 years instead of 45 years. Furthermore, only reservoirs with a minimum storage capacity of 10 Mt has been considered while maximum well injection capacity has been set to 1 Mt per year, the latter determining the number of dedicated injection pipelines. In the CO_2 infrastructure analysis of this work only cost for transport of CO_2 has been calculated, no cost for storage is included apart from the cost of dedicated injection pipelines.

Investment cost for pipelines have been calculated applying the CO_2 pipeline cost equation given in [16], while cost for booster pumps have been taken from [17]. All investments have been annuitized with 20 years depreciation time and a discount rate of 8%. Operational cost of pipelines have been set to 3% of total investments while operational cost for pumps have been assumed to 5% of investments plus cost of electricity which was taken from the ELIN modeling; € 0.056/kWh representing the average electricity price over the period studied. All costs have been converted to € 2011 based on average annual exchange rate for Euros versus US dollar as provided by the European Central Bank and IHS UCCI (Upstream Capital Cost Index). Annual cost 2020 to 2050 have thereafter been summarised and divided by the cumulative amount of CO_2 that has been transported over the same period to derive specific cost per ton. For each country, system specific cost has been calculated adding annual CAPEX and OPEX over the period for all pipelines relevant for that particular country, and then the sum has been divided by the cumulative amount of CO_2 transported over the same period (2021 to 2050). When two or more countries have shared a pipeline segment, the cost has been shared between the countries involved based on their share in the cumulative flow through that particular pipeline segment.

Since there are large uncertainties with respect to public concerns for onshore storage in saline aquifers, two different scenarios have been analysed. The first case assumes that all storage sites in the EU GeoCapacity project are available. The second assumes that onshore saline aquifers are not available.

3. Results

Figure 1 shows the aggregated generation by fuel between 2005 and 2050 (Figure 1a) and the corresponding annual volumes of CO_2 being emitted and captured (Figure 1b) as obtained from the ELIN model. Figure 1a implies a significant contribution from renewable sources and, due to the effect of demand management and measures to raise efficiency there is a relatively modest increase in demand. The grey areas in Figure 1a refer to the existing system being phased out over time (as a result of that the plants have reached their assumed technical life time or become too costly to operate due to the endogenous increase in CO_2 penalty).



a. b.

Figure 1. Generation by fuel/technology 2005-50 as modelled by ELIN (a) for a CO_2 emission reduction of 85% until year 2050. The grey areas show generation from existing plants being phased out over time. Corresponding amount of CO_2 emitted (blue) and captured (red) 2005-2050 (b).

According to model results, CCS starts up in 2020 at relatively modest levels, after which captured volumes of CO_2 increases rapidly to reach almost 900 Mt per year in 2050 and cumulatively, some 15.2 Gt CO_2 is transported over the period. Italy, Germany and Hungary account for the largest volumes of CO_2 being transported over the period; 4.1, 3.5 and 2.0 Gt respectively.

In the case when storage in onshore aquifers is allowed, the total European system comprises 19,100 km of pipelines including 1,000 km offshore segments. Total investments reach € 31.4 billion with corresponding system specific cost amounting to € 5.1 per ton. Specific cost on national levels ranges from € 0.7 to 12.4 per ton. As an example; for Italy, it has been assumed a total storage capacity of 7.5 Gt [10] which gives an annual injection capacity corresponding to 167 Mt. However, according to model results, Italy exceeds their domestic injection capacity in 2040 leading to export of some 570 Mt to reservoirs in Poland yielding a marginal specific cost of € 24.0/ton.

Almost 2 Gt are injected on aggregate between 2020 and 2050 into three aquifers in the Paris basin; Buntsandstein, Lias and Dogger with annual injection peaking in 2050 at 169 Mt. This is close to the maximum injection capacity assuming a minimum injection period of 45 years (176 Mt per year). Large amounts of CO_2 are also injected into aquifers in Poland, some 3.2 Gt in aggregate by 2050 but still well below the estimated maximum annual injection capacity of almost 390 Mt assuming a total storage capacity of 17.5 Gt [11]. Figure 2 shows the final European transport system in 2050 for the scenario *allowing* storage in onshore aquifers.

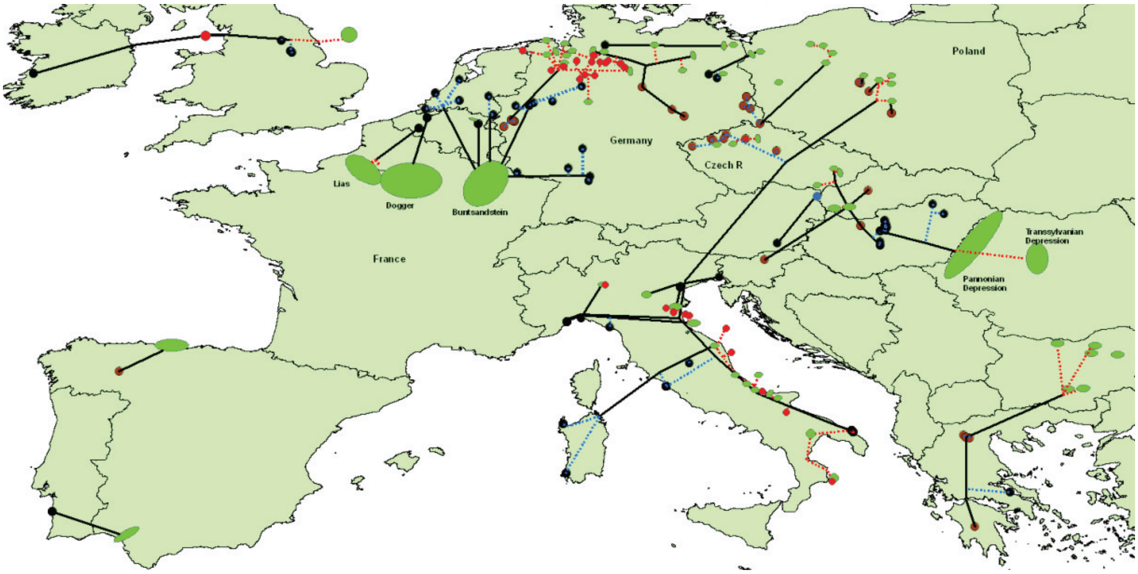


Figure 2. Final transport system in 2050 in the case where onshore aquifer storage is allowed. Blue lines indicate collection pipelines, black lines bulk pipelines, red lines distribution pipelines while gas, oil fields and aquifers are shown in red, blue and green respectively. Black circles denote coal plants while brown circles denote lignite plants.

In the case where storage in aquifers is restricted to offshore reservoirs, total pipeline length increases to 28,100 km including 6,200 km offshore pipelines, mostly in the North Sea. Total investments more than doubles to € 72.3 billion while corresponding specific cost reach € 12.2 per ton. Specific cost on national levels ranges from € 3.1 to 30.3 per ton. Italy, Germany and Hungary, all having large part of their storage capacity in onshore aquifers, are then forced to export large volumes of CO_2 to the North Sea; 1.0 Gt from Italy (plus 1.2 Gt to France and Spain), 2.1 Gt from Germany (of which 700 Mt in German aquifers in the North Sea) and 1.8 Gt from Hungary. It should also be noted that while this study analyses cost for transport only, cost for storage is also likely to increase markedly if large volumes have to be stored offshore. Figure 3 shows the European transport system in 2050 when aquifer storage is restricted to offshore reservoirs.

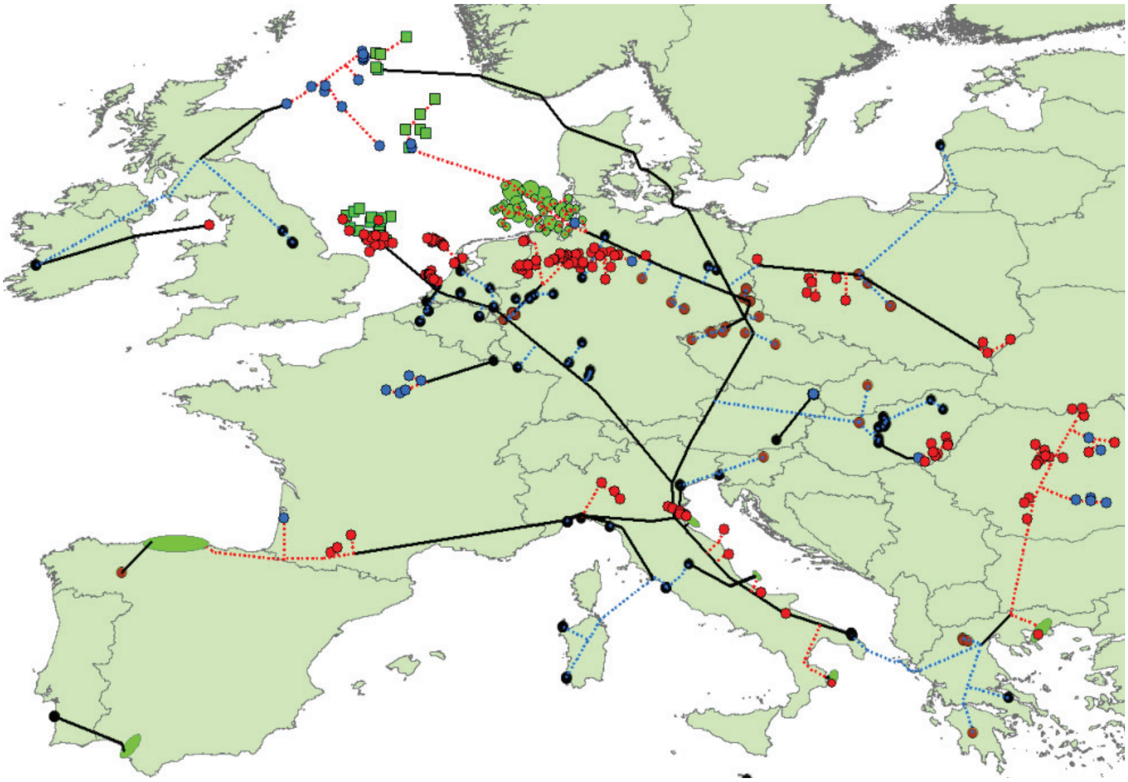


Figure 3. Final transport system in 2050 in the case where onshore aquifer storage is *not* allowed. The graphs correspond to the fully developed system in year 2050. Blue lines indicate collection pipelines, black lines bulk pipelines, red lines distribution pipelines while gas, oil fields and aquifers are shown in red, blue and green respectively. Black circles denote coal plants while brown circles denote lignite plants.

4. Discussion

In both scenarios, the collection and distribution networks account for 55% of the total system cost. The bulk system developed by InfraCCS refers to a cost minimized system while the corresponding collection and distribution networks developed by Chalmers have not been subject to cost minimization since all pipelines have been designed based on plateau flow. However, given the accurate location of both sources over time and storage sites applied in this study and the relatively rapid build-up of CO_2-volumes in combination with the fact that there is considerable economy of scale in pipeline transport, most pipeline systems calculated in this study should nevertheless have cost fairly close to the lowest possible cost.

As mentioned above, in the scenario where storage in onshore aquifers is allowed, large volumes of CO_2 are injected into aquifers in the Paris basin and in Poland. However, more recent storage data suggests that the estimated storage capacity in onshore Polish aquifers is almost 50% lower than previous estimates in [11], yielding a capacity of only 9 Gt [18]. Also, the applied storage capacity in aquifers in the Paris basin has, by GeoCapacity, been characterized as "theoretical conservative capacity" indicating that true storage capacity may be significantly lower. This is not at least demonstrated by the GeoCapacity project in the so-called "Resource-reserve Pyramid Concept" where theoretical capacities are quoted to "include large uneconomic/unrealistic volumes referring to regional estimates without storage efficiency"

[19]. In addition, several onshore storage projects in Europe have met considerable local opposition leading to that the project has been abandoned (e.g. Shell's Barendrecht project in the Netherlands and RWE's plans to store CO_2 in an aquifer in northeast Schleswig Holstein). In other words, considering 1) the large uncertainties related to true storage capacity in European onshore aquifers, 2) the experiences so far with regard to public and local acceptance of onshore storage and 3) the large volumes of CO_2 considered in this report, it appears likely that large-scale penetration of CCS in Europe will require substantial offshore storage which in turn will lead to a significant cost increase as evidenced above. It could be argued that the storage capacity could be higher than GeoCapacity's conservative value but so far the experience has been the opposite, both in for instance Germany and Poland where the estimated storage capacity has been considerably reduced over time as more knowledge has been acquired.

The pipeline networks have in both scenarios been designed applying Chalmers databases of power plants and CO_2 storage sites assuming conservative and updated data on storage capacities while it has been assumed a minimum injection period of 45 years required to fill up a reservoir. Accurate data on storage capacity and injection capacity is vital for development of large-scale CO_2 transportation networks, in particular since such networks usually will require long periods for planning and implementation. Yet, data on individual reservoirs storage and injection capacity is highly site specific and in many cases it will probably require drilling in the reservoir to provide reasonably accurate estimates which, however, is unlikely to happen unless there are firm plans to actually capture, inject and store the CO_2.

A decision to install capture equipment on a facility will require large up-front investments and the investment itself as well as the *timing* of the investment will most certainly be based on company specific conditions, i.e. the spatial distribution of capture plants *over time* will be based on separate decisions made in each of the respective utilities and companies involved. This fact alone may limit the build-up of large-scale pan-European CO_2 pipeline networks unless some other party is willing to take the risks of building a large-scale pipeline being initially underutilised. Moreover, as the better storage sites are likely to be utilised first, the remaining stock of storage sites and storage capacity will deteriorate over time leading to longer transport distances and higher cost which may limit the future interest in CCS, i.e. the risk for long-term underutilised bulk pipelines increases over time. This is even more so since storage capacity figures to a large extent are highly uncertain and probably will remain so for most of the stock for a considerable time since few parties will be interested in taking the cost for a detailed investigation of the site until capture becomes a realistic mitigation alternative, in particular this applies to offshore sites where investigation cost are significant.

The spatial distribution of capture plants over time along with the location of storage capacity and injection capacity are the main factors determining the routing and timing of the network and therefore also network investments. The methodology applied in this paper to introduce CCS plants both geographically and over time attempts to develop a methodology for the design of large-scale CCS infrastructure systems.

5. Conclusions

In order to analyze large-scale CO_2 transport systems in Europe this study has combined modeling of the role of CCS in Europe's electricity sector with a cost optimization tool for large-scale bulk CO_2 pipelines which, in turn has been re-designed adding a collection and distribution network utilizing Chalmers databases of CO_2-sources and sinks. Two scenarios were studied; with and without *onshore* aquifer storage.

The result shows that transport cost increase significantly when storage in aquifers is restricted to offshore reservoirs forcing large amounts of CO_2 to be stored in the North Sea, in fact total investments for the whole pan-European system more than doubles from € 31 billion when onshore aquifers can be utilised to € 72 billion in the case where onshore aquifers cannot be utilized leading to specific cost increasing from € 5.1 to 12.2 per ton. The results also show that the collection and distribution parts of the network account for a significant share of total system cost, in this study 55% in both scenarios.

The results of this work imply that uncertainties in timing for installation of capture equipment in combination with uncertainties related to accurate data on storage capacity and injectivity on reservoir level risk to seriously limit the build-up of large-scale pan-European CO_2 transportation networks.

The methodology applied in this paper to introduce CCS plants both geographically and over time attempts to develop a methodology for the evaluation and assessment of large-scale CCS infrastructure systems during a ramp-up period. This information should be of high importance for society when evaluating the role of CCS as a climate mitigation measure.

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