Optimised deployment of a European CO_2 transport network

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Abstract

If CO_2 Capture and Storage (CCS) is to become a viable option for low-carbon power generation, its deployment will require the construction of dedicated CO_2 transport infrastructure. This paper describes the *InfraCCS* model, which can determine the likely extent and cost of the optimal least-cost CO_2 transport network at European scale for the period 2015-2050, with 2015 the earliest foreseeable starting date of the CCS projects co-funded by the European Energy Programme for Recovery (EEPR), and 2050 the EU's target date for 80-95% reduction of greenhouse gas emissions. The computation is made possible by a number of methodological innovations compared to previous research, in particular: the use of *k-means clustering* to reduce the number of nodes in the network; the application of the *Delaunay triangulation* algorithm for pipeline pre-selection; and the introduction of a mathematically convenient yet realistic new pipeline costing model. The *InfraCCS* tool is applied to determine the optimal network corresponding to a CCS scenario that ensures near-complete decarbonisation of the European power sector. It is shown that the size of the CO_2 network could range from 11000 to 17000 km by 2050, requiring 16 to 36 billion Euros investment, with the higher numbers corresponding to the case when onshore aquifers are excluded as potential CO_2 storage sites. Since the model shows that by 2030 more than half of the EU Member States could be involved in cross-border CO_2 transport, international coordination seems crucial for the development of an optimised trans-European CO_2 transport network.

Keywords: CCS; CO_2; infrastructure; pipelines; optimisation; mixed-integer linear programming

1. Introduction

Fossil fuels are likely to remain the main source for electricity generation in Europe, at least in the short to medium term, despite the significant ongoing efforts to promote renewable energy technologies and energy efficiency (see e.g. Tzimas, 2009). Therefore, CO_2 Capture and

Storage (CCS) is generally considered as a promising technological option for reducing CO_2 emissions from the power generation sector, as well as from other heavy industries. CCS is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location (such as a depleted hydrocarbon field or a saline aquifer) and long-term isolation from the atmosphere (see e.g. IPCC, 2005). CCS may offer a bridge between the fossil fuels dependent economy and the carbon-free future.

Large-scale deployment of CCS in Europe will require the development of new infrastructure to transport the captured CO_2 from its sources (e.g. power plants) to the appropriate CO_2 storage sites. As pointed out before (Tzimas, 2009; Morbee et al., 2010), there are different views on how such CO_2 transport infrastructure might evolve in Europe. On the one hand, there is often a perception that CCS plants will be built in close proximity to potential storage sites in order to reduce transport costs. On the other hand, proposals for CCS projects that have become public often show that their location is dictated by other factors, such as safety and public acceptance concerns that may require that CO_2 is initially stored offshore; or the presence of old power plants that are suitable for retrofitting or refurbishing with CO_2 capture technologies. Furthermore, as echoed in a recent communication from the European Commission (2010b), the large-scale deployment of CO_2 capture facilities in Europe, which would be needed to achieve the decarbonisation of the European energy system by 2050,[1] combined with the fact that CO_2 storage sites and capacities are not uniformly distributed across Europe, will quickly exhaust local storage opportunities and require the construction of an extended transport infrastructure, which will span across national borders when countries do not have adequate domestic CO_2 storage capacity.

The evolution of the CO_2 transport network in Europe will be dictated by the level of CCS deployment and the degree of coordination for its development (Morbee et al., 2010). The simplest approach for the

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[1] For instance, a scenario such as *Power Choices* (Eurelectric, 2010), which is in line with the EU’s 80% to 95% greenhouse gas emissions reductions targets (as repeated in a recent communication by the European Commission, 2010a), projects more than 1 Gt/y of CO_2 captured in the EU by 2050.

development of the CO_2 transport infrastructure would be the construction of numerous pipelines linking individual CO_2 sources with sinks, sized to meet the transport needs of individual capture facilities. This implies that pipelines will be constructed in the context of individual CCS projects and their planning and construction will be synchronous to the development of the CO_2 capture facilities. However, as pointed out by Morbee et al. (2010), this approach is likely to impede the large-scale deployment of CCS as it will not allow for the expansion and sharing of the infrastructure with other CO_2 sources, which in turn will be required to develop their own pipelines, resulting in deployment delays due to permitting procedures, and additional costs, since pipeline costs do not scale proportionally with transport capacities. Apparently, this situation would be most detrimental for CO_2 sources that are either of small size or located away from suitable storage sites. Alternatively, as also highlighted by the European Commission (2010b), the development of integrated pipeline networks, planned and constructed initially at regional or national level and oversized to meet the transport needs of multiple CO_2 sources, would take advantage of economies of scale and enable the connection of additional CO_2 sources with sinks in the course of the pipeline lifetime. As an example, Morbee et al. (2010) and the European Commission (2010b) cite the Pre-Front End Engineering Design Study of a CCS network for Yorkshire and Humber (CO2Sense, 2010), which showed that initial investment in spare pipeline capacity would be cost-effective even if subsequent developments were not to join the network for up to 11 years. They point out that the CO2Sense (2010) study also confirmed experience from other sectors i.e. that investing in integrated networks would catalyse the large scale deployment of CCS technologies by consolidating permitting procedures, reducing the cost of connecting CO_2 sources with sinks and ensuring that captured CO_2 can be stored as soon as the capture facility becomes operational. In the longer run, according to the European Commission (2010b), such integrated networks could be expanded and interlinked to reach CO_2 sources across Europe and distant storage sites, leading to the development of a true trans-European network, similar to the existing networks for electricity and gas. The European Commission (2010b) suggests that the realisation of such CO_2

transport infrastructure would require a timely start of coordinated infrastructure planning and development at European level.

The aim of this paper is to present an optimisation model, named the *InfraCCS* model, that can describe the likely extent and cost of a CO_2 transport network at European scale for the period 2015-2050. Our work fits in the existing CCS literature on the economics of CO_2 transport. A large part of this literature deals with direct source-sink connections (with occasional attention for the benefits of coordinated infrastructure, as in e.g. Svensson et al., 2004), or with pre-defined transport system options, such as Odenberger et al. (2008) or Haugen et al. (2010). Our work, by contrast, aims at computing an *optimal* network, under the assumption of international coordination. The CO_2 network optimisation question has recently received significant attention. Kazmierczak et al. (2009), for example, provide a CO_2 pipeline network optimisation algorithm based on a heuristic approach. Rather than developing a heuristic solution, our model follows the approach of Middleton and Bielicki (2009), who formulate the problem as a mixed-integer linear programme that can be solved towards a global optimum using state-of-the art optimisation engines. Middleton and Bielicki's (2009) model is limited to a static snapshot and does not include a gradual build-up over time, apparently because the resulting model would be "extremely computationally intensive to solve" (p. 1059). Our *InfraCCS* tool, by contrast, does include the gradual deployment of infrastructure over the course of five interdependent time-steps. Timing is also considered by e.g. Broek et al. (2010a, 2010b) and Klokk et al. (2010). However, these two models are focused on one country and the applications described include only around 20 nodes (sources and sinks combined). As we will see below, the pan-European scope of our *InfraCCS* model requires close to 100 nodes, i.e. four times more than the latter two studies, and also almost double the number of nodes included in the case study of Middleton and Bielicki (2009). Since the computational complexity of the optimisation process can be assumed to be exponential in the number of nodes, the major contribution of our *InfraCCS* model is that it introduces a number of methodological improvements which allow for a pan-European scope with multiple time-steps while keeping the model computationally tractable. As will be explained below, these improvements in *InfraCCS* consist of the use of computational geometry techniques for automatic clustering and pipeline preselection[2], as well as a mathematically convenient yet realistic pipeline costing concept. Furthermore, our model contains an enhanced routing algorithm that can deliver slightly more accurate results than the eight-neighbour-cell algorithm used by both Middleton and Bielicki (2009) and Broek et al. (2010a, 2010b).

Pan-European networks of CO_2 have been considered in previous research. The *CO2Europipe* project (Neele et al., 2010) develops a large-scale European CCS transport and storage network. In contrast to our optimisation-based model, their approach is based mostly on manual design. The model developed by Mendelevitch et al. (2010) provides an optimisation view of North-West European CO_2 infrastructure over time, using a grid of cells of approximately 100x100km, with pipelines only possible in North-South, East-West and 45º angles between the cells. By contrast, the clustering and triangulation approach used in *InfraCCS* allows for free location of sources and sinks, and does not put any constraints on pipeline angles. On the other hand, Mendelevitch et al. (2010) endogenise the decision regarding the amount of CO_2 captured (as is also the case in e.g. Broek et al., 2010a, 2010b), while our *InfraCCS* model takes an external capture scenario as input.

The remainder of the paper is organised as follows. Section 2 describes the *InfraCCS* methodology and the innovations that make it computationally tractable. As an illustration of the model, Section 3 presents the input assumptions and model outcomes of the simulation of two case studies. Section 4 provides a discussion of the results, and Section 5 summarises our conclusions.

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[2] An alternative way to address the same issue is the methodology proposed by Johnson and Ogden (2010), who construct a candidate pipeline network for Texas and surroundings based on existing natural gas pipeline rights-of-way.

2. Methodology

2.1. Optimisation model

The objective of our *InfraCCS* tool is to find the optimal, i.e. cost-minimising, pipeline network that is capable of transporting given amounts of CO_2 from capture sources to the optimal sinks.[3] Let us define this problem more precisely. All sources and sinks are 'nodes' in the network. Let N denote the total number of nodes. Assume that there are P possible pipelines that connect these nodes, and T possible points in time at which these pipelines can be built. The objective of the optimisation is to find the optimal choice of pipelines (among the P possible pipelines) that should be built at each of the T points in time, in order to make sure that all CO_2 captured at each of the nodes can be transported to other nodes that have sufficient CO_2 sink capacity. The difficulty of this optimisation problem lies in the fact that pipeline construction is a binary decision: one cannot build 'half' of a pipeline.[4] As a result, the optimisation question becomes a Mixed-Integer Linear Programme, which is in many cases NP-hard[5] to solve. Let us consider the total number of combinations as a measure for computational complexity, although modern solvers obviously do not perform an exhaustive search. Since every pipeline can be built at any point in time, the number of binary decisions is $P \cdot T$ and the computational complexity of an exhaustive search is on the order $O(2^{PT})$. [6]

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[3] Transporting CO_2 by ship would be an alternative to pipelines. While our *InfraCCS* model is flexible enough to accommodate shipping, we do not consider it here, for the sake of expositional clarity. Indeed, pipelines currently seems to be the most mature technology for CO_2 transport. Despite some technical challenges compared to natural gas pipelines, the large-scale transportation of CO_2 by pipeline is an established industrial process in the USA, with 3900 km of pipelines transporting 30Mt of CO_2 annually (Morbee et al., 2010). Furthermore, the fact that many possible CO_2 sources and sinks are onshore, provides an additonal advantage to pipelines. In support of this argument, Tzimas (2009) notes that only one out of the seven archetypal projects identified by ZEP (2008) envisages CO_2 transport by ship.

[4] Obviously, it is possible to build a pipeline with half the capacity, however the point here is that the cost of such a 'half' pipeline would be much more than half the cost of the original pipeline, due to the economies of scale in pipeline construction.

[5] This term from computational complexity theory refers to a class of problems for which no efficient solution algorithm exists today. Solution time of such problems with current algorithms typically goes up exponentially as a function of the dimensions of the problem.

[6] The symbol $O(\cdot)$ is used here for "Big O notation", which describes the asymptotic behaviour of an algorithm.

Many earlier studies, such as Middleton and Bielicki (2009) and Broek et al. (2010a, 2010b), consider possible pipeline connections between all sources and all sinks. As a result, P becomes quadratic in N. Furthermore, all optimisation models mentioned in Section 1 consider multiple discrete possible diameters for each possible pipeline connection. Consequently, we find that $P = \alpha N^2 D$, with D the number of possible diameters and α a constant. The computational complexity of an exhaustive search is therefore $O(2^{\alpha N^2 DT})$, which increases very rapidly with N and hence creates challenges when the scope is pan-European (N large), especially when there are multiple time-steps ($T > 1$), as is the case in our paper.[7] Therefore, Section 2.2 proposes an automatic clustering approach that makes N as low as possible for a given desired level of accuracy. Despite the clustering approach, we find that for our pan-European scope, we require $N = 94$, which is much larger than the number of nodes in other studies, so that further reduction of computational complexity is required. Therefore, in Section 2.3, we propose a pipeline pre-selection algorithm, which makes P linear (instead of quadratic) in N. Furthermore, in Section 2.4, we develop a new CO_2 pipeline costing concept, which does not require the use of multiple discrete pipeline diameters in the optimisation, thereby making $D = 1$ without loss of generality. As a result of these improvements the computational complexity of exhaustive search is reduced from $O(2^{\alpha N^2 DT})$ to $O(2^{\alpha NT})$, which remains tractable for much larger values of N. In addition to the improvements in the optimisation model, the *InfraCCS* tool also contains an improved GIS-based pipeline routing algorithm, which is described in Section 2.5. Finally, Section 2.6 provides the full mathematical specification of the optimisation model.

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[7] It should be noted that while both Middleton and Bielicki (2009) and Broek et al. (2010a, 2010b) consider possible pipeline connections between all sources and all sinks, they do apply a subsequent reduction of the number of pipelines, by eliminating duplication of candidate pipeline segments that happen to follow the same routing. In a pan-European scope however (as in this paper), and when using a coarser cost surface, such accidental overlapping is much less common, hence we need to assume the worst-case behaviour, namely $P \sim N^2$.

2.2. Automatic clustering of sources and sinks

The E-PRTR (2010) emissions database contains 6484 CO_2 emissions sources in the EU-27, of which 1335 in the power sector. Likewise, the EU GeoCapacity database contains around 2000 aquifers and hydrocarbon fields, that can be used for CO_2 storage (Vangkilde-Pedersen et al., 2009c).[8] Obviously, if all of these sources and sinks were to be included as nodes in the network, then N would be far too large for the model to be tractable. For reasons of computational complexity, nearly all previous models mentioned in Section 1 contain some kind of 'clustering' procedure, which groups sources or sinks that are close to each other, into 'clusters'. Only the cluster centres become nodes in the network. In small-scale studies, such clusters can easily be identified manually. Given the pan-European scope of *InfraCCS*, however, we propose an automatic clustering procedure based on the *k-means* algorithm.

Let us consider C countries, and assume these countries contain M sources and sinks in total, of which M^S sources, M^A aquifer sinks and M^H hydrocarbon field sinks. The number of sources in each country c is denoted $M^{S,c}$, with $c = 1,...,C$. The geographical coordinates of the sources in country c are given by $(x_m^{S,c}, y_m^{S,c})$ with $m = 1,...,M^{S,c}$. Since sources are different in size, we assign weights $w_m^{S,c}$, $m = 1,...,M^{S,c}$. The same definitions apply to aquifers and hydrocarbon fields, with superscript S replaced by A and H respectively. We assume that the sum of all weights is 1. The objective is to determine N clusters (with $N < M$), which are distributed across all C countries. Suppose that country c contains $N^{S,c}$ source clusters, $N^{A,c}$ aquifer clusters and $N^{H,c}$ hydrocarbon field clusters.[9] The geographical coordinates of the centre of each of the $N^{S,c}$ source clusters are represented by $(\overline{x}_n^{S,c}, \overline{y}_n^{S,c})$, $n = 1,...,N^{S,c}$. Let us define the function $f^{S,c}(\cdot)$, which maps each source m in country c onto the corresponding cluster $n = f^{S,c}(m)$ (which is the cluster of which the cluster

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[8] The database also contains 227 coal fields (Vangkilde-Pedersen et al., 2009c). Due to their very limited storage capacity, we will not consider those in this paper.

[9] Sources, aquifers and hydrocarbon fields are clustered separately, because they play very different roles in the simulations (see Section 3). Furthermore, we assume that clusters cannot span across country borders, so that the model is capable of producing unambiguous outputs per country. Finally, we cluster onshore and offshore sinks separately, because that distinction also becomes important in Section 3. In practice, we do this by assuming that offshore sinks are in a 'different country'.

centre is nearest to *m*). Obviously, since $N < M$, multiple sources are mapped to the same clusters. Again, the same definitions apply to aquifers and hydrocarbon fields, with superscript *S* replaced by *A* and *H* respectively.

Since the model's computational complexity increases rapidly with the total number of clusters *N*, our objective is to minimise *N* while maintaining a given level of spatial accuracy. As a criterion for spatial accuracy, we choose the weighted root mean square (RMS) distance between the original *M* sources or sinks, and the centres of their respective nearest clusters. We impose that this RMS distance should be less than or equal to $R_{\max}$, in order to maintain sufficient spatial accuracy. The clustering question can now be formulated mathematically as follows:

Choose

$$
\begin{array}{ll}
N^{X,c} & (c = 1,\dots,C;\ X = S, A, H); \\
(\overline{x}_n^{X,c}, \overline{y}_n^{X,c}) & (c = 1,\dots,C;\ X = S, A, H;\ n = 1,\dots,N^{S,c})
\end{array}
$$

in order to minimise

$$N = \sum_{X=S,A,H} \sum_{c=1}^{C} N^{X,c}$$

subject to

$$\sqrt{\sum_{X=S,A,H} \sum_{c=1}^{C} \sum_{m=1}^{M^{X,c}} w_m^{X,c} \left[\left(x_m^{X,c} - \overline{x}_{f(m)}^{X,c} \right)^2 + \left(y_m^{X,c} - \overline{y}_{f(m)}^{X,c} \right)^2 \right]} \le R_{\max} \tag{1}$$

For simplicity of notation, we have omitted the superscript of *f*. We can solve the above optimisation problem (1) using a procedure based on Lloyd's (1982) *k-means* clustering algorithm. The *k-means* clustering algorithm is capable of finding the optimal clustering of *L* points into *K* clusters (with *K* given), so as to minimise the RMS distance. Our approach consists of two steps. In the first step, the *k-means* algorithm is applied per country, separately for sources, aquifers and hydrocarbon fields. In other words, the *k-means* algorithm is applied to each possible (X, c) combination separately. In each case the *k-means* algorithm is run repeatedly for various target numbers of clusters (i.e. various values of $K = N^{X,c}$). This results in a function $r^{X,c}(N^{X,c})$, which provides the RMS distance resulting from the clustering of all (X,c) points, as a function of the chosen number of clusters $N^{X,c}$. The function $r^{X,c}(N^{X,c})$ is computed for each (X,c) combination.

The second step of the procedure is to find all optimal $N^{X,c}$. Since the functions $r^{X,c}(N^{X,c})$ are known from the first step, the above optimisation problem (1) translates to:

Choose

$$N^{X,c} \qquad (c=1,...,C;\ X=S,A,H)$$

in order to minimise

$$N=\sum_{X=S,A,H}\sum_{c=1}^{C}N^{X,c}$$

subject to

$$\sum_{X=S,A,H}\sum_{c=1}^{C}\left[r^{X,c}(N^{X,c})\right]^2\sum_{m=1}^{M^{X,c}}w_m^{X,c}\le R_{\max}^2 \tag{2}$$

Since the functions $r^{X,c}(N^{X,c})$ are convex, problem (2) is an easy-to-solve convex optimisation programme, despite the integer nature of the variables $N^{X,c}$. Once all $N^{X,c}$ are determined, the cluster centres $(\overline{x}_n^{X,c},\overline{y}_n^{X,c})$ (which we left out from problem (2)) can be taken from the corresponding run of the *k-means* algorithm in the first step.

Figure 1 illustrates our procedure. The panel on the left shows all European sources, aquifers and hydrocarbon fields. The sources are the 1335 point sources of CO_2 in the EU-27 power sector, as obtained from E-PRTR (2010). The size of the circles corresponds to annual CO_2 emissions. Sinks are obtained from the public information available from the EU GeoCapacity project (2009a, 2009b, 2009c),[10] and the size of the circles corresponds to the 'conservative' storage capacity identified in the project. Note that while Norway (as a non-EU country) is not considered among the sources, we do consider the Norwegian storage sites, due to their relative importance. The sizes of the circles of sources and sinks are obviously used

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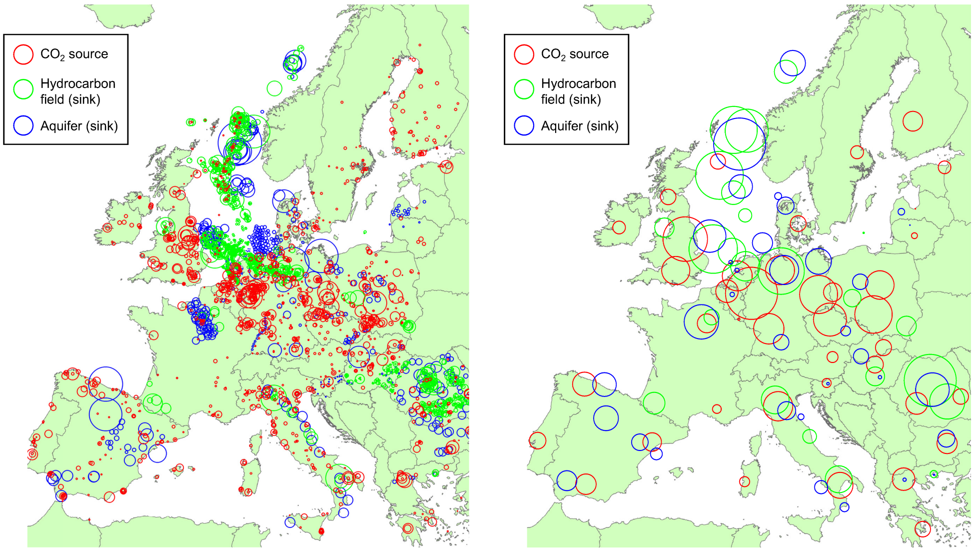
[10] Note that since we are using only the publicly available information of the EU GeoCapacity project (as obtained from published deliverables, presentations and articles), the graph is only an approximation of the EU GeoCapacity information. Any errors should not be attributed to the EU GeoCapacity project.

as weights $w_m^{X,c}$ in the clustering procedure. As xy-coordinates, we use the Lambert Conformal Conic projection of the WGS84 ellipsoid, as do Vangkilde-Pedersen et al. (2009c).

The panel on the right in Figure 1 shows the results of our clustering approach. We choose $R_{\max}$ = 100 km, which is approximately the same characteristic distance as the grid cell size used by Mendelevitch et al. (2010). Using our above-mentioned clustering approach, we find N = 94.[11] Figure 1 shows the locations of the cluster centres. The sizes of the circles correspond to the cumulative weight of all points assigned to each cluster. Throughout the rest of the paper, we will use the 94 clusters shown in Figure 1 as the nodes in the CO_2 transport network. The entire clustering procedure is performed using *MATLAB R2010a* and *Excel 2003*.

Figure 1: Illustration of the *InfraCCS* clustering procedure.
Left: All EU-27 sources, aquifers and hydrocarbon fields (3191 points).
Right: Resulting clusters (94 clusters).



2.3. Pipeline preselection: Delaunay triangulation

Once the nodes of the network are identified, the question is which candidate pipelines between these nodes should be considered in the optimisation. As mentioned before, Middleton and Bielicki (2009) and Broek et al. (2010a, 2010b) consider all possible source-sink pairs. With 94

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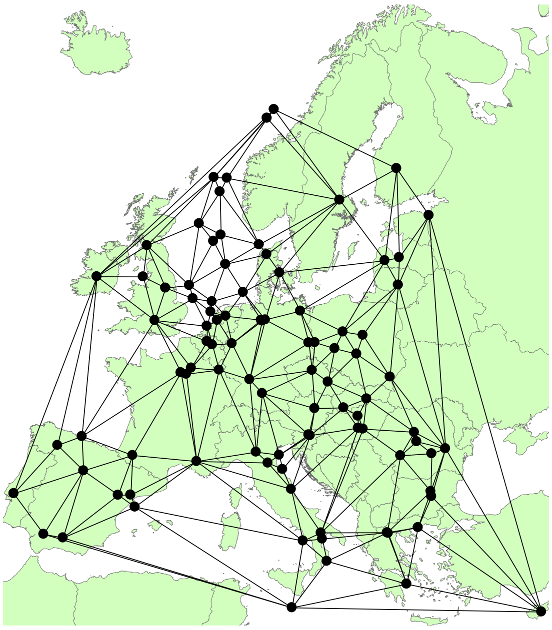
[11] N is obviously a decreasing and convex function of $R_{\max}$. For example, setting $R_{\max}$ = 150 km would lead to N = 76, while setting $R_{\max}$ = 75 km would lead to N = 118.

nodes however, such an approach would make the model impossible to solve in reasonable time. We therefore propose an approach by which each node is only connected to a number of nearby nodes, rather than to all sources or all sinks. For this purpose, we apply the triangulation algorithm developed by Delaunay (1934), which connects each node to its ‘natural’ neighbours. The algorithm is such that it maximises the minimum angle of all the angles of the triangles in the triangulation, which provides the desirable property that near-parallel pipelines get eliminated as much as possible. For *N* nodes, the Delaunay triangulation generates less than 3*N* pipelines. Figure 2 shows the results when we apply the Delaunay triangulation to the 94 nodes identified before.

Figure 2: Delaunay triangulation to identify candidate pipelines.



After the Delaunay triangulation, the tool eliminates all pipelines that go outside EU-27 plus Norway, since our focus is on finding an optimal network within the European Economic Area (EEA). In particular, this eliminates from Figure 2 the connections that go through Switzerland, Ukraine, Belarus, or the non-EU part of the Balkans. The entire pipeline preselection procedure is performed in *MATLAB R2010a*.

2.4. Pipeline costing model

The *InfraCCS* optimisation model that will be described in Section 2.6 makes an optimal choice of pipelines (and timing of investments) among the candidate pipelines identified in Section 2.3. One important input parameter to this decision is the investment cost associated with each candidate pipeline. The most important feature of pipeline investments is that they exhibit significant economies of scale, e.g. a pipeline with capacity 5 Mt/y of CO_2 may not be much more expensive than a pipeline with capacity 1 Mt/y. In fact, this is the main reason why a joint CO_2 pipeline network may be significantly cheaper than individual source-sink connections. Most earlier models have addressed this issue, by including multiple discrete candidate diameters for each candidate pipeline link in the optimisation model, and assigning to each candidate diameter an investment cost that reflects the economies of scale. For instance, Broek et al. (2010b, footnote 20) include two or three possible diameters for each candidate pipeline. They state explicitly that the study is limited to this number ‘because of computational constraints’ (Broek et al., 2010b, footnote 21). The issue of computational complexity would arise even more in our case, because our pan-European scope (which leads to very large bulk pipelines, but also relatively small feeder pipelines) would require many different possible diameters. We therefore propose an alternative costing model that does not require the use of multiple discrete pipeline diameters.

The starting point is the pipeline investment cost formula proposed by IEAGHG (2002):

$$I = (a_0 L + b_0) + (a_1 L + b_1) d + (a_2 L + b_2) d^2 \qquad (3)$$

where I is the pipeline investment cost, L is the pipeline length, and d is the pipeline diameter. For the coefficient values cited by IEAGHG (2002), the ratio b_i / a_i (i=0,…,2) is typically on the order of 10 (expressed in km). Since the average candidate pipeline in *InfraCCS* is 367 km long, we can safely assume $b_i = 0$ (i=1,…,3). Furthermore, for typical pipeline diameters in the range of 20 to 40 inch, we find that the ratio between $a_2 d^2$ and $a_1 d$ is between 5 and 10. Hence we make the mathematically simplifying assumption that $a_1 = 0$, so that equation (3) reduces to:

$$\frac{I}{L} = a_0 + a_2 d^2 \tag{4}$$

The coefficients a_0 and a_2 will be re-estimated later, in order to compensate for the fact that we have set $a_1 = 0$. Since the data points that will be used for this estimation include also the cost of compressor stations, we assume that this cost is also captured by equation (4).

In order to be able to express equation (4) as a function of the capacity of the pipeline, we take the Darcy-Weisbach equation for pressure loss along a pipeline:

$$\Delta p = f \cdot \frac{L}{d} \cdot \frac{\rho v^2}{2} \tag{5}$$

where Δp is the pressure drop, *f* is the Darcy friction factor, ρ is the mass density of the fluid (i.e. CO_2) and v is the average velocity of the fluid in the pipeline. Considering the pipeline geometry, the mass flow rate *Q* (i.e. the capacity of the pipeline) is given by:

$$Q = \rho \cdot \frac{\pi d^2}{4} \cdot v \tag{6}$$

Combining equations (5) and (6), we obtain:

$$Q = \frac{\pi}{4} \sqrt{\frac{2\rho}{f} \frac{\Delta p}{L}} d^{5/2} \tag{7}$$

Eliminating *d* between equations (4) and (7), we find:

$$\frac{I}{L} = a_0 + \beta Q^{\gamma} \qquad \text{with} \qquad \beta = a_2 \left(\frac{8 fL}{\pi^2 \rho \Delta p} \right)^{2/5} \qquad \text{and} \qquad \gamma = \frac{4}{5} \tag{8}$$

Our final simplifying assumption is that we use the approximation $\gamma = 1$. Cost data shown below will illustrate that this a reasonable simplification. More importantly, this assumption is crucial in order to allow for the inclusion of a large range of pipeline capacities in the optimisation without increasing computational complexity. The costing formulae above are meant for onshore flat terrain. For mountainous areas, we assume that costs per km are 50% higher, based on IEAGHG (2002, Table 4.13). Offshore pipelines are assumed to be twice as expensive as onshore pipelines, based on the typical ratios between offshore and onshore pipeline costing formulae in IEAGHG (2002, Tables 4.14 and 4.15). To summarise, our pipeline costing formula becomes:

$$\frac{I}{\tau L} = a_0 + \beta Q \tag{9}$$

with τ the terrain-related correction factor (1.5 for mountainous terrain; 2 for offshore; factors for other types of terrain are provided in IEAGHG, 2002).

To account for the assumptions made above, we now proceed to an independent re-estimation of the coefficients a_0 and β, based on pipeline investment cost data reported in the literature. We include all public data points from a recent survey by Schoots et al. (2010) – i.e. Denbury (2008), Hamelinck et al. (2002), Hendriks et al. (2004), IEA (2009), IPCC (2005), Lako (2006), and NEBC (1998) – complemented with data points from the recent GHGT-10 conference (ICO$_2$N, 2010; Wells, 2009).[12] Since some of the projected European CO$_2$ trunklines in our model may have far larger capacities than the above-mentioned data points available for CO$_2$ pipelines, we also include cost information from recent or ongoing European large natural gas pipeline projects (GALSI, 2010; GASSCO, 2010; Medgaz, 2010; Nabucco, 2010; Nordstream, 2010). Where the CO$_2$ mass flow rate of a pipeline is not available or not stated in the source (e.g. for the natural gas pipelines), it is estimated based on the diameter, using equation (7), assuming typical parameters f = 0.015, ρ = 850 kg/m^3 and $\Delta p / L$ = 0.3 bar/km. All cost data are converted to Euros 2010 using the CEPCI Composite index (Vatavuk, 2002) and average annual exchange rates from Eurostat (2010). The results are shown in Figure 3. With $I / \tau L$ expressed in millions of Euros per km, and the capacity Q in million tonnes (Mt) of CO$_2$ per year, we find a_0 = 0.533 and β = 0.019. These values will be used throughout the remainder of the paper. The R^2 of the regression is 0.80, which implies a reasonably good fit. One should take into account that pipeline cost data always shows relatively large scatter, as also pointed out by Schoots et al. (2010). Further details about our pipeline costing approach

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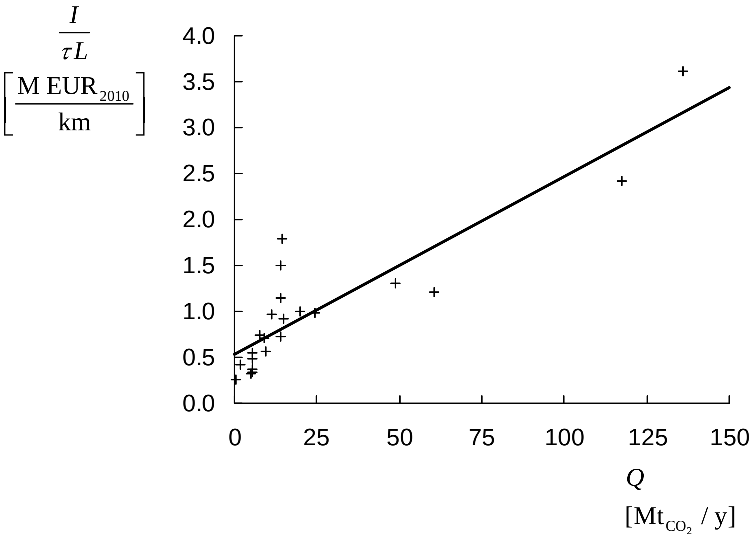
[12] To avoid confirmation bias, we exclude all data points that are directly or indirectly based on IEAGHG (2002).

can be found in Serpa et al. (2011). The statistical analysis is performed with *Stata 11*, an econometric software package.

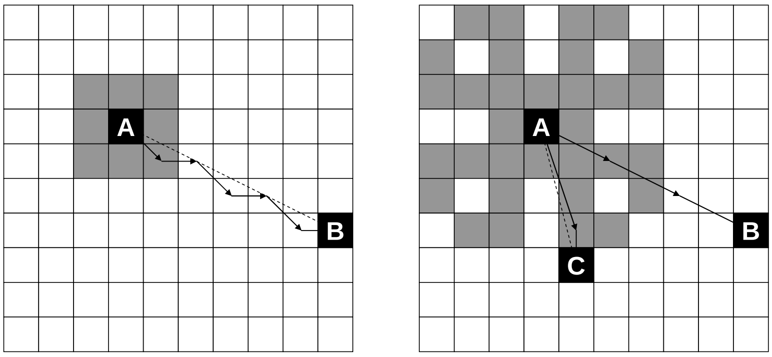
Figure 3: Estimation of equation (9) using cost data from the literature.



2.5. Pipeline routing

The candidate pipelines in Figure 2 are drawn as straight lines between the nodes. However, due to the cost factor τ in equation (9), it may be optimal to route some pipelines differently, so as to reduce costs by avoiding difficult terrain or offshore areas. Therefore, both Middleton and Bielicki (2009) and Broek et al. (2010b) apply a routing algorithm that finds the cost-minimising path between nodes, for a given ‘cost surface’. The ‘cost surface’ is a GIS-based spatial data set, which splits the region of interest into rectangular cells and provides the value of τ for each of the cells. Middleton and Bielicki (2009) use 1km x 1km cells, while Broek et al. (2010b) use 100m x 100m cells. Passing through a cell means that the corresponding cost factor τ is applied to the distance travelled through that cell. Since the cost factor τ is applied at the end of the pipeline cost calculation, the optimal routing is independent of the pipeline capacity Q. Both Middleton and Bielicki (2009) and Broek et al. (2010b) use a modified version of Dijkstra’s (1959) algorithm in order to find the optimal (least-cost) routing from source to destination, across the cells in the cost surface. In Middleton and Bielicki (2009) and Broek et al. (2010b), the pipeline is allowed to pass through the cells following orthogonal or diagonal directions. This point is illustrated in the left-hand side panel of Figure 4. Assume for the sake of simplicity that the cost surface is homogenous, i.e. τ is constant. Starting from point A, the pipeline can be routed to any of the A's 8 immediate neighbours (shown in grey), and so on. The slight disadvantage of this approach becomes clear when considering the optimal routing of a pipeline from point A to point B. The shortest path according to the algorithm is shown with arrows, and has length $3(1+\sqrt{2})$. The straight distance is shown in dotted line and has length $3\sqrt{5}$. Hence, in worst case, the pipeline distance may be overestimated by 8%. Also, the angle of the pipeline is off by up to 27º. Our *InfraCCS* model therefore includes an enhanced version of the same algorithm, which allows the pipeline to move to cells that are three neighbours away, as shown in grey in the right-hand side panel of Figure 4. Not all cells within this zone need to be included explicitly, since some of them can be reached accurately through the eight immediate neighbours (hence the white 'holes' in the grid). With this modification, there is no more overestimation in the pipeline routing from A to B. The worst-case behaviour is now for a pipeline from cell A to e.g. cell C. The potential overestimation of the shortest path is in this case reduced to less than 0.5%.

Figure 4: Least-cost pipeline routing algorithm.
Left: 8-neighbour algorithm.
Right: 32-neighbour algorithm.



Using this enhanced algorithm is a 'no-regret move'. Although it results in higher computational complexity of the pipeline routing procedure, this does not affect the computational complexity of the overall optimisation problem (which is the only real bottle-neck), because pipeline routing and costing are only a pre-processing step that serves as an input to the optimisation. Indeed, the key output from the pipeline routing is the 'effective length' of each candidate pipeline. The 'effective length' is the length of the candidate pipeline along the least-cost path, with every segment of the pipeline weighted by the cost factor τ of the cell through which it passes. We denote this effective length by $\tilde{L}$. For a given effective length $\tilde{L}$ and capacity Q, the investment cost of a candidate pipeline can be determined using equation (9). The routing algorithm is implemented using a combination of *ArcGIS 9.3* and *MATLAB R2010a*.[13]

2.6. Model specification

Consider N nodes (n = 1, …, n), P candidate pipelines between the nodes (p = 1, …, P), and T time-steps ($t = t_1, \ldots, t_T$) at which these pipelines can be built. The time-steps do not need to be at equal intervals. Note also that a particular pipeline link between two nodes can be built at multiple time-steps, e.g. a small pipeline of 5 Mt/y between A and B is built at t_2 and a subsequent larger pipeline between A and B is built along the same route at a later time-step t_4.[14] The set of P candidate pipelines is known from Section 2.3. We define the function $F(p,n)$, which is -1 if pipeline p starts at node n, 1 if pipeline p ends at node n, and 0 otherwise. Note that this implies that we assign an arbitrary direction to each of the pipelines. Since we assume that a pipeline can always be utilised in both directions, this does not cause a loss of generality. The investment cost of each pipeline p depends on its 'effective length' $\tilde{L}_p$, as computed according to Section 2.5,. We assume that the amount of CO_2 captured at each node at each time-step is exogenously given by $C_{n,t}$. The maximum amount of CO_2 that can be stored annually at each node (i.e. the injectivity) is given by $S_{n,t}$ and the

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[13] The cost surface uses the factors $\tau = 1.5$ and $\tau = 2$ for mountainous and offshore areas, respectively, as explained in Section 2.4. Unlike Middleton and Bielicki (2009) and Broek et al. (2010b), we do not include existing rights-of-way in our cost surface. This is because our model is much more 'zoomed out' (i.e. at aggregate European scale) and because the existing pipeline network in Europe is quite dense, especially in the densely populated areas in central and western Europe where right-of-way would be most crucial. As a result, many of the pipelines envisaged by the *InfraCCS* model in the simulations in Section 3 turn out to be routed more or less along existing pipelines.

[14] Note however that the cost $a_0\tilde{L}$ (with $\tilde{L}$ the effective length of the pipeline path between A and B) would be incurred twice in this case.

total capacity of the sink at each node is given by K_n. Obviously, for source nodes we have $S_{n,t} = K_n = 0$, while for sink nodes we have $C_{n,t} = 0$.

The decisions that need to be made are as follows. First of all, the optimisation needs to decide, for each candidate pipeline *p* and each time-step *t*, whether to build a pipeline *p* at time *t*. This decision is represented by a set of binary variables $\delta_{p,t}$ (1 means construction, 0 means no construction). If $\delta_{p,t} = 1$, then the optimisation also needs to decide on the capacity $Q_{p,t}$ of the pipeline being constructed. Secondly, the optimisation needs to decide on the actual flow rate $q_{p,t}$ of CO_2 through each pipeline at each point in time, because pipelines need not necessarily be fully utilised at all points in time. $q_{p,t}$ has a sign according to the direction of the pipelines as defined above. Finally, the optimisation needs to decide on the amount of CO_2 being stored at each point in time at each node, which is denoted by $s_{n,t}$.

The objective of the optimisation is to minimise the total discounted pipeline investment cost:

$$\sum_{i=1}^{T} \frac{1}{\left(1+\rho\right)^{t_i - t_0}} \sum_{p=1}^{P} \left(a_0 \delta_{p,t} + \beta Q_{p,t} \right) \tilde{L}_p \qquad (10)$$

with ρ the discount rate, t_0 the reference year, and a_0 and β from Section 2.4. We ignore operational expenditure since it is small compared to the investment cost (see e.g. the costing formulas provided by IEAGHG, 2002).

The minimisation of expression (10) is subject to the following constraints:

- Balance within each node ($n = 1, \ldots, N$; $t = t_1, \ldots, t_T$):

$$C_{n,t} + \sum_{p=1}^{P} F(p,n) q_{p,t} = s_{n,t} \qquad (11)$$

- Pipeline capacity constraint ($p = 1, \ldots, P$; $t = t_1, \ldots, t_T$):

$$-\sum_{\forall t' \le t} Q_{p,t'} \le q_{p,t} \le \sum_{\forall t' \le t} Q_{p,t'} \qquad (12)$$

- Pipeline construction constraint ($p = 1, \ldots, P$; $t = t_1, \ldots, t_T$):

$$0 \le Q_{p,t} \le \delta_{p,t} Q_{\max} \qquad (13)$$

- Sink injectivity constraint ($n = 1, \ldots, N$; $t = t_1, \ldots, t_T$):

$$0 \le s_{n,t} \le S_{n,t} \tag{14}$$

- Sink capacity constraint (n = 1, …, N):

$$\sum_{i=1}^{T-1}\Big((t_{i+1}-t_i)s_{n,t_i}\Big)+\Delta t_T s_{n,t_T} \le K_n \tag{15}$$

The parameter $Q_{\max}$ defines the upper limit of the capacity of a pipeline link that can be built at once. However, even though pipeline diameters are clearly limited, it is always possible to simultaneously build multiple large pipelines in parallel. In fact, the total cost of the multiple pipelines would still correspond rather well to the linearisation in Figure 3, because for very large pipelines the intercept a_0 becomes negligible. We therefore set $Q_{\max}$ to a very large value so that this does not constrain any pipeline construction. However, the constraint (13) is still needed in order to force $Q_{p,t}$ to 0 when $\delta_{p,t}=0$. The mathematical simplicity of expression (10) and (13) demonstrates the advantage of our pipeline costing model.[15] The parameter Δt_T defines the number of years that the network needs to remain in operation after the final time-step t_T. Note that we assume that pipelines constructed at time t are immediately available for use. Obviously pipeline construction in reality does not happen overnight. However, since the model assumes perfect foresight, the construcion of pipelines for time t can be assumed to start a few (say x) years earlier. All this would mean is that all costs would be incurred x years earlier, and hence the objective expression (10) would simply be scaled by $(1+\rho)^x$. The resulting optimal CO_2 network would not change.

The optimisation problem (10)-(15) is programmed as a Mixed-Integer Linear Programme (MIP) in *GAMS 23.5* and solved using alternatively *CPLEX 12.2* and *XPRESS 20.0*. In our experience, the fastest

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[15] The key computational advantage of our pipeline costing model is that the factor $\delta_{p,t}$ can be left out of the second term of equation (10): we can write $a_0\delta_{p,t}+\beta Q_{p,t}$ instead of $\delta_{p,t}(a_0+\beta Q_{p,t})$ because of the pipeline construction constraint, equation (13). Indeed, on the one hand, if $\delta_{p,t}=1$, then obviously $\delta_{p,t}\beta Q_{p,t}=\beta Q_{p,t}$. If, on the other hand, $\delta_{p,t}=0$, then $Q_{p,t}=0$ because of constraint (13), hence we also find: $\delta_{p,t}\beta Q_{p,t}=\beta Q_{p,t}$. This simplification makes the model significanly less complex: with $\delta_{p,t}\beta Q_{p,t}$ the model would be non-linear, while with $\beta Q_{p,t}$ the model is linear, hence the only remaining complication is the integer aspect.

results are obtained with *CPLEX*, presumably because it has specific features for solving network problems (IBM ILOG, 2010). The output of the optimisation is processed using a combination of *MATLAB R2010a* and *ArcGIS 9.3*.

3. Results

3.1. Input assumptions

In order to demonstrate the use of the *InfraCCS* tool, we apply it in order to determine the optimal network that would be required to transport all CO_2 captured in the EU-27 according the *Power Choices* scenario (Eurelectric, 2010). The *Power Choices* scenario, which is based on the PRIMES model, is chosen for this purpose because it is in line with the EU's 80% to 95% greenhouse gas emissions reductions targets by 2050 (implying near-complete decarbonisation of the power sector), and hence provides a view on large-scale pan-European deployment of CCS in the power sector.[16] The scenario implies a reduction of CO_2 emissions from the power sector to 150 Mt/y by 2050, compared to 1423 Mt/y in 2005. This is achieved through more than 40% electricity production from renewable energy sources (RES), close to 30% of nuclear power, and the remaining 30% from fossil fuels. The latter entails the construction of 63 GW of CCS-equipped power stations by 2030 and an additional 128 GW between 2030 and 2050.

Since the *Power Choices* report by Eurelectric (2010) provides the amount of CCS only at aggregate European level, we need to make an assumption on how this breaks down to individual countries. To achieve maximum realism, we use a two-pronged approach. First, we use the break-down of CO_2 captured per country as stated in the *Baseline 2009* scenario (Capros et al., 2010), which is also based on the PRIMES model. Secondly, since the total amount of CO_2 captured in the *Baseline 2009* scenario is lower than in the *Power Choices* scenario, the incremental amount of CO_2

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[16] A different choice of scenario would obviously lead to a different network structure, although many elements (e.g. bulk pipelines to the North Sea) are likely to remain similar across a relatively wide range of scenarios. A complete study of the uncertainties in CO_2 network deployment, based on a range of scenarios, is outside of the scope of this paper.

captured in the *Power Choices* scenario is allocated to individual countries proportionally to current power sector emissions. However, to avoid unrealistic fragmentation of CO_2 capture sites, countries which – based on the proportional allocation – would capture less than 5 Mt/y of CO_2, are excluded until they reach the 5 Mt/y threshold.[17] This procedure is applied to the years t_2=2020, t_3=2025, t_4=2030 and t_5=2050. For t_1=2015, we assume that the only CO_2 captured is from the 6 CCS projects funded by the European Energy Programme for Recovery (EEPR), as listed by the European Commission (2009). Our resulting assumptions about the quantities of CO_2 captured per country over time are shown in Table 1.

Table 1: Assumptions about quantities of CO_2 captured [Mt/y]

	2015	**2020**	**2025**	**2030**	**2050**
Austria	-	-	-	3.5	7.6
Belgium	-	-	-	6.1	28.4
Bulgaria	-	-	9.4	13.6	23.3
Czech Republic	-	-	10.0	18.5	58.3
Denmark	-	-	-	2.8	14.3
Estonia	-	-	-	-	9.7
Finland	-	-	3.1	7.4	22.2
France	-	-	-	9.9	25.6
Germany	1.5	5.2	95.1	181.0	315.9
Greece	-	-	-	7.9	42.4
Hungary	-	-	-	5.5	16.4
Ireland	-	-	-	-	9.9
Italy	1.5	3.2	12.0	23.6	83.7
Netherlands	1.5	4.2	10.9	16.0	48.6
Poland	1.5	4.7	24.7	43.7	138.1
Portugal	-	-	-	7.6	16.1
Romania	-	-	4.7	14.8	40.5
Slovakia	-	-	2.7	6.3	15.2
Slovenia	-	-	-	2.5	5.3
Spain	1.5	2.8	10.7	43.2	74.7
Sweden	-	-	-	-	10.1
United Kingdom	1.5	16.0	33.1	70.5	162.5
Total	**9**	**36**	**216**	**484**	**1169**

The optimisation model takes as an input the values of $C_{n,t}$, i.e. the amount of CO_2 captured at each node at each point in time. Therefore, for

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[17] In some countries, the *Baseline 2009* scenario foresees less than 5 Mt/y (but strictly more than 0 Mt/y) of CO_2 captured at some points in time. Since the *Baseline 2009* scenario is based on microeconomic modelling in PRIMES, we do not exclude these countries in such cases. Countries with under 5 Mt/y are only excluded if the amount of CO_2 captured results only from our proportional distribution of the incremental CO_2 captured in the *Power Choices* scenario compared to the *Baseline 2009* scenario.

countries with more than one source node, the assumption about the total national amount of CO_2 captured in each of the years 2020, 2025, 2030 and 2050, needs to be broken-down to the individual source nodes in the country. In the same vein as the above, the allocation is done proportionally to current CO_2 emissions per node, with the same 5 Mt/y threshold as described above. Hence, the location of CCS plants is based on current emissions from the power sector, i.e. on the location of current fossil fuel power plants. Put otherwise, we implicitly assume that CCS will be mainly deployed through retrofitting of capture units onto existing plants, or through the construction of new CCS power plants on brownfield sites of current fossil-fuel plants. For the year 2015, the amount of CO_2 captured per EEPR project is assumed to be 1.5 Mt/y (which is a realistic value since these projects are typically 250 MW plants), and this value is directly assigned to each of the 6 nodes that are closest to the 6 proposed EEPR sites. Furthermore, to improve realism of the results, the location of these 6 nodes is moved to the location of the EEPR sites.[18]

Storage capacities K_n per node are taken from our clustering exercise, so they are based on the public data available from the EU GeoCapacity project (Vangkilde-Pedersen et al., 2009a, 2009b, 2009c). However, he EU GeoCapacity project does not provide annual injectivity per storage site. There is currently large uncertainty about annual injecivity of CO_2 in storage sites, and ongoing projects such as the Sleipner project typically use only a fraction of the maximum injectivity of the reservoir. We make the assumption that the ratio $K_n / S_{n,t}$ should be comparable to the R/P ratio of the petroleum sector, i.e. we make the apparently reasonable assumption that injection of a fluid into a reservoir is technically comparable to the extraction of a fluid from the reservoir. According to BP (2010), the global R/P ratio of oil was 45.7 years in 2009. We therefore set $S_{n,t} \equiv K_n / 45.7\text{ y}$. This assumption is very similar to the approach used by Neele et al. (2010) to model large reservoirs: they use the same formula, but with 40 years instead of 45.7 years.

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[18] On average the distance between the old location and the new location of the 6 nodes that are moved is only 66 km, so this move does not fundamentally disturb the results of the clustering procedure.

We choose the discount rate $\rho = 7.5\%$, which is midway between the rate of 5.5% suggested for cost-benefit analysis of European regional investment projects (Florio et al., 2008) and typical industrial discount rates for this type of projects (10-11%).[19] Furthermore, we choose $\Delta t_T = 10$ years, implying that the infrastructure needs to be able to continue to store a constant flow of CO_2 for 10 years after the last time-step 2050. Finally, we assume that international pipeline connections can only be built after 2015, due to public acceptance issues. The main impact of this assumption is that the 6 EEPR capture sources are connected to domestic sinks, even when cross-border transport would be less costly.

3.2. Model outcomes

We run the *InfraCCS* model on the above-mentioned input data, for two cases. Case 1 includes all sinks, i.e. both aquifers and hydrocarbon fields, both onshore and offshore. Case 2 excludes the onshore aquifers as storage locations, because they are very much subject to public acceptance issues. Onshore hydrocarbon fields are included in both cases. Figure 5 and Figure 6 show the results of the *InfraCCS* optimisation, for Case 1 and Case 2, respectively. The results for year 2015 are not shown, because they are nearly identical to those for 2020.

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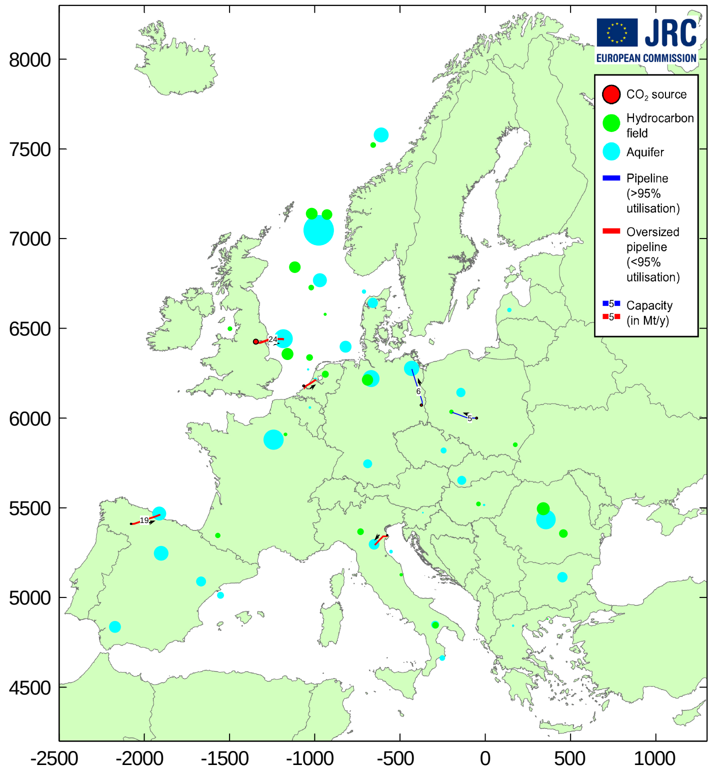
[19] The results of a sensitivity analysis using a 15% discount rate are shown in Appendix A.

Figure 5: CO_2 pipeline network deployment in Case 1 (i.e. including onshore aquifers)

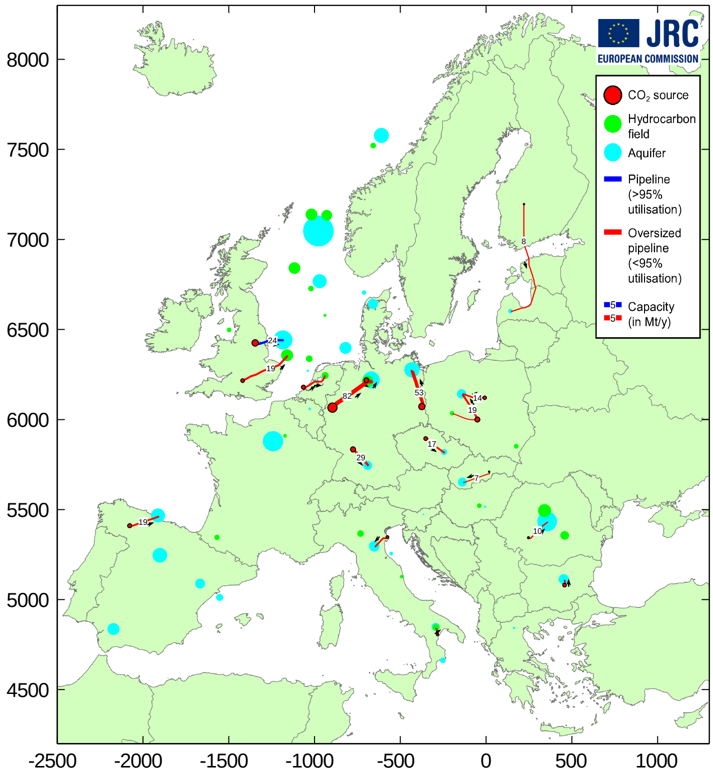
(a)

YEAR 2020 - 897km network - 0.9 billion EUR cumulative investment



(b)

YEAR 2025 - 3216km network - 3.5 billion EUR cumulative investment



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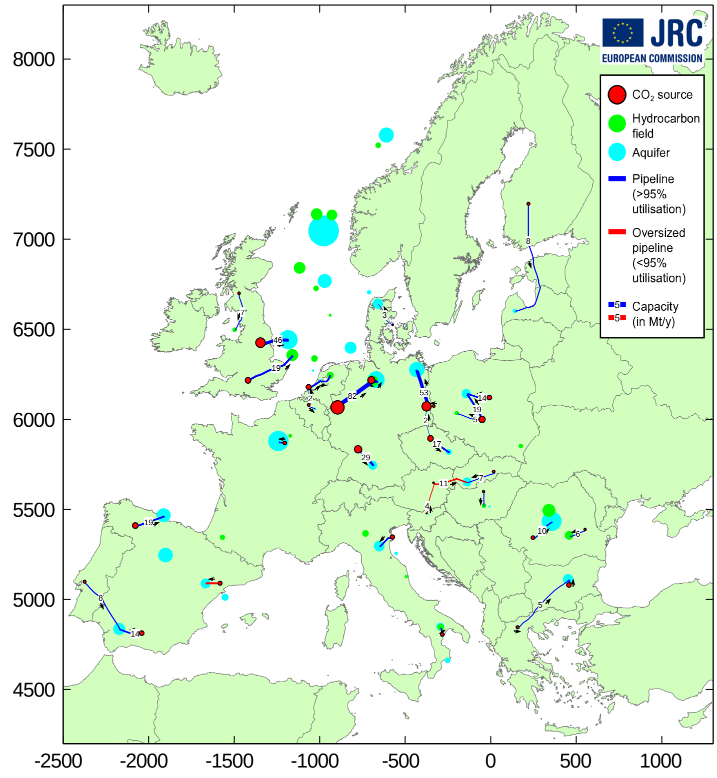
(c)

YEAR 2030 - 5551km network - 5.4 billion EUR cumulative investment



(d)

YEAR 2050 - 11276km network - 15.6 billion EUR cumulative investment

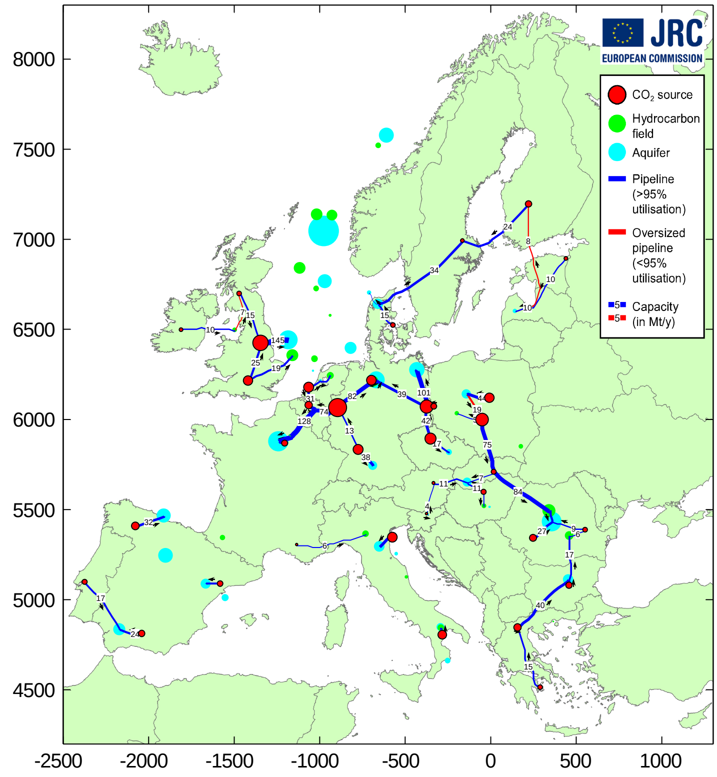
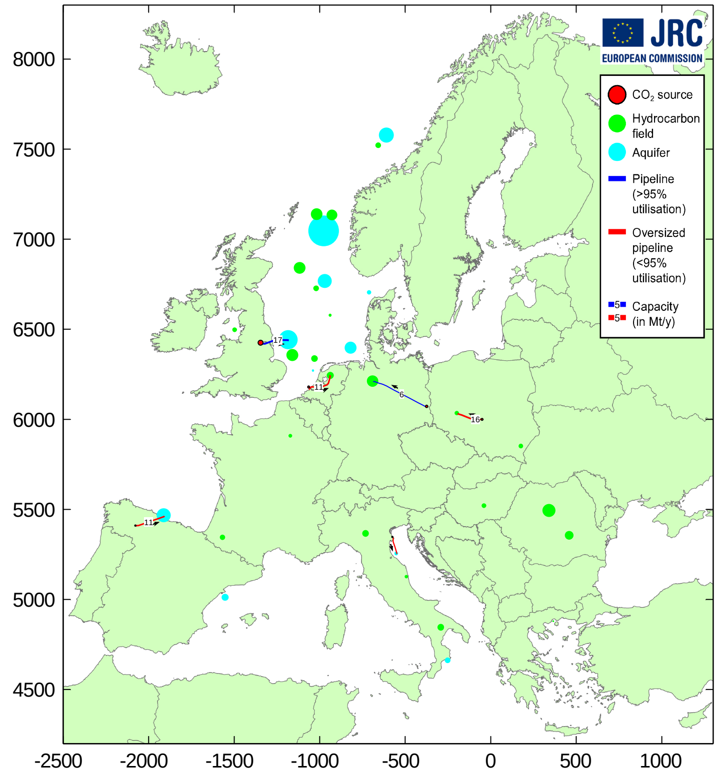


Figure 6: CO$_2$ pipeline network deployment in Case 2 (i.e. excluding onshore aquifers)

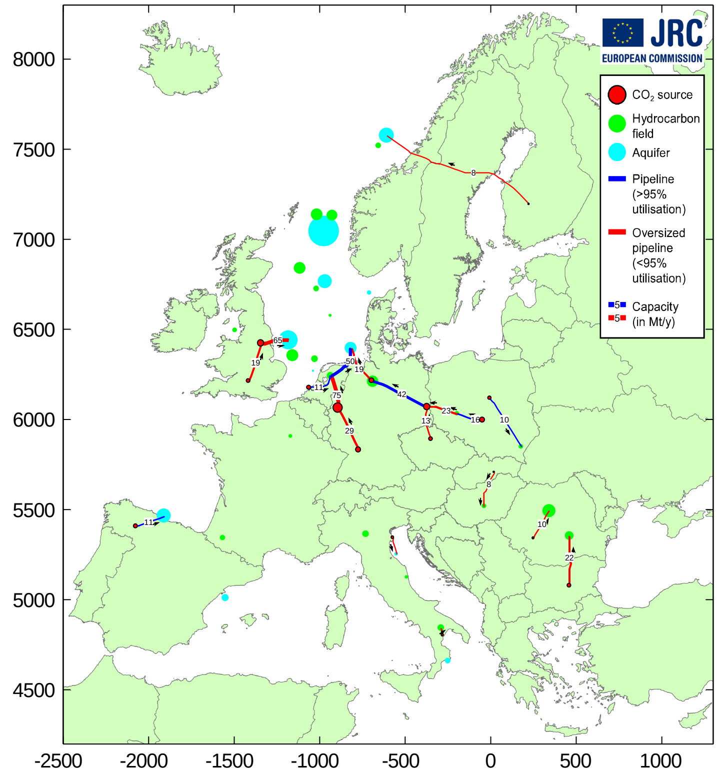
(a)

YEAR 2020 - 1114km network - 1.0 billion EUR cumulative investment



(b)

YEAR 2025 - 4589km network - 5.4 billion EUR cumulative investment



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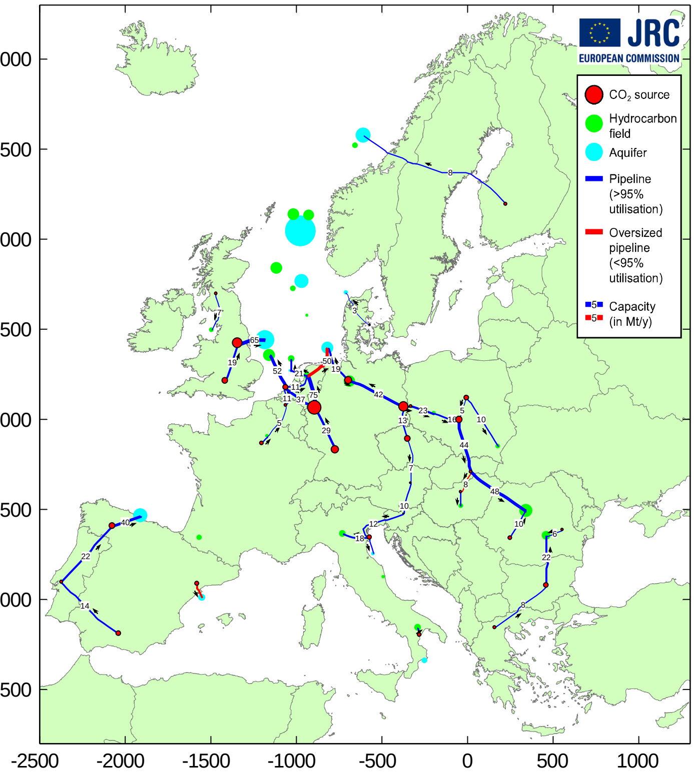
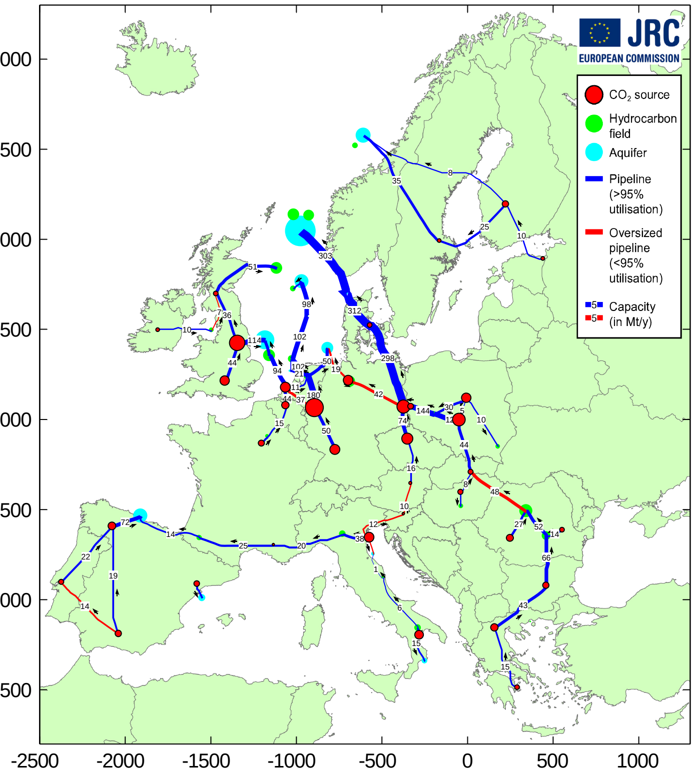
(c)

YEAR 2030 - 9212km network - 10.4 billion EUR cumulative investment



(d)

YEAR 2050 - 16918km network - 36.4 billion EUR cumulative investment



4. Discussion

In Case 1, i.e. when onshore aquifers are included, the optimal CO_2 transport network remains very local until 2030. As of 2030, the first regional networks of two to three countries start to emerge. By 2050 however, a two-part continental European backbone develops, with one part covering northwest Europe and one part covering the eastern part of Europe from Poland to Greece. Scandinavia, the Iberian peninsula, the British Isles and Italy remain unconnected to this larger network. It is striking to see that in this case almost no CO_2 is stored in the North Sea, except in the UK sector of the southern North Sea, and in an aquifer immediately offshore Denmark. Besides the public acceptance concerns of storing large amounts of CO_2 in onshore aquifers, a major caveat associated with this simulation is that it depends strongly on the large storage capacities in the Paris Basin and northern Germany, which are still highly uncertain.

In Case 2, i.e. when onshore aquifers are excluded, the optimal CO_2 transport network looks completely different. Already by 2025, a trunkline from Poland and Czech Republic to the North Sea starts to develop. By 2030, the line is extended to most of central and eastern Europe. Initially, the CO_2 is stored mostly in onshore hydrocarbon fields and in the southern part of the North Sea. By 2050 however, very large bulk pipelines are constructed to transport more than 400 Mt of CO_2 to the central and northern sectors of the North Sea. One of these is a direct corridor from central Europe through Denmark. With the assumptions in this scenario, also Italy and the Iberian peninsula become connected to this network, which spans across all of Europe, except Scandinavia.

The optimisation produces a number of interesting effects. First of all, both in Case 1 and in Case 2, many pipelines are initially ‘oversized’ (coloured red in the figures): due to the economies of scale in pipeline construction, it may indeed be more attractive to build a larger pipeline that is initially not fully utilised, instead of building a smaller pipeline that needs to be complemented with a second pipeline when flows increase beyond the capacity of the first pipeline. A second remarkable effect of the optimisation is that the flow in some pipelines reverses in the course of time. For example, in Case 2, the 48 Mt/y pipeline between Hungary and Romania (constructed by 2030) initially transports CO_2 from Poland and Slovakia to the hydrocarbon fields in central Romania. By 2050, the flow reverses and the same pipeline now brings excess CO_2 from Romania and Bulgaria to Slovakia, where it feeds into the large bulk pipeline to the North Sea.

Figure 7 summarises the main characteristics of the CO_2 networks shown in Figure 5 and Figure 6. When onshore aquifers are excluded (i.e. Case 2), the total pipeline network becomes roughly 50% longer and more than twice as expensive. In both cases, the largest growth of the network takes place between 2030 and 2050, because the *Power Choices* scenario foresees a major step-up of CCS during that period. By 2050, network length could reach 11000 to 17000 km. It is interesting to observe that these results have the same order of magnitude as the optimisation results of Mendelevitch et al. (2010): their most optimistic scenario with onshore storage requires a total pipeline network length of 13359 km, while their most optimistic scenario without onshore storage requires a total pipeline network length of 15889 km.[20]

Undiscounted cumulative investment in our simulations could reach 5 to 10 billion Euros by 2030, and 16 to 36 billion Euros by 2050. Clearly this is strongly dependent on the CO_2 capture scenario: the *Power Choices* scenario that is used here assumes near-complete decarbonisation of the European electricity system, hence a large role for CCS. However, it should be noted that the analysis does not include any CO_2 from other sectors (e.g. heavy industry), which would further increase the network requirements. In the period 2020-2050, the cost per tonne of CO_2 transported ranges from 1.7 to 3.5 EUR/t in Case 1, and from 3.2 to 4.7 EUR/t in Case 2. In the start-up phase in 2015, costs are much higher due to lack of scale and pipeline oversizing in anticipation of future flows. Indeed, in 2015 only the EEPR projects capture CO_2 and their start-up volume – typically around 1-2 Mt/y – is still very low. Costs per tonne drop dramatically by 2020 when new CO_2 sources come online, which enable the amortisisation of the

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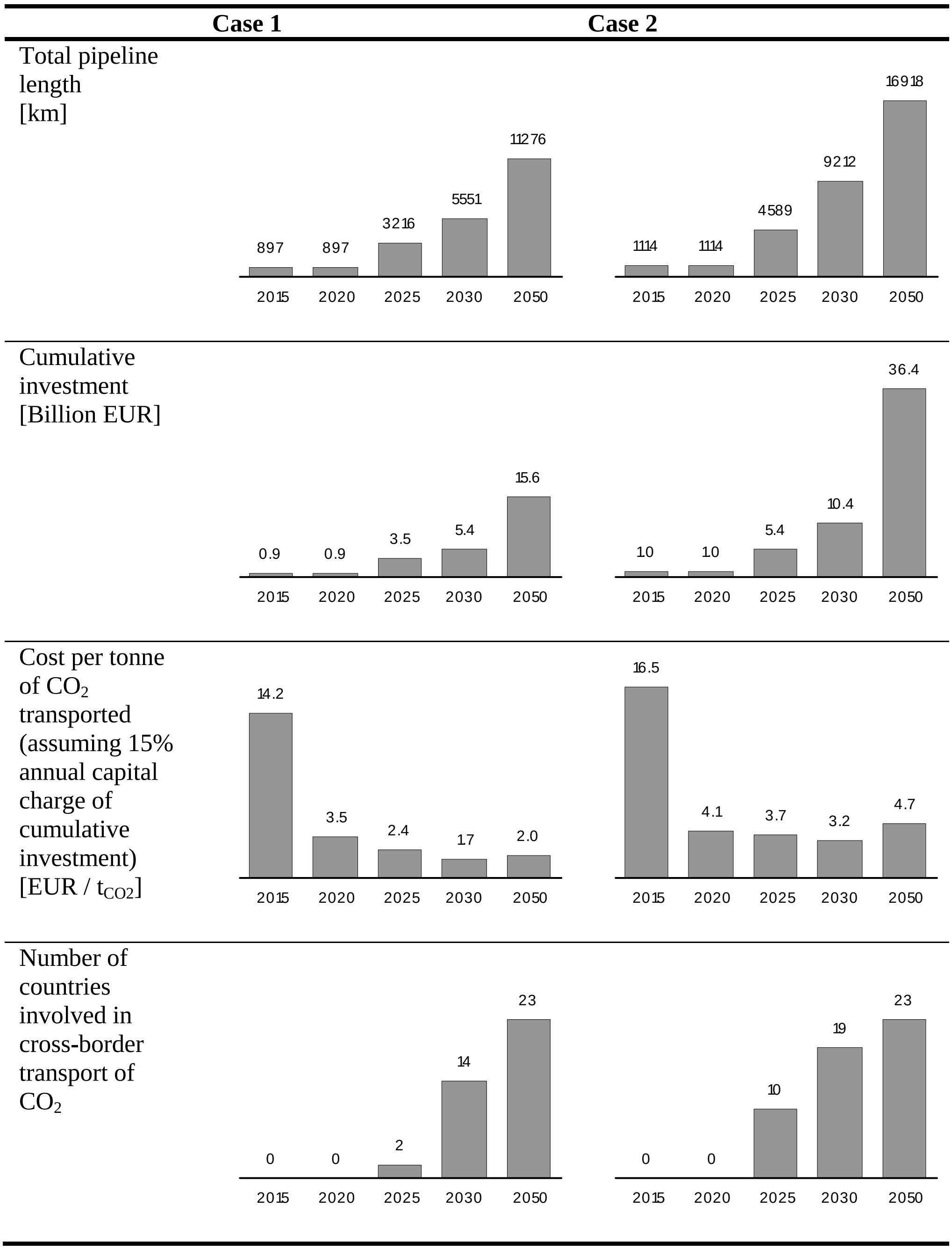
[20] As already explained in the introduction, the set-up of the model by Mendelevitch et al. (2010) is different from ours, so the comparison is only indicative.

infrastructure costs over a larger volume and the use of the afore-mentioned economies of scale in pipeline costs.

Figure 7: Characteristics of the optimal CO_2 networks



The bottom row of Figure 7 shows that in this optimised network, more than half of the EU's Member States would be involved in cross-border CO_2 transport by 2030, even in Case 1. By 2050, nearly all Member States involved in CCS are also involved in cross-border CO_2 transport.

Therefore, based on this simulation, it seems apparent that international coordination is crucial for the development of an optimised trans-European CO_2 transport network.

5. Conclusions

In this paper, we have described the *InfraCCS* model, which can estimate the likely extent and cost of a CO_2 transport network at European scale for the period 2015-2050. The computation is made possible by a number of methodological innovations compared to previous research on this topic, in particular: the use of *k-means clustering* to reduce the number of nodes in the network; the application of the *Delaunay triangulation* algorithm for pipeline pre-selection; and the introduction of a mathematically convenient yet sufficiently accurate new pipeline costing model.

The *InfraCCS* tool is applied to determine the optimal network corresponding to a CCS scenario that ensures near-complete decarbonisation of the European power sector. Under the assumptions of the scenario, the CO_2 network by 2050 is about 11000 km in length and requires 16 billion Euros investment. If onshore aquifers are excluded, the network would need to be 17000 km in length and would require 36 billion Euros investment, The large cost savings that can be obtained by using onshore aquifers indicate the need for stakeholder outreach efforts and further R&D that reduces the environmental uncertainties associated with onshore storage. Finally, since the model shows that by 2030 more than half of the EU Member States could be involved in cross-border CO_2 transport, international coordination seems crucial for the development of an optimised trans-European CO_2 transport network.

As mentioned before, the *InfraCCS* model uses an exogenous scenario of CCS deployment. Further research could focus on endogenising the amount of CO_2 captured, through soft or hard-coupling with a partial equilibrium model of the European energy system. Such an approach could also endogenise the location of new power plants, i.e. it could decide to build power plants closer to storage sites, in contrast with our current model, which locates capture plants at existing power plant sites. Furthermore, the model assumes international coordination in order to achieve a jointly optimal solution. A possible route of research would be to model under which conditions and incentive systems such cooperation would take place. Also, the current paper computes the optimal network for two cases. The same analysis could be done for a much wider range of scenarios and assumptions, to obtain a quantification of the uncertainties in infrastructure deployment. Finally, the model assumes perfect foresight. An alternative, but computationally very intensive, approach would be to consider future capture scenarios as stochastic, and determine the optimal network that would be robust against such uncertainties.

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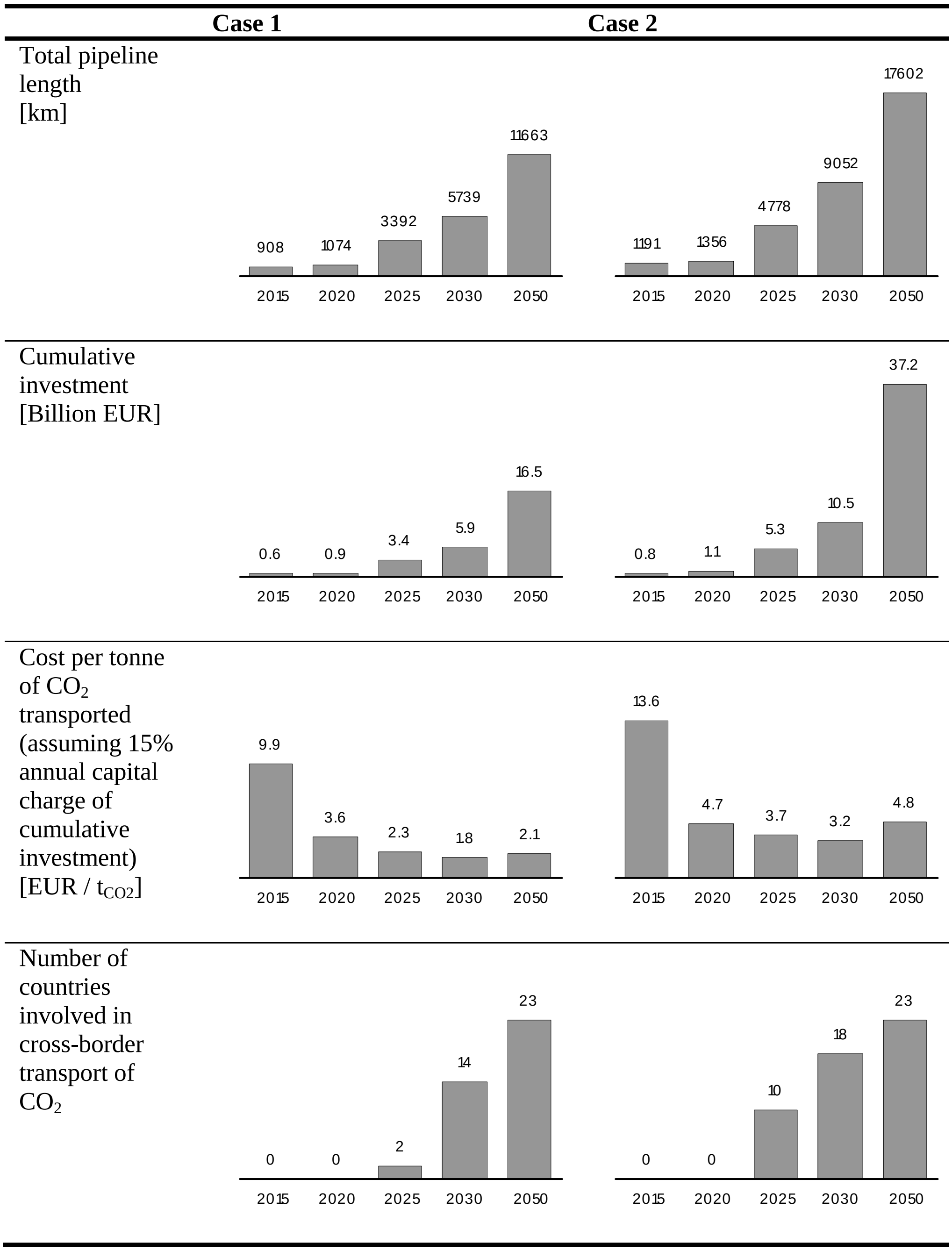
Appendix A. Sensitivity analysis regarding the discount rate

The results shown in Section 3.2 include a number of 'oversized' pipelines: pipelines which, in anticipation of future flows of CO_2, are built with a larger capacity than what is strictly needed at the time of construction. This requires very long planning horizons and implies that governments and/or industry take a volume risk, because future flows may never actually materialise. One way to account for such uncertainty is to increase the discount rate. In this appendix we therefore rerun the simulations with a 15% discount rate, i.e. twice as high as the original 7.5% discount rate used throughout the paper. The characteristics of the resulting optimised network are shown in Figure 8.

Figure 8: Characteristics of the optimal CO_2 networks assuming double discount rate



It is interesting to compare Figure 8 with Figure 7. First of all, the resulting total network length when using a 15% discount rate is greater than when a 7.5% discount rate is used for optimisation. This is a fairly intuitive result: with higher discount rates, there will be less anticipation of future CO_2 flows, hence fewer bulk pipelines are built upfront. As a consequence, more pipelines need to be built later on, resulting in greater total network length. Likewise, when a higher discount rate is used, investments in the first time steps are slightly smaller, but the total cumulative investment is larger: the difference is 0.9 billion Euros in Case 1 and 0.8 billion Euros in Case 2. This is also reflected in the cost per tonne of CO_2 transported, which is significantly lower in the beginning but 0.1 EUR/t higher by 2050 when the higher discount rate is used. All in all, however, the changes seem relatively small, hinting that the characteristics of the optimal CO_2 transport network are fairly robust vis-à-vis changes in the discount rate assumed for the optimisation algorithm.