Scrutinising the Gap between the Expected and Actual Deployment of Carbon Capture and Storage—A Bibliometric Analysis

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Abstract: For many years, carbon capture and storage (CCS) has been discussed as a technology that may make a significant contribution to achieving major reductions in greenhouse gas emissions. At present, however, only two large-scale power plants capture a total of 2.4 Mt CO_2/a. Several reasons are identified for this mismatch between expectations and realised deployment. Applying bibliographic coupling, the research front of CCS, understood to be published peer-reviewed papers, is explored to scrutinise whether the current research is sufficient to meet these problems. The analysis reveals that research is dominated by technical research (69%). Only 31% of papers address non-technical issues, particularly exploring public perception, policy, and regulation, providing a broader view on CCS implementation on the regional or national level, or using assessment frameworks. This shows that the research is advancing and attempting to meet the outlined problems, which are mainly non-technology related. In addition to strengthening this research, the proportion of papers that adopt a holistic approach may be increased in a bid to meet the challenges involved in transforming a complex energy system. It may also be useful to include a broad variety of stakeholders in research so as to provide a more resilient development of CCS deployment strategies.

Keywords: carbon capture and storage; deployment of CCS; expectation and reality; review; bibliometrics; bibliographic coupling; citations

1. Introduction and Motivation

Major reductions in greenhouse gas (GHG) emissions will be necessary in the coming decades in order for the global community to avoid the most dangerous consequences of human-caused global warming (Edenhofer et al. [1]). The discussion on deep decarbonisation has been intensified since the 2015 UN climate change conference COP21. In the "Paris agreement", the global community agreed to keep the global temperature rise well below two degrees Celsius above pre-industrial levels, and to make efforts to limit the temperature increase to 1.5 degrees Celsius by 2100 (UNFCC [2]). As a technology option that could make a significant contribution to achieving the objective of decreasing GHG emissions, carbon capture and storage (CCS) has been discussed more or less intensively for many years. CCS involves the capture of carbon dioxide emissions from fossil fuel-fired power plants or industrial sources, and the storage of the carbon dioxide underground, such as in deep saline aquifers or in depleted oil and natural gas fields, or their use for enhanced oil and gas recovery. Expectations for global CCS deployment in the power sector were high over the past 10 years. For example, the CCS roadmap of the International Energy Agency (IEA) of 2009 expected a CCS-based power plant capacity

of 22 GW in 2020 and 1140 GW in 2050, resulting in 131 and 5510 Mt CO_2/a captured, respectively [3] (p. 17). However, if the current state of global large-scale CCS power plants (a 115 MW and a 240 MW plant in operation that capture a total of 2.4 Mt CO_2/a according to Global CCS Institute [4] as of 9 February 2018, thereby defining large-scale CCS power plants "as facilities involving the capture, transport, and storage of CO_2 at a scale of at least 800,000 tonnes of CO_2 annually") is compared with the suggested modes of usage, it becomes apparent that these expectations have not yet been met.

A number of studies and articles have attempted to explain the reasons for this failure (see Table 1). The European Commission particularly highlighted the absence of business cases, public awareness, and acceptance, legal frameworks, CO_2 storage and infrastructure, and international cooperation as barriers preventing the successful development of CCS in the European Union (EU) [5]. Nykvist [6] identified four challenges that make CCS "10 times more difficult" than previously thought. The first challenge is considered to be the 10-fold increase in size from pilot plants (30 MW) to the commercial demonstration of capture, transport, and storage. Furthermore, it is shown that 10 times greater large scale demonstration plants than the current trend need to be constructed by 2020, to overcome financial problems as well as the legislative and political risks involved. This leads to the third challenge: "a 10-fold increase in the available annual funding over the coming 40 years," combined with "a 10-fold increase in the price put on carbon dioxide emissions".

Deetman et al. [7] analysed the effectiveness of mitigation measures on a global level up to 2050. Apart from a policy option using CCS, they also included an option with no additional use of CCS. This option is driven by the unclear potential for its large-scale deployment, which they justify mainly with "the lack of societal and policy support," citing Bäckstrand et al. [8] and Gough et al. [9]. Nemet et al. [10] identified capital costs, demonstration plants, growth constraints, and knowledge spillovers among technologies as central parameters "for which better information is needed for future work informing technology policy to address climate change".

Viebahn et al. [11–13] scrutinised the possible role of CCS in large coal-consuming emerging economies by analysing the possible barriers from an integrated assessment perspective. They concluded that several preconditions must be met for the successful implementation of CCS in India, China, and South Africa, respectively. As a first precondition, they identified the delayed commercial availability of the CCS technology in industrialised countries, which would have a strong impact on the implementation of CCS in the analysed countries. As a key requirement for developing a long-term CCS strategy, the existence of a reliable storage capacity assessment in each of the countries was dunned. Third, a higher carbon price would be required in order to overcome significant barriers for reaching a sufficient level for the economic viability of CCS. Furthermore, there is little public awareness of CCS, and a public debate had not yet even started.

Widening the boundary of the energy system under consideration, Viebahn et al. [14,15] and Martínez Arranz [16] illustrated the advantages and disadvantages of CCS by comparing it with other low-carbon technologies. While Viebahn et al. analysed the possible constraints for the implementation of CCS in Germany from an economic, social, and systems perspective, which might be caused by strong competition with renewable energies-based electricity generation, Martínez Arranz developed an analytical hype analysis framework and contrasted the results for CCS with those of comparable base-load renewable technologies (geothermal, marine, and solar thermal). He concluded that (power plant-based) CCS shows signs of hype when "considering indicators of expectations, commitment and outcomes" and recommended—in the light of both the manifold problems indicated above and the potential of CCS competitors in the electricity sector—shifting efforts to industrial CCS in the future.

Table 1. Barriers for the implementation of carbon capture and storage (CCS) from different perspectives.

Barriers	EU Com. [5]	Nykvist [6]	Deetman et al. [7]	Nemet et al. [10]	Viebahn et al. [11–13]	Viebahn et al. [14,15]	Martínez Arranz [16]
(1) Technical perspective							
Storage (capacity) issues	X	-	-	-	X	-	-
Infrastructure issues	X	-	-	-	-	-	-
Missing demonstration plants and upscaling	-	X	-	X	-	-	X
Commercial availability	-	-	-	-	X	X	-
Knowledge spillovers	-	X	-	X	-	-	-
(2) Economic perspective							
Absence of business cases	X	-	-	-	-	-	-
Capital costs, costs of electricity generation	-	-	-	X	-	X	-
Financial problems and risks	-	X	-	-	-	-	X
Funding problems, growth constraints	-	X	-	X	-	-	-
Carbon emission pricing	-	X	-	-	X	-	X
(3) Social perspective							
Public awareness and acceptance, societal support	X	-	X	-	X	X	-
(4) Legal perspective							
Legal frameworks	X	-	-	-	-	-	-
Legislative risks	-	-	-	-	-	-	X
(5) Political perspective							
International cooperation	X	-	-	-	-	-	-
Political risks, support	-	-	X	-	-	-	X
(6) Systems perspective							
Energy system constraints	-	-	-	-	-	X	-
Competitors in the electricity system	-	-	-	-	-	X	X

Against this background, the intention of this article is to explore whether research in CCS is prepared to meet the challenges illustrated above. Is research pressing forward and able to deliver reasonable, scientifically sound solutions to overcome these challenges? Or are urgent questions (for example, the acceptance of CO_2 storage sites, or the competition of CCS with other low carbon technologies) not addressed in reality, since only technical research is conducted? In order to answer these questions, the frontier of CCS research is analysed by applying bibliographic analysis. The frontier is understood to be online published peer-reviewed papers. Although agencies, industry, non-university research institutes etc., do not publish all of their results, unlike universities, we focus on peer-reviewed papers for three reasons: (1) These papers should provide quality-assured results illustrating the scientific research front; (2) most of these papers are included in large databases that are required as a basis for software-based comprehensive evaluation; (3) the methodology is first developed for a homogenous set of papers and may be extended later to various other groups of literature that are rather dispersed, requiring additional research to include them in bibliometric analysis.

Meta-analyses of research activities relating to CCS have been conducted in the past. Choptiany et al. [17] investigated articles with regard to the assessment of CCS projects under social, ecological, and economic criteria, while Choptiany and Pelot [18] developed an Multi Criteria Decision Analysis (MCDA) model for the systematic assessment of concrete CCS projects under these criteria. Zheng and Xu [19] reviewed CCS development trends by literature mining, and subsequently developed and examined a novel CCS technological paradigm (CCSTP) "to provide a guide for future CCS technological trends". Martínez Arranz [16] analysed the articles of the International Journal of Greenhouse Gas Control in order to illustrate the boost received by CCS-related research from 2005 onwards. However, according to the authors' knowledge, no comprehensive overview has been provided for the main CCS research fields and their proportional distribution. Each of the studies considered focused on a special selection of research, first selecting a field of interest and then searching for references in this field. In order to conduct an unbiased search and to include all fields of recent research in the present analysis, therefore, we consciously refrained from restricting our search to known fields or assessment dimensions of CCS.

The remainder of the article is organised as follows: the overall approach of the citation network analysis applied for our review is described in Section 2. In Section 3, the main research clusters found in the analysis are first identified, followed by a description of the key papers of each cluster, and the development of a conceptual model for analysing the relationships between the clusters. Finally, the results are discussed in Section 4, whilst conclusions are drawn in Section 5.

2. Methodology and Data Collection

We applied bibliometric methods to cluster the literature on CCS by topics. In the first step, we selected our paper set, based on a keyword search using the online scientific database Scopus (http://www.scopus.com (Elsevier)). This database covers a wide range of journals, including most modern sources. Applying the search term "(ccs or (carbon W/1 capture W/1 storage) OR (carbon W/1 capture W/1 sequestration)) AND (carbon OR CO_2 OR GHG OR (greenhouse w/1 gas) OR emission)" (the connector "/1" serves to include a maximum of one additional word (e.g., "and")), we obtained a set of 6231 papers that address the use of CCS in the sense of this article. Second, we undertook an analysis of keywords specified in the paper set to identify key topics and methods. We manually matched the results with the methods and approaches known from our expertise, and found that the keywords that are consistent with the areas of research in the field of CCS.

Third, we applied bibliographic coupling (Jarneving [20]), which involved linking the papers in the paper set to find out how they cluster. Links between papers are created when they share citations. Sharing citations indicates a common basis, which makes the papers form research fronts (Persson [21]). The network established contains clusters that may gather around topics or a particular focus. Boyack and Klavans [22] found that bibliographic coupling represents the research front more accurately than other citation approaches. Citations themselves are not visible in this network

(this would be the case in co-citation coupling, which does the reverse: here the network is formed by the citations when they occur together in multiple papers, also called the intellectual base. Due to the intention of our analysis, we refrain from analysing the intellectual base). The number of commonly shared citations is expressed by the degree. In the case of a node, the degree d means the number of neighbours that share at least one common citation. Cumulating all of the documents shared by the node and its neighbours yields the weighted degree wd. A degree of an edge between two nodes indicates its weight, which depends on the number of documents cited by both nodes together (see Figure 1 for an example).
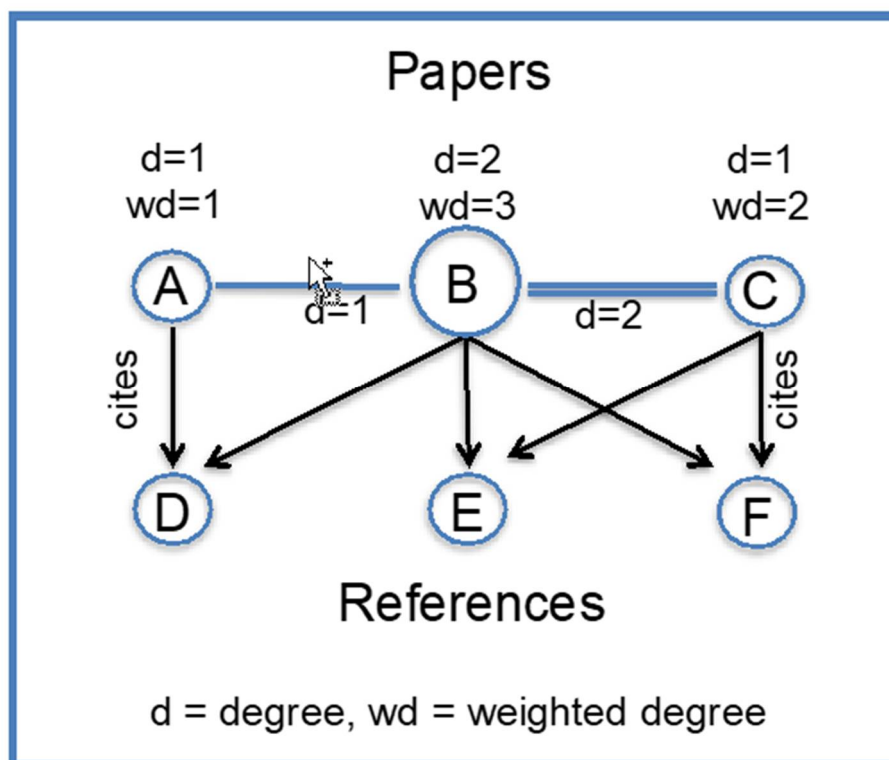
Figure 1. Bibliographic coupling and the degree of nodes and edges (based on Friege and Chappin [23] (p. 198)). Papers A and B both cite the same document D, so that A and B are connected by a line with a weight of d = 1. In contrast, B and C both cite the same documents E and F, so the edge between B and C is a double-weighted line (d = 2). Node A has a degree of d = 1 and wd = 1, while B has a degree of d = 2 and a wd = 3.

Before undertaking bibliographic coupling, however, a number of papers had to be excluded from the paper set: (1) Network analysis was generally only possible if a paper had a connection with another paper, i.e., its degree was not zero (otherwise the paper was an unconnected node in the network). (2) Due to the methodology of bibliographic coupling, a paper could only be included in the analysis if it contained references. (3) Due to spelling errors, the same paper often appeared multiple times in the database (see Appendix A for technical details). The final set of papers, which we call the base paper set, comprised 4271 out of the 6231 original papers. The difference in numbers was mainly due to the elimination of 1396 papers that did not contain references.

Fourth, we used the network analysis tool Gephi [24] to visualise and explore the clusters that resulted from bibliographic coupling. We applied the "Force Atlas" layout, which followed the basic principle that linked nodes (here: articles) attract each other, while non-linked articles were repelled. As a result, Force Atlas brought groups of papers together that interlinked more closely amongst themselves than with the other papers. However, the assignment of a paper to one cluster or another did not always occur unambiguously. Even in the border region between two clusters, the assignment of a paper to one cluster or another depended on individual references. Using the similarity index, clusters of papers that belonged together were identified and marked with a unique colour. We scaled the appearance of a node in a range of 10 to 100, related to its degree. Due to the large number of nodes in our network, in the graphical representation, we omitted the edges for the sake of clarity. We only used the edges in the manual analysis of relationships between clusters.

Finally, we manually analysed the content of the clusters. In the first step, we conducted the real review and screened a selection of papers with the 10% highest degrees of a cluster. The papers were grouped into different research fields called F$x \cdot y$, where x = the number of the cluster and y = the number of the field. If a field showed different sub-topics, we broke the field down into groups. For each field (or for each group, where relevant) we briefly described the key papers. Identifying key articles helped us to develop an understanding of the overall structure of the field—its progress and limitations. We defined the papers of a cluster that have the highest degrees within a cluster, i.e., that cite a paper that is also cited by such a number of other papers, as key papers. Normally, we would select the key papers with the three highest degrees, and add more if needed to describe the diversity of a field. While analysing only 10% of the papers, we assumed that the remaining papers in the cluster would follow the same distribution. We roughly validated this by screening the titles of the remaining 90% of papers and—if necessary—by analysing the next 10% of papers. Furthermore, in a graphically performed cross-check, we made sure that the degrees of the selected 10% of papers were among the highest 50% of degrees in each cluster. We also made sure that no relevant key papers were omitted.

In the second step, we extended the analysis and developed a conceptual model in order to analyse how the identified (sub-)clusters and their fields interact. This enabled us to learn which topics in CCS research are directly linked and where preferable links may be missing.

## 3. Research Clusters, Key Papers and Relationship between the Clusters

3.1. The Base Paper Network

The resulting network consists of 12 main clusters, which differ in size and overlap to a certain extent. Two additional clusters refer to topics outside of the field of CCS. Figure 2 shows the base paper network, limiting the number of nodes to those that have an (arbitrarily chosen) degree > 50 for the sake of clarity. (The original base paper network can be seen in Figure A1 in Appendix B). Below, each cluster is described in detail, starting with the largest cluster (C1) and proceeding in descending order. A detailed list of fields and groups found in the analysis is given in Table A2 in Appendix B. A rough validation of the "10% approach" chosen was conducted by screening the titles of the remaining 90% of papers and—in the case of Clusters 10 and 11—by analysing the next 10% of papers that roughly showed the same pattern. A graphical cross-check showed that the degrees of the selected 10% are among the highest 50% of degrees in each cluster. As Figure 3 illustrates, this is the case for all clusters. Details are given in Table A1 in Appendix B. For instance, the first 10% of papers of Cluster C1 cover a range of degree from 59 to 325, which represents 82% of all degrees in this cluster.
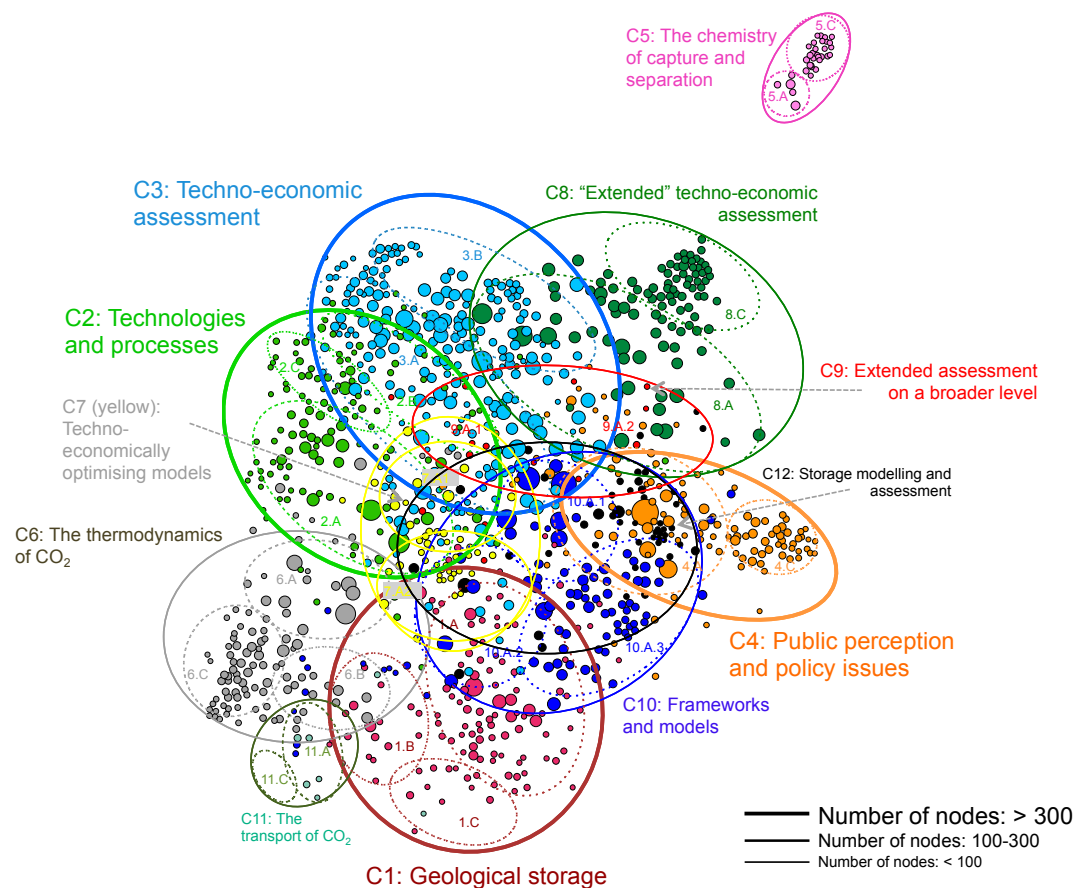
Figure 2. Schematic representation of the overall paper network, its 12 main clusters, and their sub-clusters. For the sake of clarity, only nodes with a degree > 50 are shown (1056 out of 4134 nodes); connections between nodes are not shown.
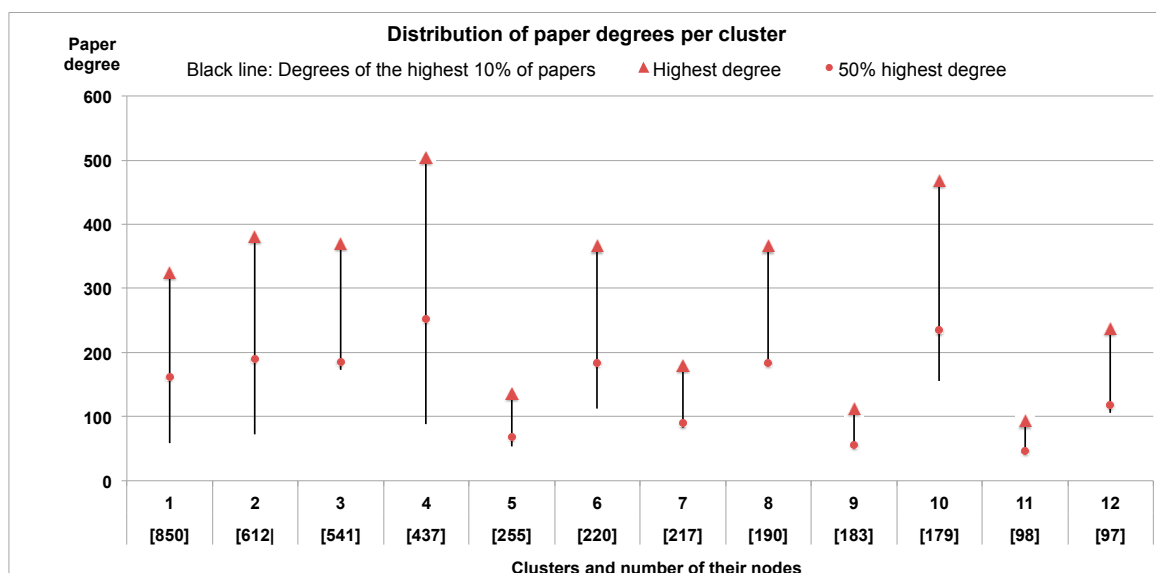
Figure 3. Relationship of the degrees of the analysed papers within the 12 main clusters compared to all papers within a cluster.

3.2. Exploring the Main Research Areas

3.2.1. Cluster C1 (Red, 850 Nodes, 19.9%)—Geological Storage of CO_2

The largest research field of this cluster, F1.1 (425 papers, 50% of C1) deals with storage mechanisms and potential. Within this group, 264 papers (31%) referred to detailed investigations of core storage processes (mostly in deep saline aquifers), such as injection processes and rates, geological trapping mechanisms, caprock quality, CO_2 solubility, and storage efficiency. With a degree of 325, Bourg et al. [25] published the paper with the largest degree by far, followed by Sun et al. [26] (d = 172) and Talman [27] (d = 127), each of them reviewing the progress and research needs in the key trapping processes. Bourg et al. formulated "outstanding" research needs in the field of three key nanoscale parameters "that contribute uncertainty to predictions of CO_2 trapping". Sun et al. illustrated major research gaps and needs for research in the field of "laboratory-scale core flooding experiments in CO_2 geosequestration under reservoir conditions" that would contribute to the main processes needed for large-scale CCS, such as "precisely estimating storage efficiency, ensuring storage security, and predicting the long-term effects of the sequestered CO_2 in subsurface saline aquifers". By reviewing the research on the consequences and geochemical effects of impurities of the CO_2 stream when injecting carbon into deep saline aquifers, Talman pointed to a further key issue of research.

Another group totalling 68 papers (8%) addressed storage site assessments and storage potentials. Key papers included Wei et al. [28] (d = 90), who developed a framework for the evaluation of storage site suitability, in which the authors took into account storage capacity optimisation, injectivity, risk minimisation, storage security, environmental restrictions, and economic issues; Civile et al. [29] (d = 71), who identified and characterised areas potentially suitable for CO_2 geological storage at a regional scale in carbonate rocks in Italy; and Frost and Jakle [30] (d = 70), who characterised areas of Palaeozoic deep saline aquifers in the Rocky Mountain West.

A third group of 51 papers (6%) referred to the modelling of gas flows during storage processes. The papers Ziabakhsh-Ganji and Kooi [31] (d = 98) and Lei et al. [32] (d = 86) both examined mixtures of gases caused by impurities contained in the CO_2 streams. Such impurities might have geophysical and geochemical impacts on the surrounding system. While the authors of the former developed a new equation of state (EoS) to simulate thermodynamic equilibrium of gas mixtures, the latter developed a "mutual solubility model for CO_2–N_2–O_2-brine systems" to examine the impacts of the co-injection of air and CO_2. Another key paper, Thomas et al. [33] (d = 80), compared different geochemical models and illustrated how "key geochemical predictions depend upon the selection of thermodynamic sub-models".

A fourth group dealt with the status of storage in general (43 papers, 5%) with two review papers as key papers: while Celia et al. [34] (d = 228) presented the status of CO_2 storage in deep saline aquifers, emphasising modelling approaches and practical simulations, Michael et al. [35] (d = 135) reviewed experiences from existing storage operations.

Field F1.2 (153 papers, 18% of C1) covered issues of storage site monitoring. A group of 81 papers (9.5%) focused on tracing methods, with the goal of more easily tracking any potential leakage of CO_2. Key papers include Humez et al. [36] (d = 190), who reviewed existing geochemical monitoring and tracing tools for shallow freshwater aquifers, complemented by an overview of sensitive indirect detection methods (which have not been applied in the field) as an avenue for further research, and Mayer et al. [37] (d = 182), who reviewed and recommended an isotopic composition of CO_2 as a suitable tracer at large CO_2 injection sites. Key papers within a second group, those of general analyses (72 papers, 8.5%), included Jenkins et al. [38] (d = 187), who examined the progress in monitoring and verification regarding the containment, conformity, and environmental impact, as well as Kim et al. [39] (d = 75), who conducted a critical review of the environmental impact monitoring of the offshore storage of CO_2, and recommended further research from a marine ecosystem perspective.

Field F1.3 (153 papers, 18% of C1) encompassed a variety of risk assessments. A total of 51 articles (6%) in this field referred to the impacts of (controlled or simulated) CO_2 releases of reservoirs

and pipelines. Key papers included Lichtschlag et al. [40] (d = 88), who analysed the effect of a controlled, 37-day-long, sub-seabed release of CO_2 on the biogeochemistry of shallow unconsolidated marine sediments, their pore waters, and the overlying water column; another was Yan et al. [41] (d = 78), who first reviewed the status of research on CO_2 release and dispersion from pipelines and subsequently studied CO_2 concentrations on the ground after small-scaled experiments on gaseous and liquid CO_2 release from a punctured small-scale underground pipeline.

An additional group of 43 papers (5%) covered risks to microorganisms and biology. Key papers in this group included Frerichs et al. [42] (d = 112), who showed that the "viability of fermentative and sulfate-reducing bacteria has to be considered" during every step of CO_2 storage if long-term safety and injectivity is to be ensured, and Ko et al. [43] (d = 86), whose authors recommended research for determining the impact of potential CO_2 leakage on plants and microorganisms, based on a review.

Various other risk factors, such as seismic, health and toxicological risks and risks for water security, were encompassed by a third group, comprising 60 papers (7%). Key papers include Hillebrand et al. [44] (d = 227), who reviewed potential toxicological risks along all parts of the CCS chain and recommended research on "acute CO_2-toxicity acute emergency management, and contaminants"; Mortezaei and Vahedifard [45] (d = 134), who statistically simulated stress changes and the resulting geomechanical deformations in the reservoir, the caprock and the fault due to CO_2 injection; and Thomas et al. [46] (d = 101), who reviewed research on hydrogeochemical monitoring methods designed to detect possible CO_2 leakages, in an effort to avoid risks to freshwater resources.

An additional 119 papers (14% of C1) of Field F1.4 dealt with storage issues in connection to other topics. Key papers include de Coninck and Benson [47] (d = 187), who investigated the reasons for the slow establishment of CCS as a mitigation technology, and in so doing included a comprehensive review chapter on storage; Jafari et al. [48] (d = 180), who analysed the storage potential for China, including monitoring and safety control issues; and Procesi et al. [49] (d = 99), who embedded the requirements for CO_2 storage sites in a comprehensive plan to allocate subsurface areas for various low-carbon technologies in a region in Italy.

3.2.2. Cluster C2 (Light Green, 612 Nodes, 14.3%)—Technologies and Processes (CO_2 Capture, Transport and Storage)

Its largest research field, F2.1 (465 papers, 76% of C2) addressed capture processes and separation technologies. The majority of this group, 298 papers (53%) focused on post-combustion processes. Key papers reviewed recent developments and research needs that would facilitate more efficient processes, such as efficiency penalties in general (Goto et al. [50], d = 210), future adsorption techniques (Due [51], d = 203), process intensification by way of chemical absorption (Wang et al. [52], d = 202), amine versus ammonia-based capture techniques (Shakerian et al. [53], d = 187), and recent advances in solvents, adsorbents, and membranes (Jones [54], d = 141). Papers with lower degrees mostly analysed novel or more advanced individual separation processes. Several papers pointed to the flexible operation of capture processes, a field of research that is attracting increasing attention with regard to the operation of power plants in a renewables-based energy system (Mac Dowell and Shah [55], d = 91, van der Wijk et al. [56], d = 89, or Alie et al. [57], d = 75). 8% of the papers analysed the water consumption of post-combustion (Zhai et al. [58], d = 165), environmental aspects in general or the greenhouse gas emissions of special processes.

Other groups included papers with a focus on the analysis of pre-combustion processes (43 papers, 7%) with one key paper Theo et al. [59] (d = 211) reviewing physical solvents and solubility models with a special emphasis on ionic liquid; papers that examine oxyfuel combustion processes (49 papers, 8%), with a key paper Skorek-Osikowska et al. [60] (d = 143) performing a techno-economic analysis of an integrated oxyfuel power plant; and new capture options (49 papers, 8%) such as papers that reviewed low-temperature capture technologies (Berstadt et al. [61], d = 156), capture from air (Jones [54]), capture with enzymes (Drummond et al. [62], d = 132), as well as papers reviewing and exploring

second-generation technologies combined with the use of solar energy (Zhao et al. [63], d = 128, and Liu et al. [64], d = 123).

Field F2.2 (104 papers, 17% of C2) contained papers looking at technologies of the total CCS chain and particularly transport and storage technologies. Among the key papers of F2.2's largest group (43 papers, 7%) were Leung et al. [65] (d = 381) and Pires et al. [66] (d = 372), the two papers with the highest degrees in this entire cluster; both reviewed the current status of all parts of the CCS chain, as well as Tan et la. [67] (d = 201), who reviewed the thermo-physical properties of the design and operation of components and processes involved in individual steps. Additional groups of papers in this field referred to transport or storage processes only (each with 31 papers, 5%). Key papers included, respectively, Roussanaly et al. [68] (d = 93), which analysed different CO_2 transport solutions within a transport network, and Olajire [69] (d = 118), who reviewed mineral carbonation technology processes for the sequestration of CO_2.

The 43 papers (7% of C2) in Field F2.3 dealt with technologies and processes embedded in a broader context of CCS, be it the need of increased (technological) learning effects (Reiner [70], d = 142), a national-scale assessment of CCS potential in China (Dahowski et al. [71], d = 141), or CCS as part of an optimisation model for regional energy planning (Arnette [72], d = 138).

3.2.3. Cluster C3 (Blue, 541 Nodes, 12.7%)—Techno-Economic Assessments of Technologies and Processes

Field F3.1 (238 papers, 44% of C3) addressed the cost assessments of CCS and macroeconomic issues in four groups. Seventy papers of the first group (13%) analysed market challenges and macroeconomic issues. Key papers included Abadie and Chamorro [73] (d = 269), Middleton and Eccles [74] (d = 230), and Koo et al. [75] (d = 192), each of which investigated the impact of carbon pricing: while the first paper analysed optimal investment strategies for CCS regarding the European market for CO_2 emission allowances and the second paper discussed the requirements of carbon pricing that would have to be put in place if all capturable CO_2 emissions, including daily variations, were to be managed, the third paper proposed a methodology aiming to "determine the optimal capacities of power plants . . . and volumes of emissions trading in the future that will meet the required emission level and satisfy energy demand... with minimum costs and maximum robustness". Additional key papers included Middleton et al. [76] (d = 244), who proposed a model for minimising CCS infrastructure costs along all parts of the CCS chain; Bowen [77] (d = 227), who understood CCS as a challenge for corporate technology strategies and analysed the delays in such investments; and Nemet et al. [10] (d = 194), who proposed a model for assessing the effects of policy instruments on the future costs of CCS-based coal-fired power plants.

Another group of papers (60 papers, 11%) reviewed the cost of the total CCS chain and its individual processes and compared different power plants with and without CCS, according to typical energy-economic indicators, such as the levelised cost of electricity or CO_2 avoidance costs. Key papers on this topic include a review paper on progress and new developments in CCS from Plasynski et al. [78] (d = 291), and cost comparisons between power plants from Tola and Pettinau [79] (d = 258) and Pettinau et al. [80] (d = 232).

An additional 60 papers (11%) focused on special features of the CCS chain and point to research and modelling lacunae. Examples are Lee et al. [81] (d = 307), who proposed a stochastic decision-making algorithm for the design and operation of a CCS network while considering the trade-off between risk and either economic or environmental objectives at the decision-making level; Akbilgic et al. [82] (d = 222), who tried to find the driving factors of variability in CO_2 avoidance cost estimates as published in scientific literature; and Sen [83] (d = 195), who discussed prospective developments of technical processes, such as future efficiency improvements.

Last but not least, the remaining group of papers (49 papers, 9%) covered the economic issues of implementing CCS in a regional and country-specific context. For example, Lai et al. [84] (d = 268) analysed China's CCS innovation system and its strengths and weaknesses; Singh and

Singh [85] (d = 255) focused on strategic and economic and regulatory aspects of future CCS in India; and Wu et al. [86] (d = 205) proposed an inexact optimisation model to aid in planning regional carbon capture under a least-cost strategy.

Having nearly the same size, Field F3.2 (233 papers, 43% of C3) brought together papers that looked at cost assessments of the individual capture technologies. With 108 papers (20%), the cost analysis of (advanced) pre-combustion technologies formed the largest group. Key papers that performed (process flow) modelling and evaluated the results by applying (techno-)economic indicators included Cormos [87] (d = 309), who analysed several gasifiers together with pre-combustion capture using gas-liquid absorption (as well as comparing it with an integrated gasification combined cycle (IGCC)) including post-combustion capture, and extended the analysis to the co-production of hydrogen, which would make the plant quite flexible for grid variations); Siefert and Litster [88] (d = 248), who combined exergy and economic analyses of advanced IGCC methods (H_2 and O_2 membrane CO_2 separation) and compared it with an advanced integrated gasification fuel cell cycle (IGFC) employing a catalytic gasifier and a pressurised solid oxide fuel cell, incorporating CO_2 sequestration (IGFC–CCS); and Cormos and Cormos [89] (d = 240), who proposed direct coal chemical looping using an iron-based oxygen carrier as an innovative carbon capture method for co-producing hydrogen and power, as well as a carbon capture rate over 99% (however, this paper did not analyse any cost indicators). Surprisingly, many more papers assessed the economic performance of pre-combustion technologies than considering the technological process by itself (43 papers in Field F2.1 "capture processes and separation technologies"). One reason for this may be that many advanced technologies reached their technological maturity in the past, and need now to be assessed with regard to their expected commercial use.

Aside from assessing advanced processes for post-combustion in yet another group (30 papers, 5.5%) a small group of papers investigated oxyfuel combustion (11 papers, 2%). The key paper from this group was Wu et al. [90], which has the largest degree by far (d = 370) of this cluster, illustrating the sharp decline in future costs of retrofitted oxyfuel power plants in China.

Furthermore, another group with 30 papers (5.5%) concerned the applications in the primary industry, such as Laude et al. [91] (d = 220), who analysed CCS retrofits applied in refineries; Kuramochi et al. [92] (d = 213), who investigated post-combustion capture from industrial combined heat and power plants; and Bielicki et al. [93] (d = 184), who proposed a large-scale integrated CCS networks connecting multiple industrial CO_2 sources and geologic storage reservoirs using the example of CO_2 emissions from ethylene production for EOR (enhanced oil recovery).

Last but not least, various other issues, such as CCS and biofuels, CCS and coal liquefaction, and storage, were allocated to a fifth group (54 papers, 10%).

Field F3.3 (70 papers, 13% of C3) encompassed papers that assessed CCS primarily from non-economic perspectives. The main group within this field (38 papers, 7%) dealt with environmental assessments: Koornneef et al. [94] (d = 274) performed an environmental impact and risk assessment of CO_2 capture, transport, and storage using the DPSIR framework (describing environmental drivers, pressures, states, impacts and responses); Veltman et al. [95] (d = 256) studied the impacts of post-combustion capture using amine-based scrubbing solvents on human health and the environment; Singh et al. [96] (d = 229) performed a life cycle assessment of a natural gas combined cycle power plant with post-combustion CCS. An additional group of 18 papers (4%) covered economic indicators as part of broader assessment frameworks. For example, Choptiany et al. [17] (d = 241) developed an MCDA model for a systematic assessment of specific CCS projects, while Ming et al. [97] (d = 174) conducted a SWOT analysis on CCS technology development in China to explore its strengths, weaknesses, opportunities, and threats (SWOT). A third group deals with assessments of the acceptance of CCS (11 papers, 2%)—however, the main cluster in this regard is Cluster C4 (next Section). As mentioned above, the assignment of a paper does not always occur unambiguously. The papers in this group seem to be included in this cluster since they cite similar basic technological papers as the other techno-economic papers do.

3.2.4. Cluster C4 (Orange, 437 Nodes, 10.2%)—Public Perception and Policy Issues

The largest field in this cluster, F4.1 (297 papers, 68% of C4), covered issues of acceptance, public perception, and stakeholder perspectives. The first group, with 114 papers (26%), performed national case studies on the public perception of CCS. For example, Setiawan and Cuppen [98] (d = 176) analysed the diversity of stakeholder perspectives on CCS in Indonesia; Lock et al. [99] (d = 173) asked about the knowledge and acceptance of CCS, and explored synergies in the nuclear discussion in the UK; and Chen et al. [100] (d = 124) performed a large national survey on public perceptions of CCS in China.

Another group of 66 papers (15%) performed meta-analyses on public perception and social research. Key papers included Johnsson et al. [101] (d = 151), who compared stakeholder attitudes on CCS in North America, Japan, and Europe; Upham and Roberts [102] (d = 111), who analysed European public perceptions of CCS in the UK, the Netherlands, Poland, Germany, Belgium, and Spain; and Jepma and Hauck [103] (d = 94), who identified a lack of social acceptance (and regulatory uncertainty) as major barriers to the large-scale implementation of CCS.

A third group of 96 papers (22%) explored how acceptance might be increased by both trust and communication measures. Key papers regarding issues of trust include Terwel et al. [104] (d = 117), who reviewed and discussed experimental research to show that laypeople's trust in stakeholders affected their acceptance of CCS implementation; ter Mors et al. [105] (d = 107), who reviewed and analysed the potential of host community compensation to help prevent or resolve CCS facility controversies; and Yang et al. [106] (d = 103), who analysed the effect of trust in CCS project implementation stakeholders on people's acceptance of CCS in China. Public communication was referred to by another set of papers, among these Vercelli et al. [107] (d = 134), who reviewed social research studies and explored key aspects of how to inform people about CCS; Bruin et al. [108] (d = 144), who highlighted three main lessons learned in developing communications about CCS; and Brunsting et al. [109] (d = 142), who applied communications theory to draw up empirical findings on the effects of major communication input factors on communication output factors. In a small fourth group, (22 papers, 5%), the role and perception of CCS among experts and engineers by themselves was analysed.

Field F4.2 (87 papers, 20% of C4) encompassed papers on policy and regulation issues of CCS, including analyses of barriers to its implementation. Key texts included Morgan and McCoy [110] (d = 279), a book that identified the barriers in current law and regulation that hinder the timely deployment of CCS and that proposed legislative options to remove such barriers; Bäckstrand et al. [8] (d = 161), an editorial that analysed the politics, policy, and regulation of CCS in cross-country comparisons, as well as in a global context; and Johnsson [111] (d = 159), an article that discussed the future perspectives for CCS and the (policy) implications for its further development.

Field F4.3 (52 papers, 12% of C4) discussed sociotechnical issues of CCS from a general perspective, be it an overview on the social dynamics on CCS (Markusson et al. [112], representing a book with d = 505), a review on the technology assessment literature on sociotechnical systems aiming to develop an interdisciplinary framework to assess the main uncertainties of CCS innovation systems (Markusson et al. [113], d = 197), or reviewing the critical ethical challenges raised by CCS (Medvecky et al. [114], d = 322) and developing a methodology for the assessment of ethical attitudes to CCS (Gough and Boucher [115], d = 135).

3.2.5. Cluster C5 (Pink, 255 Nodes, 6%)—The Chemistry of Capture and Separation

The largest field of this cluster, which was located far from the other clusters, F5.1 (176 papers, 69% of C5) dealt with technologies for capture and separation of CO_2, aiming at better selective capacity and stability, and a reduction in energy and cost requirements. The papers with the nine highest degrees were all review papers. These included Li et al. [116] (d = 133), who reviewed the status of research in metal-organic frameworks (MOFs), a class of crystalline porous materials that might be used both for adsorptive separation and for membrane-based separation of CO_2 in the future;

Zamann and Lee [117] (d = 82), who reviewed the future potential and the research needs in hybrid and modified capture technologies in terms of "capacity, selectivity, stability, energy requirements, etc."; Xiang et al. [118] (d = 78), who reviewed the application of a "multiscale approach to the simulation of the adsorption of hydrogen, methane, and CO_2 in porous coordination frameworks (PCFs) for the purpose of gas storage for energy transportation and CCS technology"; Zhang et al. [119] (d = 78), who reviewed future microporous MOFs as a way to develop and synthesise MOF materials for CO_2 adsorption; and Pera-Titus [120] (d = 76), who reviewed porous inorganic membranes that could be used for CO_2 capture.

Field F5.2 (59 papers, 23% of C5) also addresses research on the capture and separation of CO_2, but additionally covers the conversion of the separated CO_2 to products usable in the value chain (carbon capture and use (CCU)). Key papers include Yang et al. [121] (d = 81), who reviewed advanced processes on "CO_2's activation and subsequent conversion through the C–N bond formation pathway" to value-added chemicals, and Li et al. [122] (d = 68), who reviewed in situ transformation of CO_2 via C–O and C–N bond formation pathways.

Finally, the small field of F5.3 (20 papers, 8% of C5) encompassed papers that focused on the total CCS chain, and particularly on capture technologies, with the key paper being Boot-Handford et al. [123] (d = 137), who reviewed both capture processes that might be commercialised within 10 to 20 years, as well as other current processes "that are either more niche or are further away from commercialisation".

3.2.6. Cluster C6 (Grey, 220 Nodes, 5.15%)—The Thermodynamic Behaviour of CO_2

Within Field F6.1, 119 papers (54% of C6) referred to thermodynamic models for phase equilibria calculations, in which properties such as phase equilibria, density, isothermal compressibility, etc. and the behaviour of pure CO_2 and CO_2-rich mixtures during capture, processing, transport, injection and storage were analysed. According to Diamantonis et al. [124], accurate thermodynamic models are of high importance for the safe and economic design of these processes. With a degree of 367, Diamantonis et al. [125] was the paper with the largest degree by far, followed by Diamantonis et al. [124] (d = 268) and Munkejord et al. [126] (d = 191), each of them reviewing various thermodynamic models and their accuracy, together with calculations from EoS. Munkejord et al. [126] additionally reviewed the data situation for selected properties. Succeeding papers analysed the solubility of CO_2, such as Foltran et al. [127] (d = 162) and Wang et al. [128] (d = 153); explored special CO_2-rich mixtures, such as Nazeri et al. [129] (d = 133) and Ke et al. [130] (d = 120); worked out the behaviour under special temperature levels and pressures, such as Nazeri et al. [131] (d = 138) and Westman et al. [132] (d = 123); or explored special EoS, such as Aavatsmark et al. [133] (d = 126) and Ibrahim et al. [134] (d = 124).

Field F6.2 (51 papers, 23% of C6) focused on issues of CO_2 storage related to thermodynamic properties, such as analyses of thermal effects during storage processes (Vilarrasa and Rutqvist [135], d = 170), explorations of optimal operation under different market conditions (Luo and Wang [136], d = 140), or estimates of CO_2 injectivity and storage capacity in a Chinese basin by dynamic modelling, and suggestions for possible injection strategies and reservoir management options to improve storage capacity (Xie et al. [137], d = 140).

Having the same size, Field F6.3 (51 papers, 23% of C6) covered issues of CO_2 transport that were related to thermodynamic properties. The first group, with 25 papers (11.5%), referred to issues regarding the high-pressure pipeline transport of CO_2, where the papers with the highest degrees reviewed the design and operation of the mass flow meters (Collie et al. [138], d = 255), provided a device and a calibration method for a Coriolis mass flow meter (Lin et al. [139], d = 234), or modelled a CO_2 release and the subsequent dispersion of CO_2 in the atmosphere using a computational fluid dynamics model (Liu et al. [140], d = 148). Another group of 25 papers (11.5%) referred to pipeline infrastructure, with key papers including Luo et al. [141] (d = 194), who performed a techno-economic investigation into the optimal design of a CO_2 pipeline transport network;

Vandeginste and Piessens [142] (d = 153), who presented a pipeline design for a least-cost router application for CO_2 transport; and Sanchez Fernandez et al. [143] (d = 132), who evaluated the impact of varying geological conditions underground that could affect injectivity and therefore cause variations in CO_2 flow, which in turn would have an impact on the construction of CCS pipeline transportation and injection infrastructure.

3.2.7. Cluster C7 (Yellow, 217 Nodes, 5.1%)—Techno-Economically Optimising Models and Tools

Located at the centre of the network, Cluster C7 gathered knowledge from most of the surrounding clusters as the basis of its models, which could be divided into four fields of almost equal size.

Field F7.1 (50 papers, 23% of C7) dealt with the development and use of models that optimise the integration of all parts of the CCS chain from a techno-economic point of view. Huang et al. [144] (d = 143) provided a general review of optimisation methods used for the deployment of CCS power plants, such as energy expansion planning optimisation models, pipeline network planning, source-sink optimisation models, or CO_2 sequestration optimisation models. Other key papers included Han et al. [145] (d = 103), who developed a scalable and comprehensive infrastructure model that generates an integrated, profit-maximising CCS system from capture to storage of CO_2; Zhang et al. [146] (d = 99), who provided a mixed integer linear programming (MILP) model for the design of integrated carbon capture, transport, and storage infrastructure using the example of Qatar; Zhang et al. [147] (d = 95), who developed an inexact management model (ICSM) to identify optimal strategies to plan CO_2 capture and sequestration under uncertainty; and Lee et al. [148] (d = 86), who proposed a multi-objective MILP model combined with a life cycle assessment model in order to optimise both cost and environmental impacts.

Field F7.2 (50 papers, 23% of C7) focused on optimising the retrofit of power plants. Key papers included Lee et al. [149] (d = 180), who developed a mathematical model for CCS retrofit planning and considered both grid implications and source-sink matching in order to maximise the amount of CO_2 captured and stored; Chong et al. [150] (d = 140), which attempted to reach a similar goal by using a process graph (P-graph) optimisation technique based on graph theory; Zhai et al. [151] (d = 134), who presented a power plant modelling tool in order to explore the feasibility of implementing partial CO_2 capture in existing U.S. coal-fired power plants; Ooi et al. [152] (d = 115), who developed a multi-period planning methodology based on carbon-constrained energy planning (CCEP), aiming to minimise energy losses and/or power generation costs; and Sahu et al. [153] (d = 95), who presented a new algebraic targeting procedure based on pinch analysis for CCS planning for grid-wide CCS retrofits in the power generation sector using compensatory power. This paper also provided a comprehensive review of the methods, models and tools applied in recent years, in order to solve optimisation problems regarding the trade-offs between emission reductions, energy consumption and cost development.

Field F7.3 (50 papers, 23% of C7) encompassed papers that searched for optimal source–sink matching configurations. Key papers included He et al. [154] (d = 109), who proposed an MILP model with physical and temporal constraints, in order to handle interval and stochastic uncertainties; Alhajaj et al. [155] (d = 109), who presented an integrated whole-system model in order to design an optimum network linking sources and sinks, in so doing describing system behaviour and interactions along a range of length and timescales; Tan et al. [156] (d = 97), who developed a continuous-time mixed integer nonlinear programming (MINLP) model that was subsequently converted into an equivalent MILP model; Diamante et al. [157] (d = 94), who proposed a graphical approach for optimally matching multiple CO_2 sources and sinks, based on analogies with existing graphical pinch analysis approaches; and Keating et al. [158] (d = 85), who based a CCS infrastructure optimisation model on an evaluation of storage uncertainty using a hybrid system model for CO_2 sequestration performance and risk assessment.

Field F7.4 (67 papers, 31% of C7) explored optimisation models for CO_2 transport. Key papers included Fimbres and Wiley [159] (d = 140), who, after reviewing several CCS network optimisation

methodologies, proposed to start with determining the characteristics of a near-optimal CCS pipeline network by taking a whole systems approach to the minimum total cost per tonne of CO_2 avoided in a "steady-state"; Knoope et al. [160] (d = 127), who modelled a transportation network under uncertainty using a real option approach (ROA), and without uncertainty, using a perfect foresight (PF) model; and Mechleri et al. [161] (d = 110), who presented an optimisation methodology for the "right-size" CO_2 transport infrastructure, by taking into account the future variability in CO_2 flow (including periods of zero flow) due to an increasing share of renewables, and therefore a reduced load of fossil fuel-fired power plants.

3.2.8. Cluster C8 (Green, 190 Nodes, 4.45%)—"Extended" Techno-Economic Assessments of Plants and Processes

In this cluster, "extended" meant that not only were CCS technologies considered on their own, but also their integration into energy market developments. Alternatively, CCS technologies were compared with other low-carbon technologies, thereby helping to put their development into perspective.

In Field F8.1 (129 papers, 68% of C8), four different perspectives from regional to global level could be distinguished. One group, consisting of 42 papers (22%), analysed the possible prospects of CCS on a country level, thereby extending the economic perspective from business indicators such as the levelised cost of clean energy production or CO_2 avoidance cost to energy market assessments. Key papers included Višković et al. [162] (d = 367), who performed a case study on Croatia, including a market analysis regarding CO_2 prices and an assessment of the electricity market performance; Damen et al. [163] (d = 257), who explored paths towards large-scale implementation of CCS in the Netherlands; Liu and Gallagher [164] (d = 228), who analysed major carbon capture opportunities in China; and Spiecker et al. [165] (d = 187), who used both a stochastic European model and a German electricity market model to investigate possible investment strategies in German CCS power plants.

Another group of 33 papers (17.5%) extended the analysis by making a comparison of CCS with other low-carbon technologies on the country level. For example, Vögelke and Rübbelke [166] (d = 242) compared investments in CCS and PV regarding the possible merit-order effects and profitability in Germany. Al-Qayim et al. [167] (d = 216), performed a techno-economic assessment of biomass versus CCS-based coal-fired power plants in the UK. Kuramochi et al. [168] (d = 183) reviewed and analysed techno-economic prospects for CO_2 capture from distributed energy systems (combined heat and power (CHP) plants, boilers and distributed hydrogen plants).

Expanding from a country focus, an additional group of 10 papers (5.5%) considers the future role of CCS on a multi-country and supranational level, mostly the European Union (for example, the key paper Massol et al. [169] (d = 254), using both an economic modelling and a regulatory framework to analyse a possible European CO_2 pipeline project).

A total of 33 more papers (17.5%) explored the challenges of a global CCS deployment. Key papers included Chalmers and Gibbins [170] (d = 296), who discussed the key challenges for CCS, and developed a two-tranche programme for integrated commercial-scale demonstration projects; Koelbl et al. [171] (d = 221), who analysed the uncertainty of technological key parameters of CCS deployment; and Wennersten et al. [172] (d = 183), who reviewed the future prospects, economics and risks of CCS technologies.

Directly connected to this group, a group of 10 papers (5.5%) collected information on CCS as part of long-term energy models, such as Selosse and Ricci [173] (d = 180), who elaborated the possible global deployment of biomass with CCS (BECCS), by applying the bottom-up multiregional optimisation model TIAM-FR (THIMES Integrated Assessment Model); Bistline and Rai [174] (d = 352), who analysed the potential contribution of CCS to climate mitigation targets in the U.S. electricity sector by using a bottom-up modelling framework; and Luderer et al. [175] (d = 133), who showed that "renewables and CCS are found to be the most critical mitigation technologies" as result of a

"model inter-comparison exercise among regionalized global energy-economy models conducted in the context of the RECIPE project".

Field F8.2 (34 papers, 18% of C8) considered techno-economic analyses on CCS power plants that, compared to fields F3.1 ("cost assessments of CCS") and F3.2 ("cost assessments of individual capture technologies") in C3, applied an extended economic perspective. Key papers included Pettinau et al. [176] (d = 366), who compared UCS and IGCC power plants in Italy, with and without CCS, including the transport and storage of CO_2, and analysed economic incentives such as CO_2 emission licences; Lorenzo et al. [177] (d = 210), who performed an engineering-economic assessment of pre-combustion technologies (IGCC and Integrated Reforming Combined Cycle (IRCC)), addressing cost uncertainty in probabilistic terms by performing Monte Carlo simulations that included all the variables that are subject to uncertainty; and Abadie et al. [178] (d = 193), who developed a stochastic model for assessing CCS projects using CO_2 for either EOR or EGR and secondary storage in deep saline aquifers, in an effort "to understand the conditions that generate the incentives needed for early investments in these technologies".

A third, small field, F8.3 (10 papers, 5.5% of C8), contained papers that go beyond a techno-economic perspective. Key papers included Young-Lorenz and Lumley [179] (d = 203), who used a semi-quantitative methodology to assess various diverse CCS technologies using six different evaluation criteria; Kuckshinrichs [180] (d = 201), a book on the integrated technology assessment of CCS technologies by dedicating one chapter each to several criteria; Viebahn et al. [13] (d = 184) and Viebahn et al. [11] (d = 172), both of whom performed an integrated assessment of possible roles of CCS in South Africa and in India, respectively, by applying seven different assessment criteria; and Lilliestam et al. [181] (d = 142), who compared CCS with concentrated solar power using four different criteria.

Another small field, F8.4 (16 papers, 8.5% of C8) contained papers on applications of CCS in the primary industry, which take up issues from the other fields (economic analysis, models and integrated assessment). Key papers included Berghout et al. [182] (d = 159), who presented a techno-economic analysis of applying CO_2 capture for selected industrial plants; Kuramochi et al. [183] (d = 126), who performed a techno-economic analysis of various low-carbon technology options for the iron and steel sector; and Berghout et al. [184] (d = 123), who developed a method to assess the techno-economic performance and spatial footprint of CO_2 capture infrastructure configurations in industrial zones.

3.2.9. Cluster C9 (Light Red, 183 Nodes, 4.3%)—Extended Assessments on a Broader Level

The nodes of this cluster were quite interspersed, so assignments other than those described below might also be possible. The cluster also shows the smallest spread of degrees, reaching a maximum degree of 113. This may be interpreted in the sense that this cluster did not reveal the most important research front, but was however, characterised both by interdisciplinary assessments, due to connections to nearly all clusters, as well as by the utilisation of models due to the cluster's connections to C10 in particular.

Field F9.1 (71 papers, 39% of C9) contained papers on extended assessments of facilities generating different fuels (electricity, heat or liquids). Key papers include Tokimatsu et al. [185] (d = 176), who applied a global energy systems model with the aim of minimising the supply cost for the use of bioenergy with CCS (BECCS) together with various other technologies; Meerman et al. [186] (d = 152), who analysed under which market conditions flexible operation of integrated gasification polygeneration facilities would outperform static facilities based on different feedstock and generating electricity, Fischer-Tropsch liquids, methanol, and urea; and Wetterlund et al. [187] (d = 126), who investigated the effects of system expansion when assessing well-to-wheel CO_2 emissions while generating dymethylether (DME), methanol, ethanol, and electricity from biomass.

Field F9.2 (51 papers, 28% of C9) covered similar extended assessments, but focused solely on the electricity sector. Key papers included Rübbelke and Vögelke [188] (d = 226), who described individual EU-27 countries in the role of "pioneers" and of "laggards" in the deployment of CCS, and applied

a dispatched model to "assess the impact of deployment of power plants equipped with CCS on electricity production, and on electricity import and exports, as well as on the price of electricity at the spot-market"; Koelbl et al. [189] (d = 178), who applied a global multiregional input-output model to analyse the socioeconomic impacts of electricity generation strategies with and without CCS; and Li et al. [190] (d = 146), who investigated the implications of CO_2 price for China's decarbonisation of its power sector from technical, environmental, and economic perspectives.

A small field, F9.3 (31 papers, 16.5% of C9), encompassed assessments of new CCS applications such as the use of waste materials for "CCS by mineralisation" (Sanna et al. [191], d = 70) or biomass co-fired oxyfuel-fired polygeneration of liquids and electricity using CCS (Normann et al. [192], d = 124), while another small field, F9.4, of the same size, contained various other issues of CCS.

3.2.10. Cluster C10 (Dark Blue, 179 Nodes, 4.2%)—Frameworks and Models for the Assessment of Both CCS in General and Storage

This cluster supplemented Cluster C7 with regard to systems analytical issues. Within Field F10.1 (107 papers, 60% of C10, frameworks and models for the assessment of CCS), the first group of 59 papers (33%) assessed CCS from a holistic point of view by developing or using existing assessment frameworks. Key papers in this regard included Zheng and Xu [19] (d = 352), who analysed future CCS technological trends by developing and applying a CCS technology paradigm that attempted to explain the competition, diffusion, and shift of CCS technologies, and highlighted the importance of political barriers and public acceptance as major distinctions between this paradigm and conventional techno-paradigms; Martínez Arranz [16] (d = 287), who developed an analytical hype analysis framework, concluding that (power plant-based) CCS—compared to other low carbon technologies—shows signs of hype when "considering indicators of expectations, commitment and outcomes"; and Sathre et al. [193] (d = 182), who developed a framework for environmental assessment of CCS that went beyond a life cycle analysis of individual power plants and included further indicators aiming for an assessment of system-wide environmental implications.

One group comprising 18 papers (10%) explored the role of CCS for individual countries based on frameworks, such as Lai et al. [194] (d = 431), who applied a technology assessment framework consisting of several assessment dimensions to CCS in Malaysia; Meng [195] (d = 320), who explored challenges and policy choices for CCS in China by comparing CCS with renewable energy using four assessment criteria; and Middleton et al. [76] (d = 147), who developed a spatial decision support system for minimising the cost of the CCS chain in California.

An additional group of 18 papers (10%) applied simulation-based methods to minimise the cost of CCS or CCS components, such as Seo et al. [196] (d = 166) by evaluating the unavailability cost of CO_2 liquefaction processes for ship-based CCS, Lin et al. [197] (d = 163) by ranking adsorbents for their performance in CCS, and Santibanez Gonzalez [198] (d = 153) by using an MILP model to design an infrastructure supply chain network in the case of the cement industry in Brazil. While such analyses could fit into cluster C7 ("techno-economically optimising models and tools"), in these cases, some particular cited sources that might have been the deciding factor to assign these papers to C10 instead.

Finally, a group of 13 papers (7%) considered CCS in the context of energy modelling. Heitmann et al. [199] (d = 469) reviewed the status of CCS in energy system modelling and spatial optimisation in the context of policy coordination needs, to foster widespread implementation of CCS in the future. Deetman et al. [7] (d = 134) analysed the contribution of CCS to major CO_2 emission reductions in an energy system model. Luderer et al. [200] (d = 122) analysed the contribution of CCS within a broad portfolio of technologies contributing to future emission reductions in Asia.

Concerning Field F10.2 (72 papers, 40% of C10, frameworks and models for storage assessment), a group of 41 papers (23%) developed models for analysing CO_2 storage processes. Key papers include Eccles et al. [201] (d = 274), who analysed the distribution of low-cost storage sites in the U.S. by producing a geo-referenced raster of estimated storage capacity and cost; Bielicki et al. [202]

(d = 217), who explored a leakage estimation model to examine U.S. geologic carbon sequestration policies; and Celia et al. [203] (d = 147), who applied a semi-analytical model and a Monte Carlo framework to estimate CO_2 and brine leakage in old wells at a field site in Canada, and analysed the overall system behaviour over a 50-year time horizon.

A second group of 30 papers (17%) assessed CO_2 storage in general by developing or applying frameworks with regard to stakeholders. Key papers included Court et al. [204] (d = 303), who reviewed large-scale implementation challenges of CO_2 storage (water, storage, legal, and social acceptance) within a single common framework, enabling the identification of synergies by examining these challenges not in isolation, but collectively; Eccles and Pratson [205] (d = 235), who developed a "carbonshed" framework (defining "carbonsheds" as "regions in which it is cheaper to transport and store CO_2 internally than to send the CO_2 to other regions") and demonstrated that a cooperatively managed transport and storage infrastructure system would be more cost-effective than decentralised, small-scale storage; and Cai et al. [206] (d = 211), who studied pricing contracts between CO_2 emissions producers, and a transport and storage operator (the selection of optimal price and volume under uncertainty) to optimise the operator's expected profit under a CO_2 reduction regime.

3.2.11. Cluster C11 (Medium Green, 98 Nodes, 2.3%)—The Transport of CO_2

The research front of this cluster covered the thermodynamic behaviour of CO_2 and the impacts of CO_2 corrosion during transport. In Field F11.1 (69 papers, 70% of C11, thermodynamic behaviour of CO_2), one half of the papers referred to the thermodynamic behaviour of CO_2 in transport pipelines, e.g., by examining the volumetric property of CO_2 mixtures containing H_2, in an effort to facilitate the optimal design and operation of pipeline networks by Sanchez-Vicente et al. [207] (d = 71), or by analysing the effect of methane and nitrogen on the decompression characteristics of CO_2 in pipelines by Cosham et al. [208] (d = 55). Moreover, several papers investigated the behaviour of CO_2 after accidental releases from pipelines, e.g., Wareing et al. [209] (d = 63). Another group of 15 papers (15%) referred to the behaviour of CO_2 during storage, such as Li et al. [210] (d = 43), who simulated fluid convection processes, and Jiang et al. [211] (d = 38), who analysed thermal exchanges with rocks and the natural convection of water. Two additional groups with 10 papers each (10%) discussed the interactions between pipelines and wells, and various individual issues.

Papers in Field F11.2 (29 papers, 30%, mainly conference papers) analysed the impacts of CO_2 corrosion on pipe steels and other materials that might be caused by impurities in the CO_2 stream. They contained review articles such as Halseid et al. [212] (d = 78), who reviewed experimental corrosion data in the presence of flue gas impurities, and Schmitt [213] (d = 41), who reviewed the influence of materials-related, medium-related, and interface-related parameters, as well as investigations of corrosion behaviour of certain pipe steels under special conditions, such as Xiang et al. [214] (d = 94) (corrosion behaviour of X70 steel and iron in water-saturated supercritical CO_2 mixed with SO_2) or Pfennig and Kranzmann [215] (d = 47) (laboratory experiments on the reliability of steels used at a geological onshore CCS site).

3.2.12. Cluster C12 (Black, 97 Nodes, 2.3%)—The Modelling and Assessment of Storage Processes

The research front of this cluster essentially covered issues that might also have been included in other clusters. Compared to those, however, the papers in this cluster contained diverse links to other clusters, and therefore show a more interdisciplinary approach. The cluster had a dispersed structure, but it was located mainly between C10 ("frameworks and models") and C8 ("extended techno-economic assessments"). Field F12.1 encompassed 51 papers (53% of C12) that modelled parts of storage processes. Key papers included Jiang [216] (d = 237), who reviewed models and methods designed to simulate flow and transport phenomena in carbon storage, and van den Broek et al. [217] (d = 159), who coupled a geographical information system with a linear optimising energy model to derive a cost-effective CO_2 storage infrastructure. Field F12.2 (46 papers, 47% of C12) concerned assessments of storage issues that go beyond pure techno-economic issues. Key texts included Laude

and Jonen [218] (d = 189), who compared cases of early and delayed CCS deployments, to determine the influence of technical innovations on cost reduction, and Taniguchi and Itaoka [219] 2016 (d = 120), who assessed the Japanese roadmap of storage technology as a book chapter.

3.2.13. Clusters 13 and 14

Despite the carefully chosen search terms, two out of the 14 clusters referred to topics outside the field of carbon capture and storage: Astrophysics/astrochemistry (C13), where CCS serves as an example of a "carbon-chain molecule" (76 nodes, 1.8%), and medicine (C14), where CCS is used as a classification of diseases according to the Canadian Cardiovascular Society (61 nodes, 1.4%). These clusters were located at the outermost region of the network, far away from the other clusters, illustrating their tenuous relationship to the other clusters (not shown in Figure 2). Although the second part of the search term applied ought to have limited the results to the use of CCS in the sense of the present paper, in some cases, the keywords "carbon" and "emission" were also used in the aforementioned topics. In both cases, a paper connecting these clusters with the main network was identified. In the case of Cluster C14, Zhang et al. [220] built a bridge to Pratt et al. [221], a paper from Cluster C9 that analysed the impacts of potential gas leaks from storage sites on marine species. Both papers cited the source Bustin et al. [222], providing guidelines for gene transcription. Regarding Cluster C13, Kaiser et al. [223] was identified as a connection paper, which was linked to several papers on legal and regulatory issues. However, in this case, no commonly cited paper was found. Here wrong bibliographic data during the cleaning process at the preliminary stage of bibliographic coupling may have been overlooked.

3.2.14. Additional Clusters

For the sake of completeness, it should be mentioned that an additional 255 nodes (5.9%) belonging to 108 very small clusters were not analysed in detail further.

3.3. The Conceptual Model of the Base Paper Set

The conceptual model was developed in two steps: first, the main clusters were divided into sub-clusters, and the main relationships to other clusters were described. This was done by using Gephi to obtain a rough visual overview of the connections that each paper had with the same cluster or with other clusters. The papers that had similar target clusters were grouped into a sub-cluster. Preliminary analysis showed that typically, three types of sub-clusters appeared: a sub-cluster (A) contained papers that were linked to several clusters located in the direct or indirect neighbourhood, a sub-cluster (B) encompassed papers that were linked to one or two selected neighbouring clusters, and a sub-cluster (C) mostly linked papers from the same cluster. The sub-clusters were already included in Figure 2. Second, the research fields of each cluster analysed in the previous section were screened to see if they contained a topic that was simultaneously the main content of another cluster (e.g., different issues of storage). Table A3 in Appendix B illustrated the relationships found, which were interpreted below for the most relevant sub-clusters.

3.3.1. Cluster C1 (Red)—Geological Storage

Sub-cluster C1.A (50% of papers) encompassed papers that were tightly linked to Cluster C10, particularly including references to Field F10.2 ("frameworks and models for storage assessment", 71 papers) and weakly linked to C2, particularly to Field F2.2 ("particularly transport and storage technologies", 31 papers). Sub-cluster C1.B (20% of papers) contained papers that showed a close link to its neighbouring Cluster C6, particularly to Field F6.2 ("thermodynamics of CO_2 storage", 51 papers). These links made sense, since these papers complemented the papers from C1 with additional analyses, particularly by incorporating storage processes into larger frameworks, expanding the narrow view of technical process analyses, and integrating storage processes into thermodynamic equilibrium models. Moreover, Field F1.4 itself ("storage issues in connection to other topics") also contained some papers

with regard to frameworks and integrated assessment. As mentioned above, the assignment of a paper was not always unambiguous. As Figure 2 illustrates, some few red nodes from C1 entered other clusters (and vice versa), particularly to C10 ("frameworks and models"), which indicated a rather strong link, as described above.

3.3.2. Cluster C2 (Light Green)—Technologies and Processes

Sub-cluster C2.A (70% of papers) encompassed papers that were particularly linked to C3 ("techno-economic assessment"), C6 ("thermodynamics"), C7 ("techno-economically optimising models and tools") and C10 ("frameworks and models"), where they delivered the basic technological data and figures for techno-economic assessments, equilibrium models, optimisation by techno-economic modelling, and assessment by the means of frameworks and integrated concepts, respectively. In particular, all the review papers showed tight connections to these clusters, which was also the reason for their location in or near the centre of the network. Many papers from Sub-cluster C2.B (10% of papers) migrated far into C3, showing a strong relationship between technologies and their assessment. Only weak links appeared with Cluster C4 ("public perception/policy"). This made sense, since C2 was mainly concerned with non-storage technologies and processes, and detailed technical processes did not seem to be of interest in the public's perception.

3.3.3. Cluster C3 (Blue)—Techno-Economic Assessments

Sub-cluster C3.A (80% of papers) encompassed papers mainly connected to C2 ("technologies, processes"), C4 ("public perception/policy"), C8 ("extended techno-economic assessments"), and C10 ("frameworks and models"), which together formed the upper half of the base paper network. A few papers were also linked to C1 ("geological storage") and C7 ("techno-economically optimising models and tools"). Sub-cluster C3.B (20% of papers) encompassed papers that were particularly linked to the neighbouring clusters of C2 and C8. C3 was especially closely linked to C2, since its technologies and processes were the basis for techno-economic assessments. Since C3 and C8 shared a large area, there was also a strong link between papers providing assessments using different dimensions. The same was true with the relationship between C3 and C7, since many similar sources for techno-economic modelling might be used. Although the papers of C10 and C4 were located opposite C3, they seemed to cite similar literature.

3.3.4. Cluster C4 (Orange)—Public Perception and Policy Issues

Sub-cluster C4.A (80% of papers) encompassed papers that were linked to C10 ("frameworks and models"), strongly linked to C3 ("techno-economic assessment"), and weakly linked to C1 ("geological storage"), C7 ("techno-economically optimising models and tools"), and C8 ("extended techno-economic assessments"). These papers particularly included references to Fields F3.3 (71 papers concerning "assessments from primarily non-economic perspectives", of which 11 papers were on acceptance) and F10.1 ("frameworks and models for the assessment of CCS", of which 59 papers examined the assessment of CCS from a holistic point of view). In a similar way, acceptance was often part of a multi-criteria assessment, as captured in Field F8.3 ("assessment beyond a techno-economic perspective"), so both clusters might cite similar sources.

3.3.5. Cluster C5 (Pink)—The Chemistry of Capture and Separation

This cluster was characterised as a "closed shop", showing only very few connections of Sub-cluster C5.A (about 5% of papers) to other clusters. Many of these connections were caused by citing Boot-Handford et al. [123], who—besides technological issues—also focused on "systems integration and policy design and implications for investment". In particular, there was no connection to Field F2.1 ("capture processes and separation technologies"), which addressed the same issues, but included twice as many papers as given here. The reason for this may be that nearly all authors of C5 published in journals related to chemistry issues, so this work used a different body of knowledge

to the other clusters. Furthermore, the nodes of this cluster showed some of the smallest degrees, but some of the highest weighted degrees within the base paper set. This means that relatively few authors cited the same papers, but if they did, then they share several papers. This may be interpreted in such a way that this cluster formed a community that strongly focused on basic chemistry research.

3.3.6. Cluster C6 (Grey)—The Thermodynamics of CO_2

Sub-cluster C6.A (25% of papers) encompassed papers that were linked to Clusters C2 ("technologies, processes"), C3 ("techno-economic assessment"), C7 ("techno-economically optimising models and tools") and C10 ("frameworks and models"), and weakly linked to C4 ("public perception/policy") and C8 ("extended techno-economic assessments"). Most of the links were caused by the review papers Diamantonis et al. [124,125], Munkjeford et al. [126], and Collie et al. [138], meaning that they covered a wide range of the technical research in the broader context of CCS. Very few connections existed to C11 ("transport of CO_2"). Fields F6.3 ("issues of CO_2 transport related to thermodynamic properties") and F11.1 ("thermodynamic behaviour of CO_2") investigated rather similar issues, which again shows the smooth transition between these two clusters. Furthermore, Sub-cluster C6.B (25% of papers) was strongly linked to C1 ("geological storage"), as already described above. Together with half of the papers that were only connected with the same cluster (Sub-cluster C6.C), 75% of the cluster's papers concerned rather technical issues.

3.3.7. Cluster C7 (Yellow)—Techno-Economically Optimising Models and Tools

In contrast to the clusters mentioned so far, in this cluster, no sub-clusters of the Categories B and C could be identified. Instead, all papers were linked with several other clusters. This may be interpreted in such a way that techno-economically optimising models and tools represent a central role in the literature, which is also expressed by the central position of this cluster. Still, the cluster can be divided into two sub-clusters: Sub-cluster C7.A.1 (50% of papers) included most of the key papers characterised by more or less strong connections to C2 ("technologies, processes") and C3 ("techno-economic assessment"). This makes sense, since the models optimising the use of CCS (Fields F7.1 and F7.2) were based on technical and techno-economic data and figures. Additional connections appeared with C10 ("frameworks and models"), caused by Field F10.1 ("frameworks and models for the assessment of CCS", which also applied simulation methods to minimise the cost of CCS applications), and (less so) to C8 ("extended techno-economic assessments"), caused by Field F8.2, which encompassed (extended) techno-economic assessments. Sub-cluster C7.A.2 (50% of papers) also showed links to C3 and C10, but additionally to the technical clusters C6 ("thermodynamics") and C1 ("geological storage"). These built the basis for papers looking at the optimisation of source-sink matching and of CO_2 transport, as characterised by Fields F7.3 and F7.4, respectively.

3.3.8. Cluster C8 (Green)—"Extended" Techno-Economic Assessments of Plants and Processes

Sub-cluster C8.A (60% of papers) was strongly connected to Cluster C3 ("techno-economic assessment"), which makes sense, since both dealt with techno-economic assessments and therefore use similar sources. Both clusters also included issues of CCS in the primary industry, in which—similar to power plants—they performed a pure cost assessment in Field F3.2 ("assessments from primarily non-economic perspectives", 30 papers) as well as extending this to a broader perspective in Field F8.4 ("applications of CCS in the primary industry", 16 papers). This sub-cluster was also connected both to C4 ("public perception/policy"), since social acceptance is usually a part of multi-criteria assessment studies, and to C10 ("frameworks and models"), since both clusters made use of energy models. Probably, the assignment of an energy modelling paper to Field F8.1 ("regional to global level", 10 papers) or to Field F10.1 ("frameworks and models for the assessment of CCS", 13 papers) depended on whether the authors used more economic sources, or more sources regarding frameworks and models. Only a few or very few links appeared with the technical clusters of C1 ("geological storage"), C6 ("thermodynamics"), and C2 ("technologies, processes"). This was also reasonable, since

these were usually used in techno-economic assessments (C3), while C8 papers perform extended assessments sharing a more holistic point of view.

3.3.9. Cluster C9 (Light Red)—Extended Assessments on a Broader Level

Although the nodes were quite interspersed between other clusters, two sub-clusters could be identified: Sub-cluster C9.A-1 (60% of papers) was located within the border regions of clusters C2 ("technologies, processes"), C3 ("techno-economic assessment"), C7 ("techno-economically optimising models and tools") and C10 ("frameworks and models"), and showed connections to nearly all other clusters as well, particularly to C4 ("public perception/policy") and C10 ("frameworks and models"); this was explained by relationships to models and frameworks. In contrast, Sub-cluster C9.A-2 (40% of papers) was located within the border regions of Clusters C8 ("extended techno-economic assessments") and C4, and particularly showed connections to C8.

3.3.10. Cluster C10 (Dark Blue)—Frameworks and Models for the Assessment of Both CCS in General and Storage

Similar to C7 ("techno-economically optimising models and tools"), this cluster did not provide delimitable sub-clusters of the Categories B and C, but shows manifold connections of all parts to other clusters. Therefore, this cluster had a similarly central role in the literature as C7. This was also expressed by the overlap of many nodes and the occasional far migration of nodes into a neighbouring cluster. All areas of C7 had more or less strong connections to C1 ("geological storage"), C3 ("techno-economic assessment"), C4 ("public perception/policy"), and C8 ("extended techno-economic assessments"). Field F10.2 ("frameworks and models for storage assessment") complemented Field F1.1 ("storage mechanisms and potential") as well as F2.2 ("storage mechanisms and potential") and F6.2 ("thermodynamics of CO_2 storage"). The papers in Field F10.1 performed general assessments of CCS and therefore had strong connections to F3.3 ("assessments primarily from non-economic perspectives") and to C8 ("extended techno-economic assessments", including multi-criteria analysis). Furthermore, C10 complemented Field F4.2 ("policy and regulation issues"), both by assessing CCS from a holistic point of view (F10.1), and by integrating frameworks utilising stakeholder perspectives (F10.2).

Some areas showed individual connections to selected clusters. Sub-cluster 10.A.1 (20% of papers) was additionally linked with C2 ("technologies, processes") and weakly linked with C6 ("thermodynamics"), pointing to basic technological knowledge also being used in C10. Generally, this sub-cluster showed the most diverse links to nearly all other clusters in the paper set, which may be caused both by several review and overview papers as well as by the nature of its main content—the development of frameworks and models. Sub-cluster 10.A.2 (20% of papers) also had strong links to, and was located closely to C7 ("techno-economically optimising models and tools"), which also makes sense, since the modelling activities may use several common sources.

3.3.11. Cluster C11 (Medium Green)—The Transport of CO_2

Sub-cluster C11.A (50% of papers) was connected to C10 ("frameworks and models"), where transport technologies are a part of CCS-based models, and strongly connected to C2 ("technologies, processes"), particularly to Field F2.2 on transport technologies. Few links existed to C1 ("geological storage"), C6 ("thermodynamics"), and C3 ("techno-economic assessment"). The former made sense, since C11 concerned both the behaviour of CO_2 in pipeline transport, and storage and the interaction between pipeline and well. For the latter, C11 served as a basis for the techno-economic assessment.

3.3.12. Cluster C12 (Black)—The Modelling and Assessment of Storage Processes

Sub-cluster C12.A (95% of papers) shows diverse connections to most other clusters, particularly to C1 ("geological storage"), C8 ("extended techno-economic assessments"), and C10 ("frameworks and

models"), but also to C2 ("technologies, processes"), C3 ("techno-economic assessment"), C4 ("public perception/policy"), and C6 ("thermodynamics"), illustrating the interdisciplinary approach of this small cluster. In addition, a small Sub-cluster C12.B (5%) showed a very strong connection to C1 ("geological storage").

4. Discussion

In order to answer the research question, it is first discussed how the central research topics relate to each other (see Figure 4 for the main findings).

Technologies form the content of several large and smaller clusters. They encompass issues of geological storage, such as core storage processes, tracing methods, or storage potentials (C1), transport, and all types of capture technologies (C2), supplemented by the thermodynamic behaviour of storage and transport processes (C6) and other issues of transport (C11).

- Three main principles are visible: first, as previously expected, these technical clusters are connected to clusters concerning modelling or assessments of the technologies (C3, C7, C8, C10). Papers in these clusters usually base their assessments on sources from C1, C2, C6, C11, which provide the relevant technological knowledge. The more sources they cite together with neighbouring papers, the larger the nodes are, and the closer they are located towards the border of the connected cluster. Therefore, review papers appear particularly frequently, describing the current status of development and actual research and development (R&D) issues, while citing many sources from several clusters. Second, on the one hand, the technologically oriented clusters are connected to other such clusters with similar content, though their emphases diverge (for example, storage mechanisms of C1 are related to storage processes of F2.3 ("technologies and processes embedded in a broader context of CCS")). On the other hand, no or only a few connections are visible from these clusters to other technical options, such as transport options (C11) or capture technologies (C5). Third, these clusters include sub-clusters in which the sources are connected mostly to the same cluster. This may be interpreted to mean that in these clusters, the core technical research takes place based on quite subject-specific sources. These sources show comparatively low degrees, in any case lower degrees than the papers located more towards the network's centre. Consequently, these clusters are placed at the border of the base paper network.
- However, some differences appear between the technical clusters. Concerning the relationship to non-technical clusters, C1 ("geological storage") is mainly connected to C10, particularly to F10.2 ("frameworks and models for storage assessment"). Zero or only a few connections to C3 ("techno-economic assessments"), C7 ("techno-economically optimisation models"), and C8 ("extended techno-economic assessments") appear. This is also illustrated by the position of this cluster, which is close to and connected with C10, but far away from the other assessment clusters. This means that it is mostly capture and transport that are included in assessment studies, be it techno-economic assessments, energy market assessments, energy models, or multi-criteria assessments. On the one hand, this might be justified, since the storage cost is only a minor part of the overall CCS cost. On the other hand, in order to consider risks and therefore possible additional costs, as well as to draw the "full picture" of CCS and consider the uncertainties of storage potentials, especially in multi-criteria assessment studies, issues of storage processes should increasingly be taken into account.
- Furthermore, in contrast to previous expectations, C1 ("geological storage") shows only a few links to C4 ("public perception/policy"). This means that both storage mechanisms and monitoring/risk assessment play only a small role in such studies, which do not seem to be based on detailed technical storage issues. On the one hand, detailed technical storage processes go behind what stakeholders are interested in. On the other hand, such details are necessary for assessing and evaluating the potentials and risks of storage, so that more attention should be paid to these issues when discussing public perceptions and issues of policy and regulation.

- In contrast to storage issues, the technically oriented clusters of C2 ("technologies, processes") and C6 ("thermodynamics") show far more divergent connections, which means that capture technologies and their processes play a far greater role in the discussion. This is understandable if one considers that the capture cost accounts for the vast majority of the total avoidance cost. Therefore, there is a natural link to techno-economic assessments (C3) and techno-economically optimisation models (C7), focusing on the cost-optimal design of capture processes. Since basic technological issues are not usually needed to perform extended assessments, such as regional or national studies on CCS, comparisons of CCS to other low-carbon options or multi-criteria assessments, there is only a weak link to C8 ("extended techno-economic assessments"). Furthermore, and similar to C1 ("geological storage"), only a few links appear to C4 ("public perception/policy"). Similar to C3 ("techno-economic assessments"), this cluster does not base its studies on purely technological issues, but on the results of techno-economic assessments.

The role of the non-technical clusters has already been discussed in the previous paragraphs. The graphical analysis helps to fully understand their role in the network.

- In accordance with the graphical pattern from the base paper network, they form two groups: directly neighbouring the technical clusters C2 ("technologies, processes") and C6 ("thermodynamics") are both the techno-economic assessment cluster (C3) and the techno-economically optimising models and tools cluster (C7). These links have already been explained above. However, a second group of clusters extends these approaches and methods, and therefore provides extended techno-economic assessments (C8, C9) and frameworks and models for the assessment of CCS in general (C10). This group of clusters encompasses significantly fewer nodes (550) than the first group (750), and is not located in the direct neighbourhood of the technical clusters. The second group shows very strong connections to the first group of non-technical clusters, but only a few to the original technical clusters. This may be interpreted to mean that the articles of the second group provided more general assessments, and are not "interested" in technical details. Instead, they based their work on articles that had already assessed or modelled the technologies by themselves, so that they could look at the "bigger picture" of CCS with respect to the overall context of the energy (economic) system and climate change. C10 ("frameworks and models") therefore reveals itself to be the cluster with the largest variety of links to other clusters, and is therefore the most "holistic" cluster of the network.
- Finally, squeezed between the green, blue and dark blue clusters, and stretching out from the actual network, C4 deals with questions of public perception and policy issues. Since public perception is a strongly discussed issue with regard to a rapid and massive implementation of CCS, it makes sense to refer to it in an individual cluster. However, as already discussed above, there are no or only very few links to the technical clusters. Instead, like the other assessment and modelling clusters, C4 is connected with fields of assessments primarily from non-economic perspectives (F3.3) and assessments beyond a techno-economic perspective (F8.3). Furthermore, one might expect that C7 ("techno-economically optimisation models") would also have connections to C4, since the non-acceptance of CCS might cause a risk for implementing CCS measures, which would also have to be regarded as a cost factor. However, issues of acceptance do not yet seem to have been included in such models.
- Unexpectedly, environmental assessments appear only marginally in the network. Only one field of papers within the techno-economic assessments of C3 considers non-economic assessment dimensions (F3.3). These might be placed as part of C3, since that cluster uses many base papers that are also used for the economic assessment. Within this field, a sub-field of 38 papers (0.9% of the base paper network) was identified that actually did take environmental assessments into consideration. Additional environmental assessments might have been performed as part of multi-criteria assessments, which were identified as a very small sub-field within the extended

techno-economic assessment of C8. Due to the importance of ecological issues occurring during the application of CCS, many more such assessments would have been expected.

Last but not least, several advanced technological developments of CCS have been identified. These are characterised by research issues that go beyond the common applications of CCS.

- Directly visible are new capture options (49 papers as part of F2.1 "capture processes and separation technologies"), cost assessments of advanced pre- and post-combustion technologies (108 and 30 papers as part of F3.2 "cost assessments of the individual capture technologies"), and applications of CCS in primary industry. The latter papers were identified as individual fields, namely Field F3.2 and Field F8.4 ("CCS in industry"), but they are also part of other clusters.
- By contrast, other research fields that were expected to be part of the CCS frontier, such as biomass-based CCS (BEECS) or negative-emission technologies (NET), appeared only marginally.
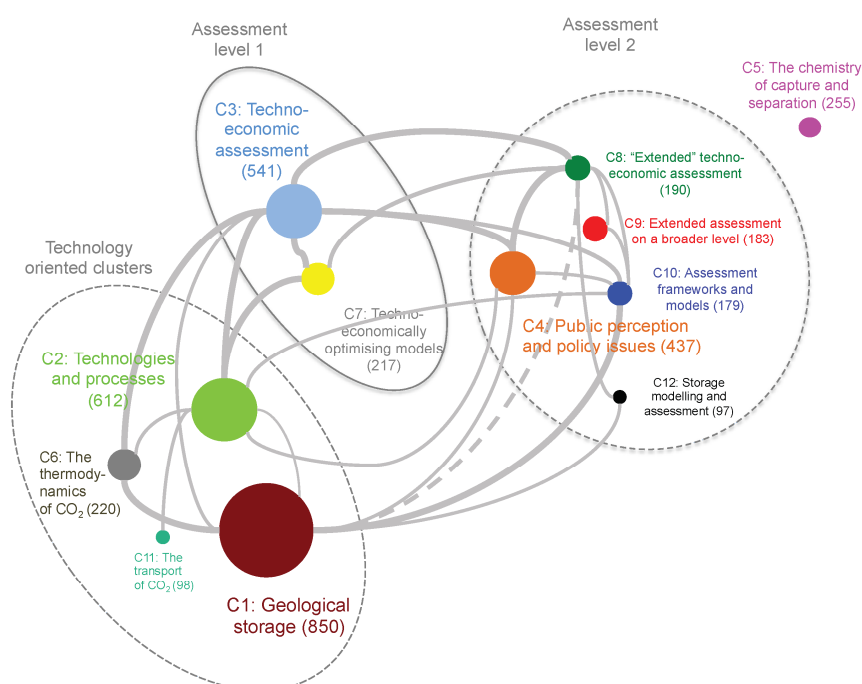
Figure 4. Main relationships between the central research clusters (the thicker the lines, the stronger the connection).

In order to place these observations properly together with regard to the research question, they are put into perspective by providing the numerical strength of the individual research topics. In Figure 5, the clusters, or parts of a cluster as analysed in Table A2 in Appendix B, are put together into seven meta-clusters (MC). As is clearly visible, the largest group of papers (meta-cluster MC.A = 50% out of 3879 papers) refers to technologies or technological issues. The technical assessment and modelling meta-clusters MC.B and MC.C, totalling 19%, are strongly related to these. In total, 69% of all papers take the development and cost-optimal design of technologies and processes into consideration. The papers of MC.D (17%) extend assessments into further dimensions, such as environmental or particularly social issues. Only 14% consist of papers that put CCS in a systems-oriented perspective (MC.E, MC.F and MC.G). Of these papers, 7% of the total put CCS into a broader context (such as performing country-based studies, extended techno-economic assessments, market challenges, and comparisons with other low-carbon technologies), 4% of the total number assess CCS from a holistic perspective, by developing or using existing assessment frameworks, performing multi-criteria assessments and/or portfolio analyses, and 1% consider CCS in energy models.
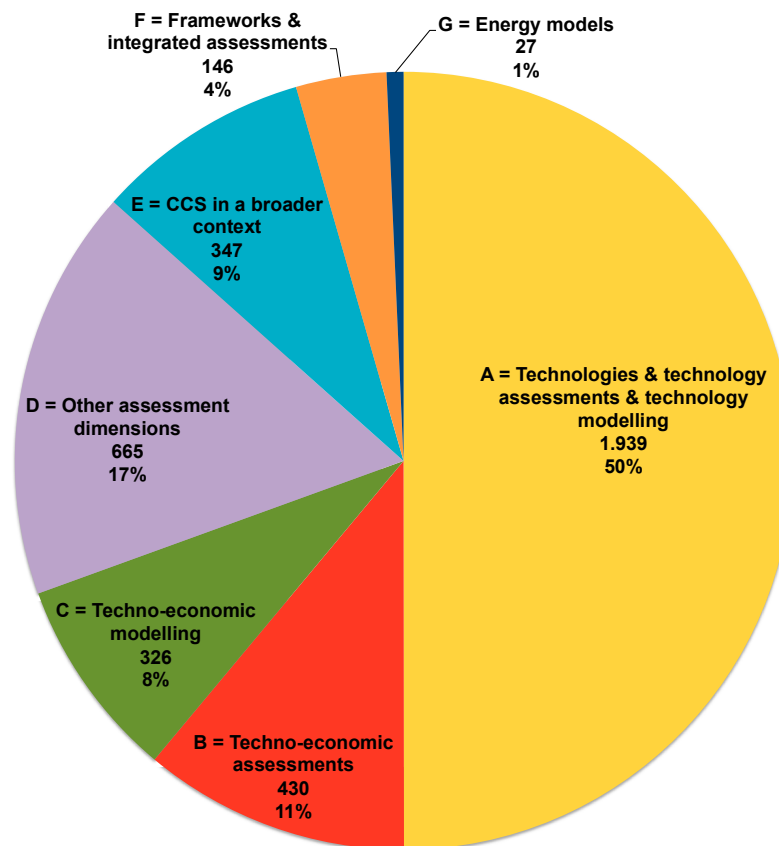
Figure 5. Meta-clusters (MC) of the overall paper network, their number of nodes, and their share as a percentage of the total number.

A summary of the identified relationships between the clusters shows that the research front as defined in Section 1 is on the one hand dominated by technical research (69%). As such, many papers investigate current developments, such as advanced capture technologies. On the other hand, the 31% of non-technical issues represents a higher proportion than previously expected. While in the past it was quite important to focus on developing capture and storage technologies and reducing their cost, more and more papers are more focused on the circumstances of their implementation, particularly by exploring issues of public perception, policy, and regulation. This complies with the analysis of barriers for the implementation of CCS (Table 1). While the technological perspective is also mentioned, technological development itself does not seem to be a problem. This research seems to be covered sufficiently by the technically-oriented clusters and the clusters of the first assessment level (Figure 4). The barriers predominantly refer to issues that are included in the second assessment level, in accordance with the 31% of non-technical oriented meta-clusters M.D–M.G., whether this is includes (macro)economic issues, the social, legal, and political perspective, or the overall systems perspective. Therefore, research is advancing and trying to meet the challenges faced by CCS. However, it is important to scrutinise whether the proportion of papers that consider both a broader view of CCS implementation (MC.E, 9%) and assess CCS from a holistic perspective (MC.F, 4%) may be too low to close the gap between expectations and realised deployment.

Furthermore, the cluster analysis revealed that some issues are quite neglected in the scientific discussion and might be taken on in future research: (1) issues of CO_2 storage, such as the uncertainty of storage capacity potentials, might be considered during (multi-criteria) assessments and studies on public perception, as well as policy and regulation; (2) issues of public perception might be considered in techno-economical optimisation models; (3) environmental assessments seem to be quite underrepresented in the analysed papers, and might be more strongly considered in (multi-criteria)

assessments or energy models, thereby not only considering the GHG reduction effects, but also trade-offs due to other increasing environmental impacts.

It should be noted that the findings illustrated above are subject to a number of uncertain assumptions and data. During the manually performed data processing steps, mistakes might occur, e.g., if not all double entries were found and eliminated. If a different algorithm is applied in Gephi (e.g., using Yifan Hu's multilevel layout), slightly different results will appear, e.g., papers in the border region of two clusters might be moved to a different cluster than if they are allocated using the Force Atlas layout. Although the "10 percent rule" was carefully designed, we did not find any important papers hidden in the other 80% or 90% of their cluster, as a result of their having a low degree. Furthermore, several key papers consist of review papers that not did necessarily present original research, but summarised research from the past. However, this was nevertheless accepted since they drive future research, pointing out next steps in the research front. Last but not least, the papers of a main cluster were not aligned along a time axis of their publication. In future research, this might also provide additional insights about how research on CCS has developed.

It should also be pointed out that the results may differ if scientific articles other than peer-reviewed ones were included in the assessment. Governmental agencies or non-university research institutes, for example, may adapt their research towards the implementation of CCS instead of basic technical research. Since they do not always publish their results in peer-reviewed papers, the share of non-technical research may increase. The next step, therefore, could involve extending the methodological approach outlined by a method that facilitates the exploration of publications that are issued in rather dispersed and diverse media.

5. Conclusions

The main conclusion is that the research front of CCS covers many non-technical issues that are required in view of the challenges that CCS implementation is faced with. They address, for example, problems of public awareness and acceptance, legal frameworks, the development of a CO_2 infrastructure, or the need of economic incentives such as emission allowances. However, we contemplate whether—in addition to an assessment from the necessary individual disciplinary perspectives—more research aiming for an interdisciplinary, holistic approach will be needed. It would also be important to explore at greater depth individual fields that were analysed as barriers to the faster implementation of CCS. However, it would be necessary to take a more integrated approach to meet the challenge that the transition of a complex energy system in the light of a low-carbon future might increasingly require. One example is the highlighted missing link between cluster C7, which considers techno-economically optimisation models, and cluster C4, concerned with public perception and policy issues. In a more holistic approach, "soft factors" considered in C4 may be integrated in modelling frameworks to also consider possible non-technical risks in deployment scenarios.

It may also be helpful to additionally perform more transdisciplinary work by evaluating drivers and barriers, opportunities and challenges, reflecting on recent technical developments, and discussing these aspects with all relevant stakeholders. According to Martínez Arranz [16], the high expectations regarding CCS seem to be "driven by the expectations and commitments of the close-knit community of expert-advocates that formed around CCS in the early to mid-2000s." By including a broad variety of stakeholders and their views, whether in modelling work, roadmapping, foresight processes, and technology assessments, etc., it may be possible to achieve a more resilient development of CCS deployment strategies.

In order to avoid similar mismatches when future technologies or applications of CCS are introduced, an increasing assessment at an early stage of their development is recommended. One example is the application of CCS in primary industry, where it is mostly technical and techno-economic studies that have been conducted (Field F3.2); these could be accompanied by multiple assessment methods. Another example are technologies for direct air capture of CO_2 as part of negative emission technologies, which have been increasingly discussed in the face of unsuccessful

climate policies, but where an early assessment from a technical, economic, ecological, and social point of view is called for (Anderson and Peters [224]).

All of the perspectives outlined depend on the provision of additional (funding) resources to enable research to be strengthened in individual topics, and research to be performed with a more holistic and transdisciplinary focus. Furthermore, the methodology outlined should be extended to also cover applied research, which is not necessarily published in peer-reviewed papers. This would enable recommendations for future research to bed based on an even broader footing.

Author Contributions: P.V. performed the conceptual analysis, its discussion and conclusion, and managed the overall writing process. E.J.L.C. was responsible for setting up the bibliometric methods and performing the technical analysis.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Technical Details of Data Processing Using the Five-Step Approach

Note to Step 1: From a technical perspective, for each paper, the citations and keywords were collected and their links to the paper was stored in our paper set. In addition to references to scientific articles, books and grey literature have also been recorded (however, since Scopus only encompasses scientific articles, books as primary sources cannot be captured). This dataset formed the input for the bibliometric methods.

Note to Step 3: The exclusion of papers (1) whose degree is zero and (2) which do not contain references were handled with self-written Bash scripts in Ubuntu. Double-counted papers (3) were manually eliminated with the help of Google Refine (see Friege and Chappin [23] for a description of the procedures). Furthermore, in order to prepare the base paper set for the actual cluster analysis using Gephi, papers using the same references had to be coupled, for which several scripts had to be used. These scripts were also applied to clean the data (for example, to correct spelling errors in titles and author names). All changes made have been documented in a list both containing the original cells and the changed cells ("look-up table"). All Bash scripts had to be updated to be able to manage large datasets in an efficient way (scripts are available on request).

Appendix B. The Base Paper Network
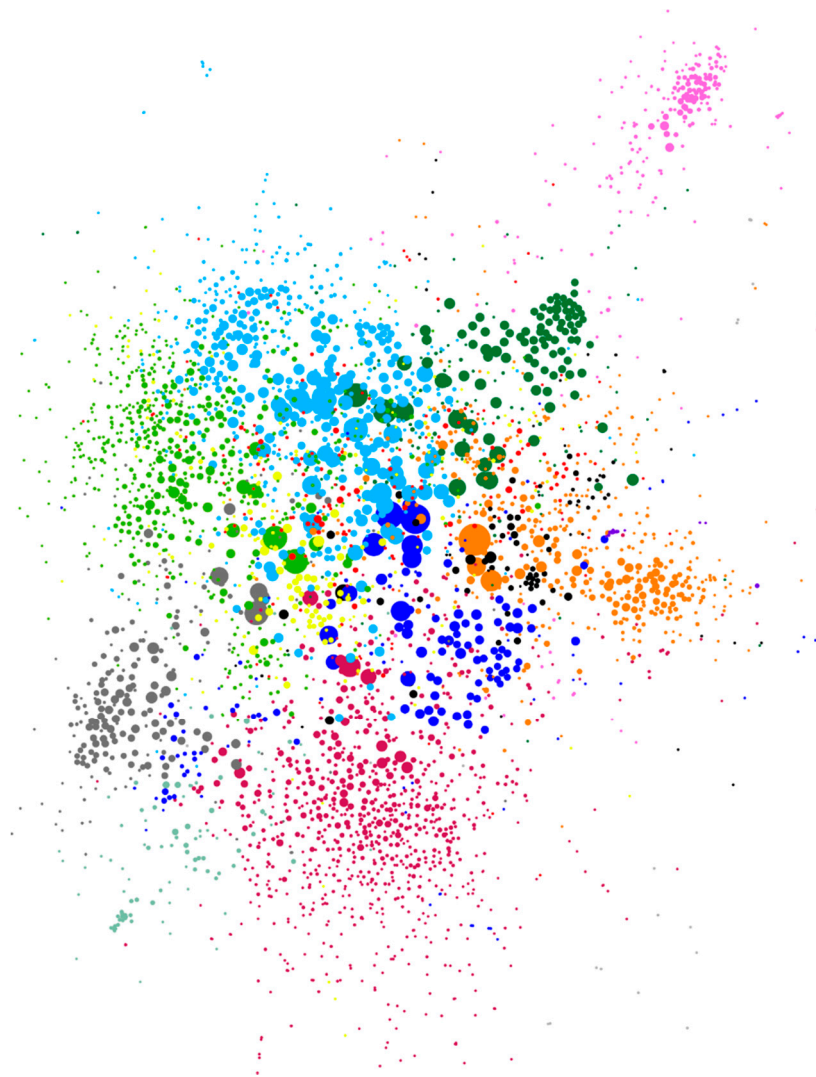
Figure A1. The base paper network and its 12 main clusters in its original version (4134 articles with degrees between 1 and 506).

Table A1. Topics and data of each base paper network cluster.

No.	Colour	Content	Number of Nodes	Share of Nodes in %	Highest 10% of Degrees	Degrees < 50 in %	Degrees < 10 in %
C1	Red	Geological storage	850	19.9	59–325	86	40
C2	Light green	Technologies and processes	612	14.3	73–381	79	33
C3	Blue	Techno-economic assessment	541	12.7	173–370	46	24
C4	Orange	Public perception and policy issues	437	10.2	89–505	74	28
C5	Pink	The chemistry of capture and separation	255	6	54–137	86	45
C6	Grey	The thermodynamics of CO_2	220	5.15	113–367	50	20
C7	Yellow	Techno-economically optimising models and tools	217	5.1	83–180	78	36
C8	Green	"Extended" techno-economic assessments	190	4.45	183–367	58	30
C9	Light red	Extended assessments on a broader level	183	4.3	49–113	91	38
C10	Dark blue	Frameworks and models for the assessment of both CCS in general and storage	179	4.2	155–469	49	29
C11	Medium green	The transport of CO_2	98	2.3	47–94	92	32
C12	Black	The modelling and assessment of storage processes	97	2.3	106–237	87	33
Total_1			3879	88.1	-	-	-
Rest		108 clusters, each of them representing a few nodes	255	5.9	-	-	-
Total_2			4134	94	-	-	-
C13	Violet	Astrophysics/astrochemistry (outside of the main network)	76	1.8	-	-	-
C14	Brown	Medicine (outside of the main network)	61	1.4	-	-	-
Total_3			4271	100	-	-	-

Table A2. Detailed description of the clusters, their fields and their groups. A = Technologies & technology assessments & technology modelling, B = Techno-economic assessments, C = Techno-economic modelling, D = Other assessment dimensions E = CCS in a broader context, F = Frameworks & integrated assessments, G = Energy models.

No./Nodes/Share	Cluster	Field	Share (%)	Nodes	Group	Share (%)	A	B	C	D	E	F	G
1 Red 850 19.90%	Geological storage	(1.1) Storage mechanisms and potentials	50	425	Core storage processes	31	264	-	-	-	-	-	-
					Storage site assessment; potentials	8	68	-	-	-	-	-	-
					Modelling of gas flows	6	51	-	-	-	-	-	-
					Status of storage	5	43	-	-	-	-	-	-
		(1.2) Storage site monitoring	18	153	Tracing methods	9.5	81	-	-	-	-	-	-
					General monitoring processes	8.5	72	-	-	-	-	-	-
		(1.3) Risk assessment	18	153	Impacts of CO_2 releases	6	51	-	-	-	-	-	-
					Risks for microorganisms and biology	5	43	-	-	-	-	-	-
					Various other risk factors	7	60	-	-	-	-	-	-
		(1.4) Storage in connection to other topics	14	119	-	14	32			65	11	11	-
2 Light green 612 14.30%	Technologies and processes	(2.1) Capture processes and separation technologies	76	465	Post-combustion capture and separation technology processes	53	298	-	-	26	-	-	-
					Pre-combustion processes	7	43	-	-	-	-	-	-
					Oxyfuel technologies	8	49	-	-	-	-	-	-
					New capture options	8	49	-	-	-	-	-	-
		(2.2) Total CCS chain, transport & storage	17	104	Total CCS chain	7	43	-	-	-	-	-	-
					Transport technologies	5	31	-	-	-	-	-	-
					Storage processes	5	31	-	-	-	-	-	-
		(2.3) Broader context of CCS	7	43	-	7	8	8	4	12	12		
3 Blue 541 12.70%	Techno-economic assessment	(3.1) Cost assessments of CCS and macroeconomic issues	44	238	Market challenges and macroeconomic issues	13	-	70	-	-	-	-	-
					Cost of the total CCS chain and its technologies and processes	11	-	60	-	-	-	-	-
					Special features of the CCS chain	11	-	60	-	-	-	-	-
					Economic issues in a regional and country-specific context	9	-	-	-	-	49	-	-
		(3.2) Cost assessments of the individual capture processes	43	233	(Advanced) pre-combustion technologies	20	-	108	-	-	-	-	-
					(Advanced) post-combustion processes	5.5	-	30	-	-	-	-	-
					Oxyfuel technologies	2	-	11	-	-	-	-	-
					Primary industry	5.5	-	30	-	-	-	-	-
					Various issues	10	-	54	-	-	-	-	-
		(3.3) Assessments primarily from non-economic perspectives	13	70	Environmental assessment	7	-	-	-	38	-	-	-
					Assessment frameworks	4	-	-	-	-	-	18	4
					Acceptance	2	-	-	-	11	-	-	-

Table A2. *Cont.*

No./Nodes/Share	Cluster	Field	Share (%)	Nodes	Group	Share (%)	A	B	C	D	E	F	G
4 Orange 437 10.20%	Public perception and policy issues	(4.1) Acceptance, public perception, and stakeholder perspectives	68	297	National case studies on public perception	26	-	-	-	114	-	-	-
					Meta-analyses of studies on public perceptions and social research	15	-	-	-	66	-	-	-
					Trust and communication measures for increasing acceptance	22	-	-	-	96	-	-	-
					The role and perception of CCS among experts and engineers	5	-	-	-	22	-	-	-
		(4.2) Policy and regulation	20	87	-	-	-	-	-	87	-	-	-
		(4.3) Sociotechnical assessments from a general perspective	12	52	-	12	-	-	-	52	-	-	-
5 Pink 255 6.0%	The chemistry of capture and separation	(5.1) Capture and separation technologies	69	176	-	-	176	-	-	-	-	-	-
		(5.2) Capture and conversion technologies	23	59	-	-	59	-	-	-	-	-	-
		(5.3) Total CCS chain with particularly capture technologies	8	20	-	-	20	-	-	-	-	-	-
6 Grey 220 5.15%	The thermodynamics of CO_2	(6.1) Thermodynamic modelling	54	119	Thermodynamic modelling (equilibrium model), CO_2-X mixtures, CO_2 properties	54	119	-	-	-	-	-	-
		(6.2) Thermodynamics of CO_2 storage	23	51	Issues of CO_2 storage related to thermodynamic properties	23	51	-	-	-	-	-	-
		(6.3) Thermodynamics of CO_2 transport	23	51	Mass flows in pipelines	11.5	25	-	-	-	-	-	-
					Pipeline infrastructure	11.5	25	-	-	-	-	-	-
7 Yellow 217 5.10%	Techno-economically optimising models and tools	(7.1) Optimisation models across the total CCS chain	23	50	-	-	-	-	-	50	-	-	-
		(7.2) Optimisation models for retrofit	23	50	-	-	-	-	-	50	-	-	-
		(7.3) Optimisation models for source-sink matching	23	50	-	-	-	-	-	50	-	-	-
		(7.4) Optimisation models for transport	31	67	-	-	-	-	-	67	-	-	-
8 Green 190 4.45%	"Extended" techno-economic assessments	(8.1) Regional-to-global level	68	129	Energy market assessments of CCS on country level	22	-	-	-	-	42	-	-
					Comparisons of CCS with other low-carbon technologies on a country level	17.5	-	-	-	-	33	-	-
					Prospects of CCS on a multi-country/supranational level	5.5	-	-	-	-	10	-	-
					Global CCS deployment challenges	17.5	-	-	-	-	33	-	-
					CCS as part of long-term energy models	5.5	-	-	-	-		-	10
		(8.2) Project studies with extended techno-economic assessments	18	34	-	-	-	-	-	-	34	-	-
		(8.3) Assessments going beyond a techno-economic perspective	5.5	10	Multi-criteria assessment; portfolio analysis	-	-	-	-	-	-	10	-
		(8.4) CCS in primary industry	8.5	16	-	-	-	-	-	16	-	-	-
9 Light red 183 4.30%	Extended assessments on a broader level	(9.1) Extended assessments of low carbon power, heat, and fuel production	39	71	-	-	-	-	-	-	71	-	-
		(9.2) Extended assessments of power generation in general	28	51	-	-	-	-	-	-	51	-	-
		(9.3) Assessments of new CCS applications	16.5	30	-	-	-	-	-	30	-	-	-
		(9.4) Other issues	16.5	30	-	-	-	-	-	30	-	-	-

Table A2. *Cont.*

No./Nodes/Share	Cluster	Field	Share (%)	Nodes	Group	Share (%)	A	B	C	D	E	F	G
10 Dark blue 4.20% 179	Frameworks and models for the assessment of both CCS in general and storage	(10.1) Frameworks and models for the assessment of CCS	60	107	Assessments of CCS from a holistic perspective by developing or using existing assessment frameworks	33	-	-	-	-	-	59	-
					Role of CCS for individual countries based on frameworks	10	-	-	-	-	-	18	-
					Simulation-based methods to minimise cost of CCS or CCS components	10	-	-	18	-	-	-	-
					CCS in the context of energy modelling	7	-	-	-	-	-	-	13
		(10.2) Frameworks and models for storage assessment	40	72	Models for analysing CO_2 storage processes	23	-	-	41	-	-	-	-
					Assessments of CO_2 storage in general by developing or applying frameworks with regard to stakeholders	17	-	-	-	-	-	30	-
11 Medium green 98 2.30%	The transport of CO_2	(11.1) Thermodynamic behaviour of CO_2	70	69	Behaviour of CO_2 in transport pipelines	35	34	-	-	-	-	-	-
					Behaviour of CO_2 during storage	15	15	-	-	-	-	-	-
					Interaction between pipeline and well	10	10	-	-	-	-	-	-
					Various other issues	10	10	-	-	-	-	-	-
		(11.2) Impacts of CO_2 corrosion	30	29	-	30	29						
12 Black 97 2.30%	The modelling and assessment of storage processes	(12.1) Modelling of storage processes	53	51	-	-	51	-	-	-	-	-	-
		(12.2) Extended assessments of storage issues	47	46	-	-	-	-	46	-	-	-	-
					Total	1939	430	326	665	347	146	27	1939
					Share in (%)		50	11	8	17	9	4	1	50

Table A3. Main relationships between clusters (conceptual model). Papers that have similar target clusters are grouped into a sub-cluster. Sub-clusters (A) contain papers that are linked to several clusters located in the direct or indirect neighbourhood (close to the network centre), sub-clusters (B) encompass papers linked to one or two selected neighbouring clusters, and sub-clusters (C) mostly link papers from the same cluster (located at the network's border). The third column shows the (estimated) share of each sub-cluster. Evaluation symbols: XX: very strong connection X: strong connection (X): little connection ((XX)): very little connection.

Cluster			1	2	3	4	5	6	7	8	9	10	11	12
Number/Name/Nodes	No.	%	Red	Light Green	Blue	Orange	Pink	Grey	Yellow	Green	Light Red	Dark Blue	Medium Green	Black
1 (Red)	1A	50	-	(X)	-	(X)	-	-	((X))	-	-	XX	-	((X))
Geological Storage	1B	20	-	-	-	-	-	X	-	-	-	-	-	-
850	1C	30	-	-	-	-	-	-	-	-	-	(X)	-	-
2 (Light green)	2A	70	-	-	X	(X)	-	X	X	(X)	-	X	((X))	-
Technologies, processes	2B	10	-	-	(X)	-	-	-	-	-	-	-	-	-
612	2C	20	-	-	-	-	-	-	-	(X)	-	-	-	-
3 (Blue)	3A	80	(X)	X	-	X	-	((X))	(X)	X	-	X	-	-
Techno-economic assessment	3B	20	-	X	-	-	-	-	-	(X)	-	-	-	-
541	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 (Orange)	4A	80	(X)	((X))	XX	-	((X))	((X))	(X)	(X)	-	X	-	((XX))
Public perception/policy	-	-	-	-	-	-	-	-	-	-	-	-	-	-
437	4C	20	-	-	((X))	-	-	-	-	((X))	-	-	-	-
5 (Pink)	5A	5	-	((X))	((X))	(X)	-	-	-	(X)	-	(X)	-	-
The chemistry of capture and separation	-	-	-	-	-	-	-	-	-	-	-	-	-	-
255	5C	95	-	-	-	-	-	-	-	-	-	-	-	-
6 (Grey)	6A	25	-	X	X	(X)	-	-	X	(X)	-	X	((X))	-
The thermodynamics of CO$_2$	6B	25	XX	-	-	-	-	-	-	-	-	X	-	-
220	6C	50	-	-	-	-	-	-	-	-	-	(X)	-	-
7 (Yellow)	7A-1	50	-	X	XX	-	-	-	-	(X)	-	X	-	-
Techno-econom. optimising models	7A-2	50	(X)	((X))	X	-	-	X	-	((X))	-	X	((X))	-
217	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8 (Green)	8A	60	(X)	(X)	XX	X	-	((X))	(X)	-	-	X	-	((XX))
"Extended" techno-econ. assessments	-	-	-	-	-	-	-	-	-	-	-	-	-	-
190	8C	40	-	-	(X)	-	((X))	-	-	-	-	(X)	-	-
9 (Light red)	9A-1	60	((X))	(X)	(X)	X	-	-	-	(X)	-	X	-	-
Extended assessments broader level	9A-2	40	-	-	((X))	(X)	-	-	-	X	-	(X)	-	-
183	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10 (Dark blue)	10A-1	20	X	X	XX	X	-	(X)	((X))	XX	-	-	-	(XX)
Frameworks, models for assessment	10A-2	20	(X)	-	X	X	-	-	XX	X	-	-	-	-
179	10A-3	60	(X)	-	X	X	–	-	-	(X)	-	-	-	-
11 (Medium green)	11A	50	(X)	XX	(X)	-	-	(X)	((X))	-	-	X	-	-
The transport of CO$_2$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
98	11C	50	-	-	-	-	-	-	-	-	-	(X)	-	-
12 (Black)	12A	95	X	(X)	(X)	(X)	-	(X)	((X))	X	((X))	XX	-	-
Modelling & assessment of storage	12B	5	XX	-	((X))	-	-	(X)	-	X	-	X	-	-
97	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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