Exploring the Potential Role of Carbon Capture and Storage (CCS) for Power Plants in the German and the International Context – a Multi-Dimensional Assessment Approach

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Contents

List of Abbreviations, Units and Symbols

Abbreviations

2DS	2°C scenario
B2DS	Beyond 2°C scenario
BECCS	Biomass and CCS
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CHP	Combined heat and power
COP21	UN Climate Change Conference 2015 in Paris
DAC	Direct air capture
DACCS	Direct air capture and CCS
DLR	German Aerospace Centre
e.g.	For example
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
ETP	Energy Technology Perspectives
EU	European Union
EC	European Commission
GHG	Greenhouse gas
GHGT	International Conference on Greenhouse Gas Control Technologies
i.e.	That means
IAM	Integrated Assessment Model
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle assessment
LCOE	Levelised cost of electricity
MC	Meta-cluster
MCA	Multi-criteria assessment
NDC	Nationally Determined Contributions
NET	Negative emission technologies
NGCC	Natural gas combined cycle
NRW	North Rhine-Westphalia
PC	Pulverised coal
PCI	Project of Common Interest
R&D	Research and development
RE	Renewable energy sources
SDS	Sustainable development scenario
SRREN	Special Report Renewable Energy Sources

TA	Technology assessment
TRL	Technology readiness level
WEO	World energy outlook

Units and symbols

%	Per cent
°C	Degree Celsius
CO	Carbon monoxide
CO_2	Carbon dioxide
E1-E3	Long-term coal development pathways E1-E3
EUR	Euro
Gt	Gigaton
GW	Gigawatt
H_2	Hydrogen
I	Industry scenario I
kWh	Kilowatthours
Mt	Megaton
MWh	Megawatthours
S1-S3	Storage scenarios S1-S3
t	Ton
USD	US dollar

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1 Summary

In the Paris Accord to the UN Climate Change Conference COP21 in 2015, the international community agreed to “make every effort” to reach a significant reduction in greenhouse gas (GHG) emissions and to limit global average temperature rise to preferably 1.5°C by 2100 (UNFCC 2018). A transition to a climate-friendly energy supply, however, would come largely at the expense of coal – a fossil fuel with large global reserves that are also widely dispersed regionally. Therefore, especially since the turn of the millennium, the question has been raised as to how coal could be used in a climate-friendly way in the future. So far, the only way to do this is to apply CCS technology or CCU. CCS involves the capture of carbon dioxide (CO_2) emissions from fossil fuel-fired power plants or industrial sources and its storage underground, such as in deep saline aquifers or in depleted oil and natural gas fields, or their use for enhanced oil or gas recovery (EOR/EGR). When carbon capture and utilisation (CCU) is applied, the CO_2 is further used, for example as feedstock for the production of durable plastics. Due to the relatively low potential of CCU compared to CCS (IPCC 2005), only CCS is considered in this thesis.

The majority of studies and roadmaps have discussed CCS as a technology option that could make a significant contribution to achieving the objective of decreasing GHG emissions for many years (IPCC 2014a, 2018). Particularly in the power sector, however, these expectations have not yet been met. As of November 2019, worldwide only two small base-load power plants, capturing a total of 2.4 Mt CO_2/year and mainly using it for EOR, are in operation, together with a few pilots in industrial applications and, in particular, natural gas processing (in total 30 Mt CO_2/year) (Global CCS Institute 2019).

Early on, it became clear that the predicted high deployment targets and their underlying studies should be critically questioned for various reasons. Particularly due to the lack of a systems-analytical evaluation of this technology (which was relatively new at the time), no reliable answers could be given about the ecological, economic, social and structural effects of its large-scale application. Such analyses are, however, a pre-condition for comprehensively classifying the contribution of a new technology as a promising option for a sustainable energy supply system and assessing it in comparison to other technologies.

To address these challenges, several studies, most of which initiated by the author, were conducted on this topic between 2004 and 2018. The resulting papers became the basis for this thesis. Accordingly, the aim of the thesis is to undertake an (energy) systems-analytical assessment of CCS in the power sector that would make it possible to draw conclusions about the potential future role of CCS. This meant pursuing three main research questions:

1 | **What role could the application of CCS in the power sector play from a holistic perspective in a decarbonised, technologically open energy system? How would conceivable CCS paths look like (e.g. technologies, infrastructures, development periods, investments)?**

The answers to this question differ according to the countries under analysis. In the case of *Germany*, the potential for CCS as analysed in the studies is very limited. If the politically defined strategies are considered, including the massive deployment of renewable energy sources (RE), the rise of combined heat and power (CHP) plants, and increased efficiency in energy consumption, the potential of CCS is limited alone for structural reasons (e.g. systems compatibility). Additional challenges working against CCS include late large-scale availability and the economic conditions, as well as ecological and social issues. The social factor was the most decisive factor at that time, as society, insofar as it was affected by the transport or, in particular, the storage of carbon dioxide, did not accept CCS in Germany. Accordingly, CCS in the power sector was no longer a politically feasible option in the power plant sector in Germany. On the other hand, the acceptance analysis showed that CCS is seen as neutral to rather positive as long as people are not directly affected by it in their own surroundings. As CCS has also been rated more positively with regard to industry than with regard to power plants, the future use of CCS for energy-intensive industry could come to be seen more positively.

The role of CCS at the *European* level was evaluated only marginally. However, it can be assumed that, due to similar energy systems structures and available portfolios of CO_2 mitigation options as those within Germany, there will also be restrictions on the expansion of CCS. Though these restrictions may not be as strict as in Germany, they also particularly depend on the expansion of renewable energy sources. Currently the focus in Europe is mainly on the application of CCS in industry and the development of a corresponding supranational transport and storage system in the North Sea. Holistic evaluations are also lacking here, however.

In contrast, CCS would not be competing directly with a low-carbon energy strategy in the emerging coal-consuming countries of *India*, *China* and *South Africa*. In order to even cover the rapidly growing energy consumption, investments are being made in all available technologies, including coal-fired power plants, nuclear power plants or renewable energy sources. Against that background CCS could help here to shape a more climate-friendly energy system. Any potential CCS strategy would depend on careful consideration of a couple of challenges, in particular a reliable assessment of CO_2 storage sites, appropriate economic conditions and improvements in the efficiency of the capture processes to reduce the additional energy demand. As long as there is a considerable lack of energy in these countries, strategies that actually require additional energy may not have top priority. This might be part of a public debate that has not yet started due to very low public awareness of CCS. Since a comparison with other low-carbon technology options was deliberately avoided, systems-analytical studies would also be necessary to identify restrictions and dependencies within the complex energy system before the role of CCS can finally be determined.

2 | What are the key determinants of the high expectations for CCS in the electricity sector?

The IEA's (International Energy Agency) 2009 CCS technology roadmap and other roadmaps and scenarios seem to have assumed a straightforward implementation of CCS, which at least for the countries analysed here contradicts its supposed role and challenges stemming from it. This is why the IEA has assumed a much faster implementation of CCS than reality currently suggests. The analyses carried out within this thesis suggest that several determinants are responsible for this discrepancy.

One main challenge is that it was not possible to reduce the capital and operating costs of post-combustion processes to the expected extent; this means that learning rates used from the beginning in energy models have proven to be too high afterwards. Accordingly, models incorporated higher deployment rates than what was realistic. On the other hand, learning rates for renewable energy sources were often underestimated, so that cost-optimising energy models favoured CCS as the optimal solution. Such energy models have usually been the basis for technology roadmaps, both for the IEA and also for the EU (European Union). Furthermore, from the beginning, CCS was propagated as a bridge into the renewable age, without recognising or wanting to perceive the fact that renewable power generation was already considerably further in its technology life cycle. Even at an early stage, papers contained in this thesis raised the ever-increasing cost advantage of renewable energy sources compared to CCS on a power-plant basis.

At the same time, challenges from non-economic perspectives were not addressed, such as the necessary structural fit of CCS to existing energy systems (system compatibility), the considerably higher consumption of energy and water, the total GHG reduction rates of only 59-87% for the most relevant technology paths while assuming a CO_2 capture rate of 90%, partly increasing other environmental impacts, the views and influence of various stakeholders (some with negative attitudes about CCS), and conflicting development targets of non-industrialised and emerging countries (such as reducing poverty and inequality, providing electrification and increasing resilience to the impacts of climate change). Furthermore, rough estimations of theoretical CO_2 storage potential suggested great potential for CCS, that in practice (considering the effective potential) will be most likely emerge as considerably smaller. Last but not least, technical aspects predominated in research, while more holistic technology assessment studies including a broader set of criteria are rare.

3 | Have the approaches and methods used so far as basis for policy advice been suitable for the assessment of complex low-carbon technologies? If not, what possible options are available to assess a technology in a future-oriented way?

Individual techno-economic assessments and cost-optimising macroeconomic energy models have been the basis for technology roadmaps for a long time. This approach might no longer be sufficient for policy advice, particularly in view of the challenges posed by a complex system as the energy system with hundreds of moving parts. Instead, a more integrative and inter-temporal systems-analytical view is necessary. This thesis took up this idea in the following aspects:

- Extending techno-economic assessments to holistic assessments, taking into account different assessment dimensions;
- Evaluating a technology with respect to a complex system environment in which it is embedded;
- Taking a long-term perspective with a time horizon of 2050 or longer in order to be able to consider the dynamics of future developments;
- Evaluating an emerging technology like CCS not only as a standalone technology, but also in comparison with competing technologies.

In addition to these methods, policy advice should be supplemented by the following activities:

- Integrating elements of holistic technology assessments in both Integrated Assessment Models (IAM) and pure energy models;

- Particularly with regard to the evaluation of the potential role of CCS: Considering CO_2 storage capacity potentials in (multi-criteria) assessments as well as in IAMs and energy models;
- Enabling greater public participation and comprehensive public discussion of various future technology paths and their advantages and disadvantages.

In the future, in addition to methodological questions such as coupling broader technology assessment with IAMs and energy models, the following applications of CCS currently under discussion should be examined in particular. There is also a risk here that political decisions will only be made on the basis of techno-economic assessments, which would fail to examine the full implications of these decisions.

- Assessing the implications of a possible future retrofit of China's and India's coal-fired power plants with CCS on costs, environment, social aspects and infrastructure issues. The possible retrofitting should concurrently be compared with other options such as the increased expansion of renewable energy sources.
- Scrutinising the possible role of CCS in energy-intensive industries (steel, cement, chemical, glass, and pulp and paper). Here CCS is often regarded as a "panacea", while on the other hand a large number of alternative measures are also being developed to reduce process-induced CO_2 emissions.
- Assessing the possible role of CCS with regard to hydrogen production, looking from a holistic perspective. Hydrogen is seen as a central future source for synthetic fuels and alternative industrial processes. The key question to be comprehensively assessed is how hydrogen provided by renewable energy sources ("green hydrogen") compares with its production by natural gas ("blue hydrogen") and coal ("grey hydrogen"), each combined with CCS.
- Investigating the effects of storing CO_2 in solid state in comparison to a gaseous state that is primarily discussed so far. Cooling down CO_2 to lower than minus 78°C yields dry ice, which would require huge ice deposits and constant cooling over hundreds of years. One alternative option would be to mix CO_2 with water and discharge it as carbonic acid into basalts where it forms carbonates, as demonstrated in Hellisheiði, Iceland (Reykjavik Energy 2018).
- Assessing the role of CCS with regard to the potential need of negative emission technologies (NET) such as biomass and CCS (BECCS) or direct air capture and CO_2 storage (DACCS) that might become necessary to an enormous extent in the future according to the Intergovernmental Panel on Climate Change (IPCC). There is considerable need to analytically assess these and other NET, including their effects on energy consumption and resource consumption and requirements for the construction of infrastructure systems (transport, storage).

2 Zusammenfassung

Als Ergebnis der UN-Klimakonferenz COP21 im Jahr 2015 in Paris hat sich die internationale Gemeinschaft darauf geeinigt, „alle Anstrengungen zu unternehmen“, um eine deutliche Reduzierung der Treibhausgas (THG)-Emissionen zu erreichen und den Anstieg der globalen Durchschnittstemperatur bis 2100 auf möglichst 1,5°C zu begrenzen (UNFCC 2018). Ein Übergang zu einer klimafreundlichen Energieversorgung würde jedoch stark zu Lasten der Kohle gehen. Daher wurde insbesondere in den letzten 20 Jahren die Frage diskutiert, wie Kohle in Zukunft klimafreundlich genutzt werden könnte. Die derzeit verfügbaren Optionen hierfür sind der Einsatz von CCS und CCU. CCS (carbon capture and storage) bezeichnet die Abscheidung von Kohlendioxid (CO_2) aus fossilen Kraftwerken oder industriellen Anlagen und deren unterirdische Speicherung in tiefen salinen Aquiferen oder in erschöpften Öl- und Erdgasfeldern, sowie seinen Einsatz zur Öl- und Gasgewinnung (enhanced oil or gas recovery, EOR/EGR). CCU (carbon capture and utilisation) dagegen meint die Weiternutzung des abgeschiedenen CO_2 in der Industrie, z. B. zur Herstellung von langlebigen Kunststoffen. Da die Nutzungspotenziale für CCU relativ gering sind (IPCC 2005), wird in dieser Arbeit nur CCS betrachtet.

CCS ist seit längerem in vielen Studien und Roadmaps als eine Option enthalten, die erheblich zur THG-Reduktion beitragen könnte (IPCC 2014a, 2018). Insbesondere im Stromsektor haben sich diese Erwartungen jedoch bisher nicht erfüllt. Mit Stand November 2019 sind weltweit nur zwei kleine Grundlastkraftwerke mit einer CO_2-Abscheidung in Betrieb, die 2,4 Mio. t CO_2/Jahr speichern bzw. für EOR nutzen. Zusammen mit anderen Pilotprojekten in der Industrie und der Erdgasaufbereitung werden insgesamt 30 Mt CO_2/Jahr abgetrennt.

Schon früh zeigte es sich, dass die hohen prognostizierten Einsatzziele und die diesen zugrunde liegenden Studien kritisch hinterfragt werden sollten. Insbesondere aufgrund einer fehlenden systemanalytischen Bewertung dieser damals relativ neuen Technologie konnten keine ausreichenden Antworten auf die ökologischen, ökonomischen, sozialen und strukturellen Auswirkungen einer möglichen großskaligen Anwendung gegeben werden. Solche Analysen sind jedoch Voraussetzung dafür, um die Rolle einer neuen Technologie für eine nachhaltige Energieversorgung einstufen und im Vergleich zu anderen Technologien beurteilen zu können.

Zwischen 2004 und 2018 wurden diese Fragen daher in mehreren Studien, die größtenteils vom Autor initiiert wurden und deren resultierende Paper die Grundlage für diese Habilitationsschrift sind, bearbeitet. Dementsprechend ist das Ziel dieser Schrift die (energie-)systemanalytische Bewertung von CCS im Energiesektor. Dabei wurden drei zentrale Forschungsfragen verfolgt:

1 | **Welche Rolle könnte die Anwendung von CCS im Stromsektor aus einer ganzheitlichen Perspektive in einem dekarbonisierten, technologisch offenen Energiesystem spielen? Wie würden denkbare CCS-Pfade (z. B. hinsichtlich Technologien, Infrastrukturen, Entwicklungsperioden oder Investments) aussehen?**

Im Hinblick auf die in dieser Arbeit analysierten Länder unterscheiden sich die Antworten jeweils. Im Falle *Deutschlands* ist das in den Studien analysierte CCS-Potenzial sehr begrenzt. Geht man von den politisch vorgegebenen Strategien wie z. B. dem massiven

Ausbau erneuerbarer Energien, dem Ausbau der Kraft-Wärme-Kopplung und Effizienzsteigerungen beim Energieverbrauch aus, so ist alleine aus strukturellen Gründen (Systemkompatibilität) wenig Bedarf für CCS gegeben. Weitere Herausforderungen wie die späte technische (großskalige) Verfügbarkeit, nicht ausreichende wirtschaftliche Bedingungen sowie ökologische und soziale Perspektive sprechen ebenfalls nicht für CCS. Entscheidend war insbesondere die nicht gegebene soziale Akzeptanz von CCS, zumindest in den direkt vom Transport oder der möglichen Speicherung betroffenen Regionen. Dementsprechend ist CCS im Kraftwerksbereich keine politische Option mehr. Andererseits zeigte die Akzeptanzanalyse, dass CCS als neutral bis eher positiv bewertet wird, solange die Menschen nicht direkt betroffen sind. Da CCS auch im Hinblick auf die Industrie positiver als hinsichtlich Kraftwerken bewertet wurde, könnte der zukünftige Einsatz von CCS für die energieintensive Industrie positiver gesehen werden.

Die Rolle von CCS auf *europäischer Ebene* wurde nur am Rande untersucht. Es ist jedoch davon auszugehen, dass das Potenzial für CCS je nach energiewirtschaftlichen Voraussetzungen, z. B. dem Ausmaß beim Ausbau erneuerbarer Energien, auch in anderen Ländern eingeschränkt ist. Derzeit liegt der Schwerpunkt der Diskussion in Europa vor allem auf der Anwendung von CCS in der Industrie und der Entwicklung einer entsprechenden supranationalen Transport- und Speicherinfrastruktur in der Nordsee. Ganzheitliche Auswertungen fehlen aber auch hier.

In den analysierten aufstrebenden Kohleländern *Indien, China und Südafrika* würde der Ausbau von CCS dagegen nicht direkt mit einer low-carbon Energiestrategie konkurrieren. Um den stark wachsenden Energieverbrauch überhaupt decken zu können, wird in alle verfügbaren Technologien investiert, insbesondere Kohle- und Kernkraftwerke oder erneuerbare Energien. Da sich jedoch auch diese Länder zunehmend ambitionierteren Klimaschutzzielen verpflichten, könnte auch CCS zu einem dekarbonisierten Energiesystem beitragen. Eine mögliche CCS-Strategie bedarf jedoch insbesondere einer zuverlässigen Bewertung potenzieller CO_2-Speicher, angemessener wirtschaftlicher Bedingungen und einer höheren Effizienz bei den Abscheideprozessen, um den zusätzlichen Energiebedarf zu reduzieren. Solange es in diesen Ländern einen erheblichen Energiemangel gibt, haben Strategien, die zusätzliche Energie benötigen, möglicherweise nicht höchste Priorität. Dies müsste jedoch Teil einer öffentlichen Debatte sein, die aufgrund des sehr geringen Bekanntheitsgrades von CCS noch nicht begonnen hat. Da für diese Länder bewusst auf einen Vergleich mit anderen low-carbon Technologieoptionen verzichtet wurde, wären ebenso entsprechende systemanalytische Untersuchungen notwendig, um die Rolle von CCS endgültig bestimmen zu können.

2 | Was sind die wichtigsten Determinanten für die hohen Erwartungen an CCS im Strombereich?

Die erste CCS-Technologie-Roadmap der IEA von 2009 und andere Roadmaps und Szenarien dürften von einer uneingeschränkten Umsetzung von CCS ausgegangen sein, was zumindest für die hier analysierten Länder im Widerspruch zu der aufgezeigten Rolle und den Herausforderungen von CCS steht. Vergleicht man die angenommen Installationsraten und die wenigen bisher realisierten Anlagen, zeigt sich eine erhebliche Diskrepanz. Hierfür sind mehrere Faktoren verantwortlich.

Eine der größten Herausforderungen besteht darin, dass die Investitions- und Betriebskosten des im Vordergrund stehenden post-combustion-Verfahrens bisher nicht im erwarteten Umfang reduziert werden konnten, so dass sich die in den Energiemodellen von Beginn an verwendeten Lernraten als zu hoch herausgestellt haben. Dementsprechend wurden höhere Installationsraten modelliert als realistisch waren. Andererseits wurden die Lernraten für erneuerbare Energien oft unterschätzt, so dass kostenoptimierende Energiemodelle CCS als optimale Lösung favorisierten. Solche Energiemodelle sind in der Regel die Grundlage für Technologie-Roadmaps der IEA und auch der EU. Darüber hinaus wurde CCS von Beginn an als Brücke zu den erneuerbaren Energien propagiert, ohne zu erkennen oder wahrnehmen zu wollen, dass die regenerative Stromerzeugung in ihrem Technologie-Lebenszyklus bereits deutlich weiter fortgeschritten war. Einige Arbeiten dieser Schrift haben bereits frühzeitig auf den immer größer werdenden Kostenvorteil der erneuerbaren Energien im Vergleich zu CCS hingewiesen, bezogen auf die reinen Stromgestehungskosten.

Gleichzeitig wurden Herausforderungen aus nicht-ökonomischer Perspektive in der Regel nicht hinterfragt, wie die strukturelle Passgenauigkeit von CCS zu bestehenden Energiesystemen (Systemkompatibilität), dessen deutlich höherer Energie- und Wasserverbrauch, Netto-Reduktionsraten der THG-Emissionen bei den relevantesten Technologien von nur 59-87% (bei gleichzeitigem teilweisem Anstieg anderer Umweltauswirkungen), die verschiedenen Stakeholder mit ihren teilweise negativen Einstellungen zu CCS sowie dem Ausbau von CCS entgegen stehende Entwicklungsziele von Nicht-Industrieländern und Schwellenländern (z. B. Verringerung von Armut und Ungleichheit, zunehmende Elektrifizierung und Steigerung der Resilienz in Bezug auf die Auswirkungen des Klimawandels). Zudem suggerieren grob abgeschätzte theoretische CO_2-Speicherpotenziale ein großes Potenzial an CCS, das jedoch in der Praxis (effektives Speicherpotenzial) in der Regel erheblich kleiner ist. Nicht zuletzt dominierten auch in der Forschung technische Aspekte, während mehr ganzheitlich ausgerichtete Studien zur Technikfolgenabschätzung, die ein breiteres Set von Bewertungskriterien beinhalten, selten sind.

3 | Sind die bisher in der Politikberatung verwendeten Ansätze und Methoden für die Bewertung komplexer low-carbon Technologien geeignet? Wenn nicht, wie müsste man vorgehen, um eine Technologie zukunftsorientiert bewerten zu können?

Isolierte techno-ökonomische Bewertungen und kostenoptimierende makroökonomische Energiemodelle bilden bisher die Grundlage für Technologie-Roadmaps. Dieser Ansatz dürfte für die Politikberatung nicht mehr ausreichen angesichts der Herausforderungen, die ein komplexes System wie das Energiesystem mit Hunderten von Stellschrauben mit sich bringt. Stattdessen wird eine integrativere und intertemporale systemanalytische Vorgehensweise empfohlen. Im Rahmen dieser Arbeit wurde dies in den folgenden Aspekten aufgegriffen:

- Erweiterung technisch-ökonomischer Bewertungen zu ganzheitlichen Bewertungen unter Berücksichtigung verschiedener Bewertungsdimensionen.
- Bewertung einer Technologie im Hinblick auf das Gesamtsystem, in das sie eingebettet ist.
- Betrachten einer langfristigen Perspektive mit einem Zeithorizont von 2050 oder länger, um die Dynamik zukünftiger Entwicklungen berücksichtigen zu können.
- Bewertung einer neuen Technologie wie CCS nicht nur als alleinstehende Technologie, sondern auch im Vergleich zu konkurrierenden Technologien.

Zusätzlich zu diesen Methoden sollte die Politikberatung durch weitere innovative Verfahren ergänzt werden:

- Integration von Elementen einer ganzheitlichen Analyse sowohl in Integrierte Assessmentmodelle (IAM) als auch in Energiemodelle.
- Insbesondere im Hinblick auf die Bewertung von CCS: Berücksichtigen von CO_2-Lagerstättenpotenzialen in (multikriteriellen) Bewertungen, Akzeptanz-Studien und IAMs sowie Energiemodellen.
- Ermöglichung einer stärkeren Beteiligung der Öffentlichkeit und einer umfassenden öffentlichen Diskussion über die verschiedenen zukünftig denkbaren Technologiepfade sowie deren Vor- und Nachteile.

Neben methodischen Fragen wie der genannten Kopplung von umfassenden Technologiebewertungen mit IAMs und Energiemodellen sollten in Zukunft insbesondere die nachfolgend beschriebenen Anwendungen von CCS untersucht werden. Wie bei der Entwicklung von CCS-Roadmaps für den Stromsektor besteht hier ebenfalls die Gefahr, dass politische Entscheidungen nur auf der Grundlage technisch-wirtschaftlicher Bewertungen getroffen werden, die zur Bewertung der teilweise erheblichen Auswirkungen dieser Technologien nicht ausreichen.

- Bewertung der Auswirkungen einer möglichen zukünftigen Nachrüstung von Kohlekraftwerken mit CCS in China und Indien auf Kosten, Umwelt, soziale Aspekte und Infrastrukturfragen. Die mögliche Nachrüstung mit CCS sollte gleichzeitig mit anderen Optionen wie dem verstärkten Ausbau erneuerbarer Energien verglichen werden.
- Ganzheitliche Analyse der möglichen Rolle von CCS in der energieintensiven Industrie (Stahl, Zement, Chemie, Glas sowie Zellstoff und Papier). Hier wird CCS oft als „Allheilmittel“ angesehen, während andererseits eine Vielzahl alternativer Maßnahmen zur Reduzierung der prozessbedingten CO_2-Emissionen entwickelt wird.
- Bewertung der möglichen Rolle von CCS bei der Herstellung von Wasserstoff, der als zentrale Energiequelle der Zukunft für synthetische Kraftstoffe und für alternative industrielle Prozesse gilt. Die Kernfrage, die umfassend zu bewerten ist, ist, wie Wasserstoff aus erneuerbaren Energien („grüner Wasserstoff“) im Vergleich zu seiner Erzeugung aus Erdgas („blauer Wasserstoff“) bzw. Kohle („grauer Wasserstoff“), jeweils unter Anwendung von CCS, aus ganzheitlicher Sicht abschneidet.
- Untersuchung der Auswirkungen der Speicherung von CO_2 im festen Zustand im Vergleich zum bisher diskutierten gasförmigen Zustand. Die Abkühlung von CO_2 auf unter minus 78°C ergibt Trockeneis, das riesige Trockeneisdeponien mit einer permanenten Kühlung über Hunderte von Jahren erfordern würde. Eine alternative Möglichkeit besteht darin, CO_2 mit Wasser zu versetzen und als Kohlensäure in Basalte einzubringen, wo es innerhalb von zwei Jahren in Karbonate bildet, wie in Hellisheiði (Island) nachgewiesen wurde (Reykjavik Energy 2018).
- Bewertung der Auswirkungen von negativen Emissionstechnologien (NET) wie Biomasse und CCS (BECCS) oder der direkten CO_2-Abscheidung aus der Luft mit nachfolgender Speicherung (DACCS), die in Zukunft laut des Weltklimarates (IPCC) in großem Umfang genutzt werden könnten. Es besteht erheblicher Bedarf, diese und andere NET einschließlich ihrer Auswirkungen auf den Energieverbrauch, den Ressourcenverbrauch oder den Bedarf für den Bau von Infrastrukturen (Transport- und Speichersysteme) analytisch zu bewerten.

3 Introduction

A significant reduction in greenhouse gas emissions will be necessary in the coming decades to avoid the most dangerous consequences of man-made global warming. According to the Intergovernmental Panel on Climate Change (IPCC), this includes in particular keeping global average temperature increases well below 2°C above pre-industrial levels by 2100 (IPCC 2014b). In the Paris Accord to the UN Climate Change Conference COP21 in 2015, the international community agreed to "make every effort" to reach this goal and to limit global average temperature rise to preferably 1.5°C by 2100 (UNFCC 2018).

While there have been many energy and climate scenarios and studies based on them in the last 10-15 years that have illustrated ways to achieve the 2°C target, there have been few studies on the 1.5°C target to date. In contrast to the 2°C target, such a restrictive target requires comprehensive and, above all, rapid change in almost all sectors, with a significant reduction in greenhouse gas emissions by 2030, i.e. within a good ten years (IPCC 2018).

Despite the considerably higher efforts required, some studies have shown that this goal can also still be achieved with existing technologies and services. In addition to renewable energy sources, which are becoming more and more cost-effective, these studies have particularly pointed out the considerable potential for energy savings. These, however, must be tackled resolutely and at once. Nevertheless, they consider neither carbon capture and storage (CCS) nor nuclear energy (Grubler et al. 2018; Moriarty and Honnery 2019; Teske 2019; Teske et al. 2015).

On the other hand, coal is a fossil fuel with significant global reserves, which are widely dispersed regionally. Long-term scenarios for the development of the energy system drawn up early on showed that the transition to a climate-friendly energy supply would come largely at the expense of coal. The more strictly the global climate target is set, the higher the necessary proportion of renewable energy sources will likely be, as an evaluation in the IPCC's Special Report on Renewable Energy Sources (SRREN) showed (IPCC 2011). This is why, especially since the turn of the millennium, the question has been raised as to how coal could be used in a climate-friendly way in the future. So far, the only way to do this is to apply CCS technology or CCU.

CCS involves the capturing of carbon dioxide (CO_2) emissions from fossil fuel-fired power plants or industrial sources, and their storage underground, such as in deep saline aquifers or in depleted oil and natural gas fields, or their use for enhanced oil and gas recovery (see Section 4). Its successful use could make it possible to provide "CO_2-free" (or at least low-CO_2) final energy carriers on the basis of coal, which is particularly important in the generation of electricity (and of hydrogen as a universally usable storage energy carrier). When carbon capture and utilisation (CCU) is applied, the CO_2 is further used, for example as feedstock for the production of durable plastics. Due to the relatively low potential of CCU compared to CCS (IPCC 2005), only CCS is considered in this thesis.

The majority of studies and roadmaps have discussed CCS as a technology option that could make a significant contribution to achieving the objective of decreasing GHG emissions more or less intensively for many years (IPCC 2018). International organisations such as the International Energy Agency (IEA) and the European Commission (EC), countries such as Australia, lobby organisations such as the Global CCS Institute, and a number of companies have also begun to advocate widespread use of CCS in the power sector and in hydrogen production.

One example of this advocacy is the IEA's 2009 CCS technology roadmap, which forecast a CCS-based power plant capacity of 22 GW in 2020 that would continuously rise to 1,140 GW in 2050 and result in 131 Mt CO_2 captured in 2020, and 5,510 Mt CO_2 captured annually by 2050 (IEA 2009). However, a comparison of the global status of large-scale CCS power plants with the forecast expansion targets shows that these expectations have not yet been met. Ten years later, as of November 2019, there are only two base-load power plants in operation worldwide, capturing a total of 2.4 Mt CO_2/year and mainly using it for EOR. Together with a few other pilot projects in industrial applications and fuel processing, a total of 30 Mt CO_2/year are captured (see Section 4).

Early on, it became clear that the predicted high deployment targets and their underlying studies should be critically questioned for various reasons. Particularly due to the lack of a systems-analytical evaluation of this technology (which was relatively new at the time), no reliable answers could be given about the ecological, economic, social and structural effects of its large-scale application. Such analyses are, however, a pre-condition for comprehensively classifying the contribution of a new technology as a promising option for a sustainable energy supply system and assessing it in comparison to other technologies. To address these challenges, several studies, most of which initiated by the author, were conducted on this topic between 2004 and 2018. The resulting papers became the basis for this thesis.

Accordingly, the aim of this thesis is to undertake an (energy) systems-analytical assessment of CCS in the power sector that would make it possible to draw conclusions about the potential future role of CCS and to answer the question of how the discrepancy between "desire and reality" described above could arise. The thesis is therefore understood to be part of systems science ("Systemwissenschaft"). It consists of ten peer-reviewed papers, complemented by three additional (editor-reviewed) papers published in journals relevant for applied sustainability research in the energy sector (see Table 1 in Section 6).

The remainder of this thesis is organised as follows: First, an excursus gives a short overview of the background and the current state of CCS for power plants (Section 4). This moves to an explanation of the aim of the research and the overall research questions of this thesis, grouped into four different clusters (Section 5). Section 6 starts with an overview of the four clusters and their papers, followed by the respective research questions, the methods and a summary of the results for each cluster. Section 7 combines the findings of the clusters and answers the overall research questions, and Section 8 concludes with a look towards future research.

4 Excursus: Carbon Capture and Storage (CCS) – the Technology and its Status

CCS technology in its early stage was the subject of two crucial scientific theses. Chris Hendriks from the Netherlands (Utrecht University) can be regarded as one of the main scientific pioneers and later promoters of CCS. In his dissertation, he analysed various methods for the capture and storage of CO_2 in coal-fired power plants at an early stage (Hendriks 1994). In Germany, Gerold Göttlicher's dissertation (Duisburg University) followed in 1999, with a comprehensive techno-economic analysis of power plant processes with CO_2 capture (Göttlicher 2004). In the early years, the discussion mainly focused on the power plant sector and fuel processing, but in recent years it has extended to industry. The following sections give a brief introduction to CCS in the power sector that is at the centre of this thesis.

The capture of carbon dioxide

The first part of the CCS chain involves the capture of CO_2 emissions from fossil (or biomass) fuel-fired power plants. The capture processes can be subdivided into three technological groups (Figure 1), as basically described in Viebahn et al. (2010).

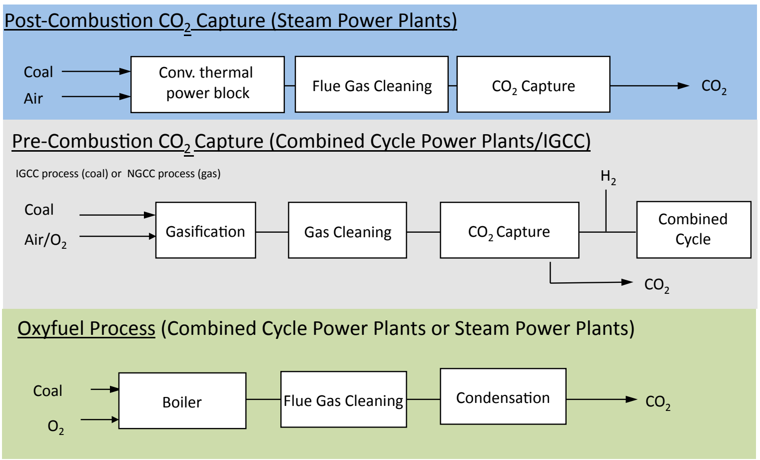

Figure 1: Overview of various technological routes to CO_2 capture

Source: Based on Ewers and Renzenbrink (2005)

- *Post-combustion*: In these processes, CO_2 is captured from the flue gas of power plants or industrial sites. The low CO_2 concentration makes the economically viable capture of the greenhouse gas difficult, since a huge volume of gas needs to be treated; this requires large amounts of chemicals and energy. Compared with other capture processes, however, post-combustion processes have the highest short to medium-term achievable potential for CO_2 reductions. This is because they are also capable of being retrofitted on existing plants, if sufficient space for installing the capture units is available. Post-combustion processes are the most developed technological path to CO_2 capture. The most common capture processes are absorption, adsorption, membrane-based, and biological processes. For some years now, several second and third-generation amine scrubbing processes have been developed which, in particular, promise to further improve energy and cost performance (IEAGHG 2017). Additional improvements reported during the 14th GHGT[1] conference include an "increased number of emerging capture technologies (i.e. solid sorbents, calcium looping, polymeric membranes) demonstrated at large pilot level (TRL 6-7),"[2] advances in capture plant design and configuration, and in meeting "the challenges posed by high-temperature degradation of amines" (IEAGHG 2019).

- *Pre-combustion*: In these processes, the fuel is transformed by gasification into a synthesis gas, consisting mainly of carbon monoxide (CO), hydrogen (H_2) and CO_2. The proportion of the CO content of the synthesis gas is reduced in a shift reactor, creating a gas with considerably higher CO_2 concentrations than in the flue gas from conventional power plants. The CO_2 can be separated with considerably less energy consumption than in post-combustion processes. Despite their comparatively efficient methods of capture, pre-combustion processes have been a lower priority for R&D recently. This is explained by the fact that the distribution of IGCC (integrated gasification combined cycle) plant technologies has not yet extended beyond individual demonstration plants due to the high investment expenditure involved, amongst other issues.
- *Oxyfuel processes*: In these processes, virtually pure oxygen (over 95%) is used in place of air for the combustion of fuel. In this way, the CO_2 concentration in the flue gas can be increased to 80%, enabling CO_2 to be captured by simply condensing it out. Oxyfuel processes are considered to be a promising alternative to post-combustion and pre-combustion processes, but are still at an early stage of development.

The following challenges are of particular relevance for technology assessment:

- The capture processes require a relatively high energy input, which significantly reduces the efficiency of the power plants.
- Due to the chemical processes, the power plants must in principle be operated at base load, which contradicts the need for controllable power plants. However, flexible CCS power plants have also begun to emerge as a research focus (IEAGHG 2017).
- Some processes consume very large amounts of water.
- Despite many years of research, CCS has relatively high penalty costs. In particular, advanced capture configurations exhibit high operational costs (IEAGHG 2019).
- When retrofitting power plants, both the temporary downtime and the remaining service life of the power plant play an important role in assessing economic efficiency.

The storage of carbon dioxide

After compressing the CO_2 and transporting it by truck, by ship or, for larger amounts, by pipeline, the last but main step of the CCS chain is geological storage. The most important storage options are depleted oil and gas fields and deep saline aquifers (Figure 2), but basalt deposits also promise a potential solution, as basically described in Viebahn et al. (2010).

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[1] GHGT = International Conference on Greenhouse Gas Control Technologies

[2] TRL = Technology Readiness Level, which is usually indicated on a scale of 1-10.

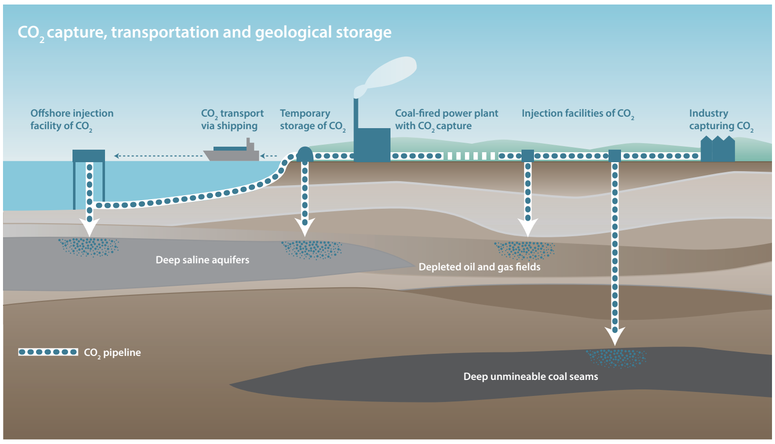

Figure 2: **Overview of various options for CO_2 storage**

Source: Wuppertal Institut/Vislab 2011

- *Oil and gas fields*: Depleted oil and natural gas fields are ideal for storing CO_2 underground. For millions of years, depleted oil and natural gas fields have served as suitable cap rocks for hydrocarbons; these cap rocks are assumed to be equally impermeable for CO_2. Above all, the formation of carbonic acid, caused by the dissolving of CO_2 in any sources of water present, creates an acidic and therefore corrosive environment. One major advantage of storing CO_2 in hydrocarbon fields is that plenty of data is available. The fields have been thoroughly analysed and researched following decades of exploitation, so the necessary geological information is available.

- *Enhanced oil recovery (EOR):* The expansion of tertiary oil production was seen from the beginning as facilitating the commercial application of CCS, since EOR has already been applied for decades in the USA. The percentage of recovery of the original oil can be extended from 10 to 30% to 35 to 55% through secondary recovery. Additionally, CO_2-based EOR contributes another 5 to 15%. However, the CO_2 also blends with the oil and has to be separated afterwards. Nevertheless, EOR could contribute to the establishment of a CO_2 pipeline system that could later be used for real storage of CO_2. When EOR shuts down, the depleted field could also be used afterwards for CO_2 injection and sequestration. A similar process is *enhanced gas recovery* (EGR) which is, however, not as popular as the oil option for a number of reasons. Several EOR projects have been set up in the past; currently, 11 of 15 CCS projects in the USA supply CO_2 for EOR (IEA 2016).

- *Deep saline aquifers*: Unlike oil and gas fields, groundwater-saturated sediment formations, also referred to as deep saline aquifers, are relatively underexplored. Although there is a lack of reliable data, the injection of CO_2 into deep saline aquifers is generally considered to be the most attractive solution in terms of volume. The availability of suitable sedimentary basins is widespread, and can be found in almost all parts of the world. These formations contain water that has a very high salt content and is, therefore, undrinkable anyway. One additional property of potential storage formations is the extremely slow flow of the groundwater. Research suggests that the injected CO_2 would remain safely underground in the long term due to dissolution and mineralisation.

One essential prerequisite for CO_2 storage in aquifers is the connection of the injection area to the rest of the formation. There are two main types of systems – “open” and “closed” – according to the structure of the aquifer. In both cases, the injection of CO_2 is followed by compression and displacement of the pore water. The compression increases the pressure in the system. If the system is closed, the maximum pressure increase of the aquifer system controls the amount of CO_2 to be injected because the pores are saturated with salt water and disruption of the cap and leakage has to be prevented. If the system is open, this saline water can be displaced from the structure to other parts of the system. It is important that there are measures preventing this displacement of highly saline water from contaminating other environments. The ratio to which the theoretical potential can actually be used is referred to as the *efficiency factor*. Accordingly, the storage potential can be represented as a pyramid that shrinks from the theoretical to the efficient to the later actually usable practical potential (“techno-economic resource-reserve pyramid for CO_2 storage capacity,” Bachu (2007)). In recent years, significant progress has been made in the understanding and quantification of CO_2 trapping mechanisms as well as in the modelling of subsurface geology and CO_2 fate and transport on time scales of hundreds of years (IEAGHG 2017).

- *Basalt:* Some studies have also considered storage in basalt deposits. The EU’s long-term CarbFix project demonstrated that CO_2 remains permanently stored as carbonate (Reykjavik Energy 2018). In Hellisheiði, Iceland, CO_2 was mixed with water and discharged as carbonic acid into 700 m deep basalt rocks, where it combined with the minerals magnesium, calcium and iron present there. Due to the high temperatures in the basalt (approx. 400°C), carbonate formation occurred within two years after injecting the CO_2.

CCS in the power sector – expectations and current status

Although the expectations for global CCS deployment in the power sector were high at the beginning of its development, they have decreased over the past ten years.

- The IEA’s 2009 CCS Technology Roadmap anticipated a CCS-based power plant capacity of 22 GW in 2020, which would continuously rise to 1,140 GW in 2050 and result in 0.131 Gt CO_2 captured in 2020, and 5.5 Gt CO_2 captured annually by 2050. This was to include 18 CCS projects by 2015, 100 by 2020 (of which 38 would be power plants) and 850 by 2030, capturing 2,700 Mt CO_2/year (360 for power plants) (IEA 2009).
- Ten years later, as of November 2019, only two base-load power plants retrofitted with post-combustion capture systems are in operation: one 115 MW (Boundary Dam, Canada) and one 240 MW (Petra Nova, Texas, USA), which capture a total of 2.4 Mt CO_2/year, mainly for use in EOR. Large-scale CCS power plants are defined as “facilities involving the capture, transport, and storage of CO_2 at a scale of at least 800,000 tonnes of CO_2 annually” (Global CCS Institute 2019). Nine such power plant projects, together capturing 14.5 Mt CO_2/year, are classified as being in early development and have been announced to come into operation in the 2020s. Therefore, including the two power plants already in operation, by 2030, 11 power plant projects, capturing a total of 17 Mt CO_2/year, might be feasible.
- When the high expectations failed to materialise, the IEA subsequently reduced the deployment figures. The IEA’s most recent World Energy Outlook (WEO) has acknowledged that “carbon capture, utilisation and storage (CCUS) needs to play an important

role in meeting climate goals, but there are very few projects operating or planned" (IEA 2018). In the WEO 2018 Sustainable Development Scenario (SDS), CCS starts in 2040 with 224 GW coal-based CCS (20% of 1,119 GW of installed coal capacity, mostly in the USA and China) and 168 GW natural gas-based CCS (7% of 2,406 GW installed capacity), totalling 392 GW capturing 2.4 Gt of CO_2 (IEA 2018). Figures for 2050 and the following years are not provided. The IEA has stated that "progress in CCUS deployment and investment remains limited in practice and lags well behind the pace that would be needed in this scenario." (IEA 2018)

- The IEA's Energy Technology Perspectives (ETP) report, which has a time horizon of 2060, specifies both a "2°C scenario" (2DS) and a "beyond 2°C scenario" (B2DS). While the 2DS roughly corresponds to the SDS scenario described above, the B2DS requires considerably more CCS. In the electricity sector, 670 GW of CCS would be needed in 2045 and 950 GW in 2060, capturing 3.3 and 4.5 Gt of CO_2/year, respectively (IEA 2017). Compared to the expectations of the previous CCS technology roadmap, however, even these ambitious figures are considerably lower. The remaining fossil-fired power plants without CCS are assumed to have much lower operating hours than the CCS-based ones, as the share of power generation with CCS in Figure 3 illustrates.
- In addition, both ETP scenarios envisage large quantities of CO_2 being captured from industrial and fuel production (together with the electricity sector, this amounts to 6.8 Gt of CO_2 in the 2DS by 2060 and 11.3 Gt of CO_2 in the B2DS by 2060). In addition to the 2.4 Mt in the electricity sector, 27.6 Mt in other areas would be separated so far.

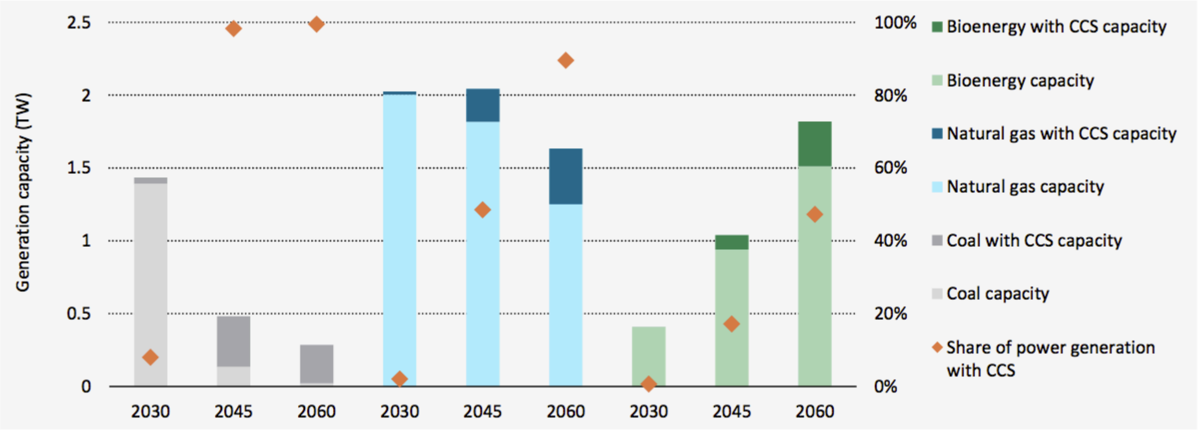

Figure 3: Share of CCS in power generation and capacity in the B2DS (beyond 2°C scenario) of the IEA's Energy Technology Perspectives 2017

Source: IEA (2017)

Many scientific papers also assume a more or less high contribution of CCS to the climate goals. The IPCC's 5th Assessment Report already showed that 36 studies envisaged CCS in the electricity sector to achieve the 450 ppm GHG reduction target (IPCC 2014a).

5 The Aim of the Research

As with other innovations, the relatively new research field of CCS for power plants initially focused on technological developments. This could be demonstrated, for example, by the GHGT conferences organised by the CCS community, which in the early years generally only offered sessions on technical topics. Even by its 13th event, 60 out of 70 sessions dealt with technical advancements, partly combined with a techno-economic assessment (GHGT 2013 https://ghgt.info/).

At the same time, this phase of the technology life cycle is initially characterised by a spirit of optimism, in which extremely high expectations are often raised about the potential of a new technology. In the case of CCS, this can be seen in the deployment roadmaps described above and additional roadmaps and scenario studies, which had already forecast very high installation goals in a short to medium-term period and only adapted them after these goals failed to materialise. Even if the technical development – to say nothing of the cost expectations – were still far away from mass application, CCS was promoted as a bridge into the renewable age, without recognising or wanting to perceive that renewable power generation was already considerably further in its technology life cycle. Martínez Arranz (2016) has impressively analysed and described this early hype for CCS in comparison to other low-carbon technologies.

Following Gartner's Hype Cycle Model (Fenn and Blosch 2018), this "Peak of Inflated Expectation" was followed by a "Trough of Disillusionment", in which public interest in CCS declined (estimated about 2012-2017). "More than 20 advanced large-scale CCS projects were cancelled between 2010 and 2016 ... across Europe, the United States and Australia" (IEA 2016). Companies and lobby organisations, however, continued to work on the development and promotion of individual CCS stages ("Slope of Enlightenment"). Over the course of the intensified climate discussion, the applications and development successes grew again ("Plateau of Productivity"), and CCS is once again increasingly promoted as "low-carbon technology"; however, it is mainly for industrial and hydrogen production (2017-2019).

To assess the possible consequences of new technologies at an early stage and to avoid undesirable developments in the technology life cycle, the method of technology assessment (TA) was developed back in the 1960s (Bullinger 1994). The TA is intended in particular to "comprehensively and foresightedly [analyse] the potentials and effects of scientific and technological developments, to explore the associated social, economic and ecological opportunities and risks" and to point out the need for action and opportunities for policymakers (Deutscher Bundestag 2019).

The direct German translation of TA (*Technologiefolgenabschätzung*) with the focus on the (long-term) consequences of a technology application reflects this intention even more. But even without assessing the political consequences in the comprehensive sense of TA, an evaluation of positive and negative (long-term) effects in the sense of a multidimensional evaluation is indispensable to be able to react at an early stage if undesirable developments emerge.

Even in the early phase of a technology development, such an evaluation could show optimisation potentials for companies and their research (e.g. by identifying hotspots of the consumption of critical metals or certain environmental impacts). Moreover, politicians would also be given important foundations for decisions regarding the promotion of technology developments if they received reports on the strengths and weaknesses of a technology, as well as the potential driving and breaking forces of it. This applies all the more to the "goodness of fit" of new technologies to an existing energy system that is being converted into a low-carbon energy system, and in which, in particular, lock-in effects have to be avoided by investing in technologies that may no longer be relevant in the medium term.

It is against this background that the need for a technology assessment of CCS emerged in the mid-2010s. Work on this the author initially began with an externally funded project (2004-2006) in the DLR's Systems Analysis and Technology Assessment Department. The resulting ground-breaking paper (P-5, so far 136 citations), with initially only a few evaluation criteria, was the basis for a series of methodological questions that arose over the next few years, the "peaking time" of the early development, analysis and testing of CCS.[3]

At the Wuppertal Institute, the author developed and worked on these research questions in additional externally funded projects, such that this thesis is composed of papers based on various projects (see Table 1 in Section 6). This also explains the long period over which these papers were developed. However, the disadvantages stemming from the thesis not being a "unified whole", developed within a limited period of time, are countered by the advantage that it has accompanied the development of CCS over a longer period of time and can thus assess the developments retrospectively.

While the research for the main papers was supported by colleagues, PhD students and research assistants with regard to data collection and the development of partial analyses, the author alone was responsible for the concept development, the acquisition of funding and the implementation. This includes in particular the development of methods, the research design, the essential analyses and the interpretation of the results. For the other papers, the author's role was to support the development of methods, the research design and the discussion as well as doing the supervision.

During the work in the research projects, the leading three research questions were:

1 | **What role could the application of CCS in the power sector play from a holistic perspective in a decarbonised, technologically open energy system? How would conceivable CCS paths look like (e.g. technologies, infrastructures, development periods, investments)?**

2 | **What are the key determinants of the high expectations for CCS in the electricity sector?**

3 | **Have the approaches and methods used so far as basis for policy advice been suitable for the assessment of complex low-carbon technologies? If not, what possible options are available to assess a technology in a future-oriented way?**

These overarching questions were addressed in a series of papers, each with their own research questions.

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[3] Even though this paper was one of the author's main papers, it is only dealt with in the second cluster of this thesis for methodological and structural reasons.

6 Research Cluster, Applied Methodologies and Resulting Papers

6.1 Overview

This section presents an overview of the different papers in this thesis, their individual research questions and applied methodologies. As illustrated in Table 1, the papers are differentiated between peer-reviewed papers (denoted with a “P”) and additional (editor-reviewed) papers (denoted with an “N”). The latter complement the former in a few important aspects that could not be dealt with in detail in the peer-reviewed papers. The full titles of all papers are given in Section 9. In order to answer the overall research questions appropriately, the papers are structured along four clusters with different content-related research questions (Figure 4):

- Cluster 1: Integrated Assessment of CCS in Coal-Consuming Emerging Economies
- Cluster 2: Integrated Assessment of CCS and Comparison with Renewable Energy Sources in Germany
- Cluster 3: Additional or Extended Assessment of Individual Issues
- Cluster 4: Meta-Analysis of the Status of Past and Current Research

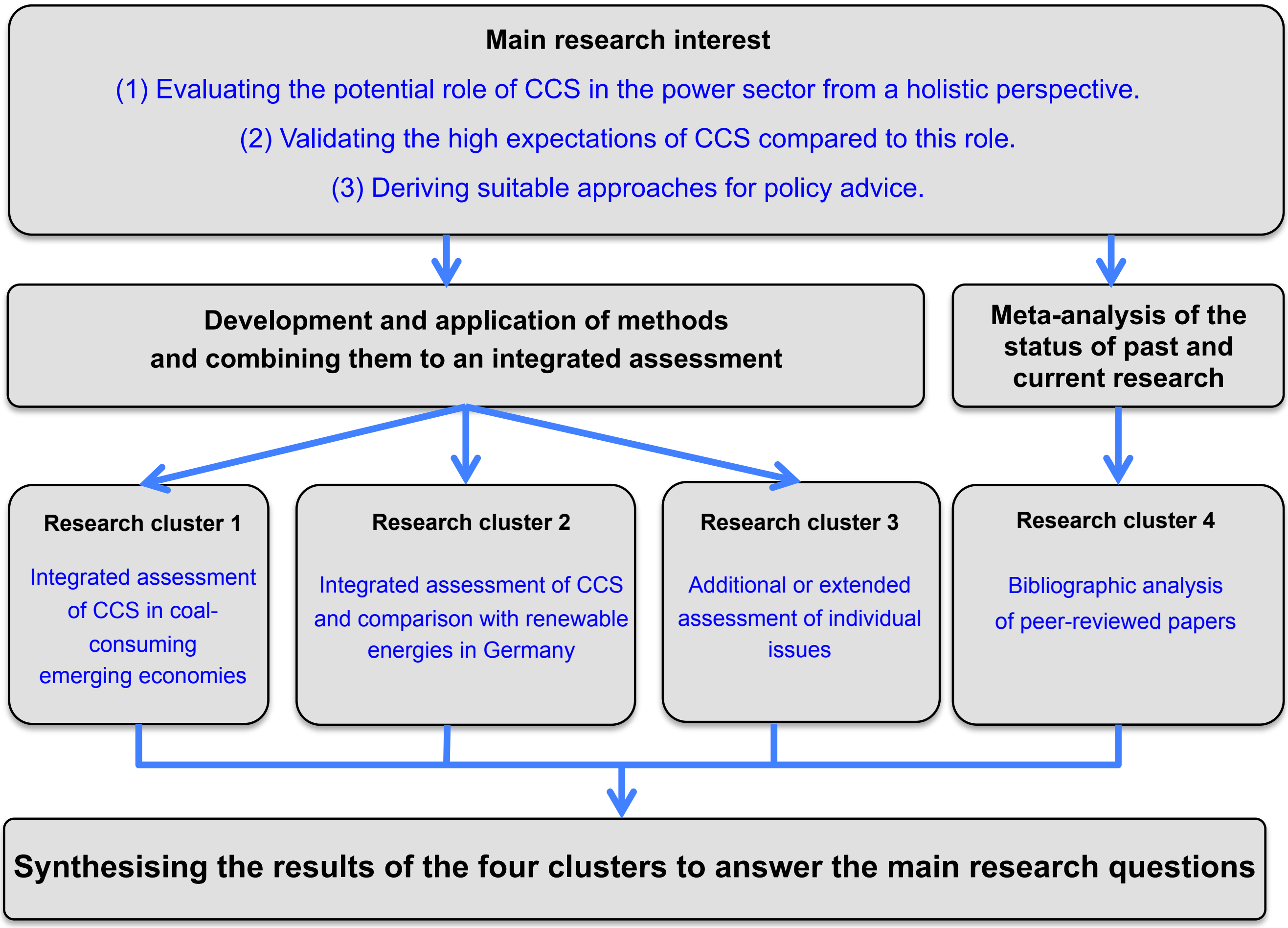

Figure 4: Research design and its structure

Source: Own composition

Table 1: Research clusters, their papers, methodologies, and regional foci

Paper					Topic	Applied Methods												Regional Focus		
Year of publ.	No. P	No. N	Main Au.	Co-Au.		Actors' an.	Biblio-metrics	Cluster An.	Comm. avail. An.	CO_2-avoid. cost an.	Industrial An.	LCA	LCOE	Public Percep-tion An.	Energy Scenario Analysis	Storage Poten-tial An.	Source-Sink-Matching	DE	EU	GLO
Cluster 1: Integrated Assessment of CCS in Coal-Consuming Emerging Economies																				
2014	P-1		X		Role of CCS in India	X		X	X		(X)	X	X		X	X	(X)			X
2015	P-2		X		Role of CCS in China	X	(X)	X	X		(X)	X	X		X	X	(X)			X
2016	P-3			X	CO_2 storage potential in China											X				X
2015	P-4		X		Role of CCS in South Africa	X		X	X		(X)	X	X		X	X	(X)			X
Cluster 2: Integrated Assessment of CCS and Comparison with Renewable Energy Sources in Germany																				
2007	P-5		X		Role of CCS in Germany compared to renewable energies				X	X		X	X		X			X		
2012	P-6		X		Role of CCS in Germany, extended	(X)			X	X		X	X		X	X		X		
2011		N-1	X		LCA of CCS							X						X	X	X
2011		N-2		X	CO_2 storage potential in the EU											X			X	
Cluster 3: Additional or Extended Assessment of Individual Issues																				
2009		N-3	X		Retrofitting CCS in NRW/Germany			X		X	X				X	(X)	X	X		
2010	P-7			X	Transporting CO_2 NRW/NL			X							(X)		(X)	X		
2014	P-8			X	CCS in Chinese industry (Cement)					X					X					
2016	P-9			X	Perceptions of CCS in Germany									X				X		
Cluster 4: Classification of the Status of Past and Current Research																				
2018	P-10		X		Review-Article CCS		X													X
P = peer-reviewed; N = non peer-reviewed (reviewed by the editor); Au = Author, An. = Analysis DE = Germany, EU = Europe, GLO = Global Comm.avail.An. = Commercial Availability Analysis, LCA = Life cycle analysis; LCOE = levelised cost of electricity production X = main issue, (X) = peripherally 1) In German																				

Source: Own composition

6.2 Cluster 1: Integrated Assessment of CCS in Coal-Consuming Emerging Economies

Research question

For many years, the use of coal has been rising unabatedly. This development is mainly driven by coal-consuming emerging economies that have experienced rapidly growing demand for energy. But many of these countries also set themselves climate targets and made corresponding commitments with regard to their "Nationally Determined Contributions" (NDC) in the context of the COP21 UN Climate Conference in 2015. As described in Section 2, the use of CCS has been seen as a key CO_2 reduction option, especially for these countries. However, CCS is only partially included in their national targets.

Therefore, the *main research question* of the first cluster of papers was to explore whether CCS could be a viable technological option for significantly reducing future CO_2 emissions in such emerging countries. India (paper P-1), China (papers P-2, P-3) and South Africa (paper P-4) were chosen as case studies since they hold vast coal reserves and have experienced rapidly growing demand for energy, based primarily on the use of coal at the time of the study. If they were not planning to change to other low-carbon energies to reduce fossil-related carbon dioxide emissions, a coal-dominated route would indeed require the introduction of CCS.

In order to assess the possible contribution of CCS and its challenges in these countries without bias, the feasibility of CCS alone was analysed on the basis of various criteria. The comparison with other low-carbon technology options, such as renewable energy sources, was deliberately avoided (such a comparison is given in the second cluster, using Germany as an example).

Methodologies

The *main methodological approach* combined a couple of individual assessment methods into an assessment framework. Each method was applied and, where necessary, adapted in order to assess CCS in the three countries appropriately. This framework was called an "integrated assessment" since it took various perspectives and integrated them to enable a holistic analysis of the future implementation of CCS. Choosing an MCA (multi-criteria assessment) approach was deliberately avoided, as the aim was not to evaluate different alternative options against each other and to rank them. Rather, in view of the novelty of CCS, it was more important to identify the strengths and weaknesses as well as opportunities and obstacles of possible CCS paths in the three countries to discuss whether and to what extent the requirements for a possible application of CCS have been met or how possible barriers could be overcome.

Even though the same analytical framework was used with the same methods for each of the three case studies, it was necessary to consider the specific situation of each country. Therefore, the individual methods were adapted to the different conditions of the countries (which included, for example, the widely varying estimates of existing storage capacities, different levels of investment and operating costs of power plants, or different proportions of methane emissions in mining) and differentiated accordingly.

The framework includes the following individual methods (Figure 5):

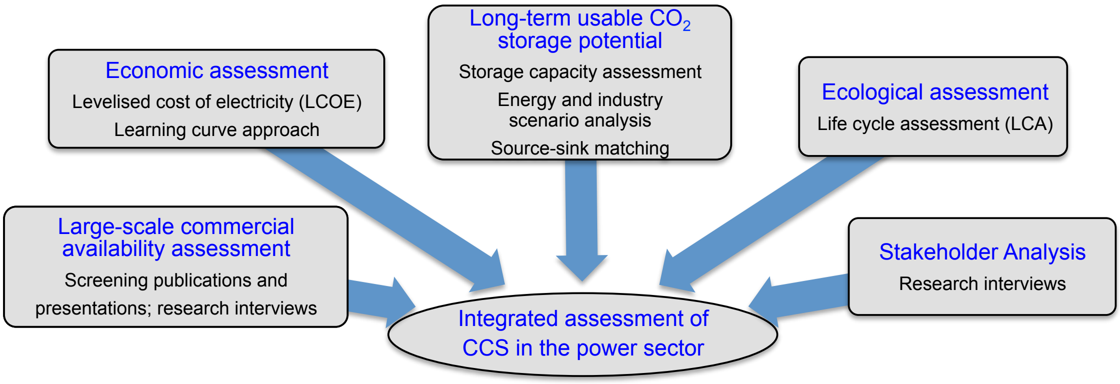

Figure 5: Integrated assessment framework of Cluster 1 (CCS in coal-consuming emerging economies), consisting of different individual assessment dimensions

Source: Own composition

- The *assessment of the large-scale commercial availability of the whole CCS chain* in the respective countries is an essential prerequisite for determining the number of installed systems and thus the amount of CO_2 to be captured. It is based on screening publications and presentations of international CCS experts and knowledge from experts interviewed over the course of the studies.
- A reliable storage capacity assessment is a key precondition that must be met for successful implementation paths for CCS from a purely technical point of view. For the *evaluation of the long-term usable CO_2 storage potential*, three different methods were developed:
  - First it was analysed how much CO_2 could potentially be stored securely and for the long term in geological formations in the selected countries. This meant systematically analysing and comparing existing capacity estimates for each country using the methodology linked to the “techno-economic resource-reserve pyramid for CO_2 storage capacity” (Bachu 2007). The estimates were grouped in three *storage scenarios* S1–S3, representing the range between a high and a low estimate of the country’s storage potential. The corresponding classification depends on estimates of the storage efficiency and therefore the storage security.

    In contrast to similar analyses for India, South Africa and Germany, China faces the difficulty that there are no nationwide storage potential studies available that have identified an effective storage capacity. As mentioned above, however, relevant conclusions on the potential role of CCS can only be drawn based on the effective potential. But even with regard to the theoretical potential, there was only one study that contained detailed data on all relevant storage types. There were, however, individual site-specific and basin-specific studies on the effective potential of aquifers in China. For this reason, paper P-3 serves as the basis for the evaluation of the long-term usable CO_2 storage potential in China on which paper P-2 is based. *Methodologically*, individual site-specific and basin-specific studies on aquifers in China were evaluated with regard to their storage efficiency parameters. Clustering them allowed a determination of low, medium and high-efficiency parameters that served as the basis to build the three storage scenarios for China used in paper P-2.[4]

- To compare the potential storage site capacity with the supply of CO_2, secondly, the quantity of CO_2 that could potentially be captured from power plants was determined dynamically according to a long-term scenario analysis up to 2050. Based on various existing long-term energy scenarios for each country, three *long-term coal development pathways for power plants* (E1–E3) were developed. They indicate a development between a "high carbon" and a "low carbon" strategy. The next step laid out hypotheses on how many of these power plants could be built or retrofitted with CO_2 capture technologies. The final step was to calculate the quantity of CO_2 that could be captured for the pathways assuming different parameters, such as the CO_2 capture rate and the efficiency penalty. CO_2 emissions were cumulated over the lifetime of all power plants newly built up to 2050. In a similar but very simplified way, also the possible use of CCS in industry was estimated in a pathway "I".
- Third, subsequent source-sink matching determined in which regions how much of the captured CO_2 could be stored. This meant combining the storage scenarios S1–S3 with the coal development pathways E1–E3 and I to obtain a total matched capacity for each possible combination. The result is the matched capacity. Due to missing data and the resulting heuristic approach, matching was performed manually without using a geographic information system. The final step was a brief analysis about how additional quantities of CO_2 captured from the basic industry would change the results.

Having addressed the technological preconditions, it became necessary to move on to consider additional non-technical assessment dimensions that could have an influence on the successful implementation of CCS.

- First, a comparative analysis of the long-term development of the levelised cost of electricity (LCOE) of coal-fired power plants with and without CCS was developed as an *economic assessment* to estimate the additional cost a country would have to expect. The analysis first determined current LCOE, based on existing investment costs as well as operating and maintenance costs, which have been obtained from studies and expert surveys. The costs were extrapolated from the application of learning rates and the adoption of technical improvements by 2050. This is based on the capacity developments determined in the E1-E3 scenarios. Whenever possible, country-specific conditions and data were taken into account. CO_2 pricing pathways used in this study are assumed to start at USD 42/t CO_2 in 2020 and to increase up to USD 63/t CO_2 by 2050.
- Second, a prospective LCA of potential future CCS-based coal-fired power plants in the year 2030 was performed to assess the possible *environmental impacts of CCS*, and

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[4] In response to paper P-3, a comment appeared that questioned the procedure for deriving the three efficiency factors, in particular the mid-case (Heinemann et al. 2017). The authors were correct that regional and local-scale efficiency factors may differ and should not be mixed. Also, the efficiency factor of the mid-case cannot be described as a "China-specific efficiency factor", which was not intended and is an issue of wording – in paper P-3, deliberately a scenario analysis was performed because the uncertainty is so great that no single value can be determined for the entire country. It was explicitly stated that the binning of efficiency factors into ranges was used to show upper and lower limits of available efficiency factors (only for descriptive reasons), and did not lead to elaborated statistical assessments. The primary result of the paper does not change if the range of the three scenarios S3 to S1 varies – for example, if taking the average of basin's efficiencies as lower value and the average of site's efficiencies as higher value.

compared the environmental impacts to power plants without CCS. The study assumes no leakage at the storage sites.

- Third, a *stakeholder analysis* revealed the positions of various stakeholders with regard to the perspectives of CCS and their integration into the development goals of the countries. Since stakeholders are important actors in the implementation and use of innovative technologies, their positions are an important indicator for assessing the potential success of a CCS strategy in the respective countries. These analyses were based on publications and presentations, supplemented by interviews developed for this purpose.

Results

It was not possible to answer the main research question of this cluster of papers fully, based on the data and expertise available at the time of doing the studies. The results showed that successful implementation of CCS and therefore a positive potential future role of CCS in India, China and South Africa would be affected by a wide variety of aspects and several preconditions that need to be fulfilled:

- In each of the analysed countries, the time of *large-scale commercial availability* of CCS depends strongly on the successful implementation of CCS technology in industrialised countries, which does not seem to be the case before 2030. This is in line with the observation that global modelling studies do not expect CCS to be applied in these countries before 2030 either. On the other hand, a large number of coal-fired power plants, in particular in China, went into operation in the 2010s, so an early retrofitting could still make sense as long as it is economically justifiable.
- One key requirement to allow an assessment of the potential role of CCS is the existence of a *reliable storage capacity assessment* for the countries. However, all existing estimates of the storage potential in the analysed countries revealed a high degree of uncertainty and are therefore highly speculative. If very optimistic assumptions are applied, a large amount of CO_2 emissions could theoretically be stored (75, 192 and 22 Gt CO_2 in India, China and South Africa, respectively). If cautious and therefore more realistic estimates of the countries' effective and "matched" storage potential are taken into account (in particular, assuming a very small efficiency factor), only a fraction of the separable CO_2 emissions may potentially be stored (5, 30 and 4 Gt CO_2, respectively). Moreover, this potential would decrease further if technical, legal, economic, risk-oriented and social-acceptance barriers are included. In contrast to India and South Africa, more detailed estimates are available for China, at least for individual basins.
- The results of the *economic analysis* revealed a significant barrier to the economic viability of CCS under current conditions, which are characterised by a low CO_2 price development in each country. China has the lowest threshold to the economic viability of CCS. In the presence of the assumed CO_2 penalty, the LCOE calculated for CCS plants is clearly lower than the LCOE of an equivalent non-CCS plant. Furthermore, it is also significantly lower than in India and South Africa, mainly due to cheaper labour and equipment costs. As a result, the incentive derived from the same CO_2 pricing pathway is significantly weaker in India and South Africa. India has the highest level of LCOE for coal-fired power generation with CCS of the three countries, as it combines rather high capital costs (due to complex ambient conditions) with high fuel prices. South

Africa's capital costs for large-scale power plants are also comparatively high, but fuel prices are low. This means that the LCOE of India's CCS plants is only slightly lower than that of non-CCS plants by 2050 if a CO_2 price is added. In South Africa, the LCOE of CCS plants is also somewhat lower than the LCOE of non-CCS plants. While the CO_2 price would compensate for the cost penalty of CCS, it would be unlikely to suffice on its own in providing a strong and clear cost advantage of CCS plants over supercritical pulverised power (PC) plants without CCS. Therefore, a higher carbon price would be required in order to function as a clear economic driver for CCS deployment.

- The *prospective LCA* of future CCS-based PC and IGCC plants yielded conflicting results regarding the environmental impacts of CCS. On the one hand, assuming a CO_2 capture rate of 90% for the most relevant power plants, the overall CO_2 emissions per kWh_{el} would be reduced by 74-78%. The reduction rates are lower than the CO_2 capture rate due to the additional energy consumption, which increases the environmental burdens upstream. The effects of transporting and storing the carbon dioxide would also have to be considered as well as further second and third-order emissions. Total GHG emission reductions per kWh_{el} are highest in India (71-74%), lower in South Africa (67-72%), and lowest in China (59-60%). The differences between the three countries are mainly due to the quantity of methane emissions released during coal mining, which is highest in China. Emissions from coal fires were omitted from the study. In cases of leakage from storage sites over time (not assumed here), the results would change significantly. On the other hand, most environmental impact factors would increase for both PC and IGCC (eutrophication, human toxicity, terrestrial ecotoxicity, freshwater and marine aquatic ecotoxicity, and stratospheric ozone depletion); in addition, acidification and summer smog would decrease in the case of PC plants and increase in the case of IGCC plants. Because of CCS's additional primary energy demands, other environmental and social issues not included in the life cycle assessment would also increase (for example, air quality, noise, mine waste, health risks, displacement and resettlement).
- The interviews conducted during the studies led to the following conclusions: In general, *public awareness* of CCS in India, South Africa and China was very low. At the time the studies were conducted, the public debate had not yet started. *Governments*, on the other hand, were all concerned with CCS. The Indian government had a cautious attitude towards the commercialisation of CCS. India's foremost energy policy priority is to provide all Indian citizens with access to electricity. Since a large proportion of the additional electricity is to be provided by central power plants and since CCS leads to substantial efficiency losses in power plants, CCS hinders this aim. The Chinese government was also not an enthusiastic advocate of CCS, mainly due to the high costs and the energy penalty incurred by the technology. However, political and industrial decision-makers in China regarded CCS as a backup or emergency technology for complying with possible long-term CO_2 mitigation obligations. In South Africa, key players have already taken important steps in terms of the research, development and politics of CCS. The government recognises that CCS could become an important CO_2 mitigation technology. Similar to India, however, most of the interviewees feared that CCS could potentially conflict with other important policy objectives, such as affordable electricity rates, reducing water usage and improving the efficiency of electricity generation.

6.3 Cluster 2: Integrated Assessment of CCS and Comparison with Renewable Energy Sources in Germany

Research question

In a similar way, the second group of papers (P-5, P-6, N-1, N-2) assessed the possible deployment of CCS for Germany. Compared to the emerging economies analysed in the first group, however, the baseline situation is completely different. On the one hand, Germany is the largest coal producer in the EU, with about 38% of its electricity supply coming from coal-fired power plants in 2018 (compared to 44% in 2008). The energy industry's interest in reducing its emissions through CCS was correspondingly high. On the other hand, the country is pursuing ambitious CO_2 mitigation targets of 40% reductions by 2020 and 80–95% reductions by 2050 (both compared to 1990 levels) and has demonstrated a strong commitment to a deployment strategy of renewable energy sources. When preparing the results for papers P-5 and P-6 (2006 and 2011), the share of renewable energy sources in the electricity mix was between 12 and 20%, which increased to 38% in 2018. This policy-directed development called for a profound and integrated scientific analysis of CCS.

The *main research question* of this cluster of papers was therefore to explore the potential future role that CCS could play in the electricity sector in Germany in terms of and in comparison with a steadily increasing share of renewable energy sources. While paper P-5 focused on the energy-structural level and presented some initial economic and ecologic analyses of CCS, paper P-6 took a broader view, particularly by considering various energy scenarios with different shares of CCS and evaluating the CO_2 storage potential required for it. Paper N-1 reviewed existing LCA studies for CCS in the power sector, and served as a basis for assessing the ecological dimension within the integrated assessment performed in paper P-6. Paper N-2 also examined neighbouring states of Germany with regard to their possible storage potential usable for Germany.

Methodologies

Even more than in the analyses for India, China and South Africa, a holistic view of a possible CCS deployment in Germany is necessary, because both CCS and the deployment of renewable energy sources and efficiency technologies are part of a complex energy system with mutual dependencies. Accordingly, the *main methodological approach* consisted of combining multi-dimensional perspectives into an integrated assessment framework. It, moreover, contained two complementary groups of methods: On the one hand, the purely CCS-focused assessment dimensions developed for the first cluster of papers were used to analyse the general feasibility of CCS in Germany and the impacts CCS would have. On the other hand, the analysis focus was extended in order to be able to consider the overall context within the energy system as well as to compare CCS-based power generation with alternative power generation options (renewable energy sources).

This is reflected in the following individual methods (Figure 6):

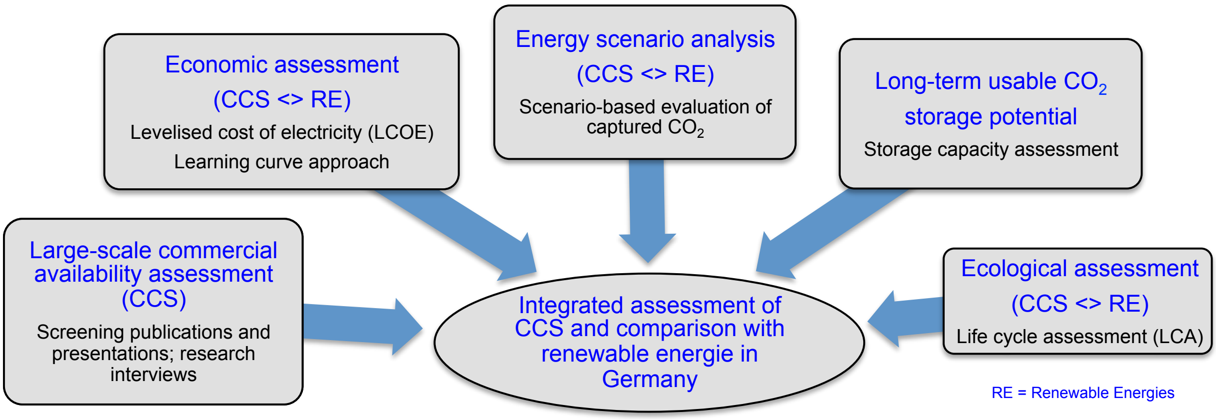

Figure 6: **Integrated assessment framework of Cluster 2 (Assessment of CCS and comparison with renewable energy sources (RE) in Germany), consisting of different individual assessment dimensions**

Source: Own composition

- The *long-term energy scenario analysis* served to dynamically determine the quantity of CO_2 that could potentially be captured from power plants up to 2050. While paper P-5 only considered the power plants that would have to be updated by 2020, paper P-6 analysed a family of six CCS deployment scenarios. This meant including the effects on the extension of CCS from the deployment of renewable energy sources (RE), the rise of combined heat and power (CHP) plants, and the increasing implementation of efficiency measures, each of which is a result of national targets as given by government energy policy. Each scenario revealed the maximal possible contribution of CCS (be it as newly built or retrofitted power plants) as well as its contribution to German long-term climate targets in 2050.

- An *economic assessment* was performed by analysing the long-term development of LCOE and the CO_2 avoidance cost of coal-fired power plants with and without CCS and by comparing them with renewable energy sources.

- An *ecological assessment* included performing a *prospective LCA* of potential future CCS-based coal-fired power plants (in paper P-5) or analysing existing such LCAs (paper P-6) based on paper N-1. Paper N-1 included studies following ISO standards 14040 and 14044 to examine relevant environmental impact categories; these modelled the whole CCS chain including second and third-order processes. The final step was to compare the environmental impacts of CCS-based power plants with those of selected renewable energy plants.

Additional methods developed and applied in papers P-6 and N-2 included the following:

- Assessment of the *large-scale commercial availability of the CCS technology* in Germany, similar to the same criteria used in Cluster 1 (paper P-6).

- *Evaluation of the long-term usable CO_2 storage potential of Germany*. For this purpose, a method was developed that would systematically analyse existing capacity estimates for Germany. This meant determining a *conservative estimate* for storage in saline aquifers, which represent the largest storage potentials in terms of quantity. This estimate was based on storage in closed aquifers, assuming a very low efficiency factor of 0.1% in the volumetric approach to minimise the risk of potential seepage into drinking water. Although this estimate represents a lower limit, it might lead to greater acceptance, since a lower risk is assumed. The quantities received were compared with the quantity of CO_2 that is captured in the different energy scenarios (paper P-6).

- *Evaluation of the CO_2 storage potential for the neighbouring states of Germany* where Germany's CO_2 emissions could possibly be stored (the Netherlands, France, the UK, Norway, Denmark and Poland). Methodologically, this was the same approach as the *conservative estimate* developed for Germany, providing a lower limit for the storage potential. That meant assuming low efficiency factors in the case of saline aquifers or adopting a conservative assessment if it already existed. The final step was to compare the estimated storage volumes with the amount of CO_2 emitted in the countries under study (paper N-2).

Results

Based on the analyses from paper P-4 and even more on an updated and more comprehensible analysis of the energy political conditions in Germany in paper P-5, the main research question can clearly be answered. Even taking into account strict climate protection targets (80-95% reduction of GHG emissions by 2050, compared to 1990) and the (energy) policy goals at that time (2007, 2012), it became apparent that there was not necessarily a need to focus on CCS in the German electricity sector.

At the same time, it could be made clear that the "bridging function" of CCS, which was often touted to be a key step towards a renewable based energy system, was a contradiction in terms, as renewable energy sources would end up being or becoming competitive with CCS in many fields. In retrospect, the analyses at that time were confirmed by the fact that renewable power generation has now seen widespread deployment, whereas there are still only two commercially operating CCS power plants with small amounts of captured CO_2 worldwide.

The following aspects of the integrated assessment contributed significantly to these conclusions:

- Based on various international sources, the time of the *large-scale commercial availability* of the whole CCS chain was estimated at that time to be between 2025 and 2030. This would have been too late to consider CCS as a means for German fossil power plants (between 2002 and 2020, 60 GW of power plant capacity were expected to be retired; in March 2006, an initial renovation programme for 32 power plants with a total installed power of 18 GW was announced for the next decade). The only option would have been to build "capture-ready" power plants, with the goal of retrofitting them with CO_2 capture at a later point (see papers N-3 and P-7 in Cluster 3 for a detailed analysis of such an option, focusing on the state of North Rhine-Westphalia).
- Much more relevant for the evaluation of a possible CCS rollout in Germany were, however, the *general conditions and the energy policy priorities* in Germany, particularly in light of the envisaged widespread deployment of renewable energy sources, the increasing share of CHP generation, and the steadily growing energy productivity. Filling the remaining gap with CCS-based power plants would in most cases lead to an overshoot of the 2050 climate target. Only two "maximum" variants would meet or fall

below the target – however, they do not seem to be very realistic due to extreme assumptions on CO_2 transport through the entire country and applying CCS to each and every small CHP plant, which are mostly located in cities. The other scenarios therefore take such restrictions into account and lead to correspondingly lower emission reductions. In the ideal case, CCS could prevent 18% of CO_2 emissions between 2005 and 2050, provided that the coal-fired power plants under construction at the time could be retrofitted as soon as possible (reaching a CCS-based power plant capacity of 24 GW). Therefore, only a limited demand for CCS appeared. Moreover, if the energy policy goals that have been set and the energy strategies based on them are rigorously implemented and further expanded, it is not necessarily needed. However, in the event that these objectives cannot be sufficiently achieved, the technology should at least be further developed.

- The results of the *economic analysis* revealed that – under assumed learning rates and mass market effects of both CCS and renewable energy sources as well as moderate fossil fuel price and CO_2 price trends – the steadily decreasing LCOE of renewable electricity could be cheaper than the (due to higher fuel costs) steadily increasing LCOE of CCS in the long term. Depending on the individual type of RE source, this could happen between 2020 and 2040. Since the LCOE for renewable energy sources has fallen much more sharply than assumed since the analysis at that time, the intersection of both cost curves would now occur much earlier. While the continuously decreasing full load hours (and therefore the power plants' capacity factors) of fossil-fired power plants were considered in that analysis (reaching 3,500 h/year in 2050), energy-economic effects associated with the expansion of renewables, such as systems cost caused by grid or storage expansions, were not.
- Performing the *prospective LCA* of potential future CCS-based PC, IGCC, and natural gas combined cycle (NGCC) plants in Germany (paper P-5) and reviewing LCA from other authors (paper P-6, based on paper N-1) exhibited somewhat better results than described for India, China and South Africa. Assuming a CO_2 capture rate of 90%, the GHG emissions of one kWh_{el} generated by the most relevant first-generation CCS-based power plants would be reduced only by 68% to 87% in the standard case (considering conditions in 2020/2025). The principles responsible for this are the same as those described in Cluster 1, except that smaller amounts of methane emissions from mining occur. The assumption of technical advancement results in a higher GHG reduction rate in 2050. Trade-offs regarding other environmental impact categories give a heterogeneous picture. In some of the reviewed studies, all emissions increase in accordance with the additional energy consumption (for example, the potentials of eutrophication, abiotic depletion, photochemical oxidation or human toxicity). Other studies model trade-offs that arise from the simultaneous reduction of other emissions in the course of the CO_2 capture process (for example, acidification potential). Finally, comparing the remaining GHG emissions of CCS-based power plants with the emissions of RE sources (most of which originate from the construction of the plants) show that renewables cause only a fraction of the total (5-24% in 2025, 7-23% in 2050).
- Large uncertainties became apparent in estimating the *CO_2 storage potential* for Germany and its neighbouring countries. Considering the conservative estimation pursued, the CO_2 emissions of German power plants at that time could be stored only for 8 to 33 years of operation in Germany. Considering, on the other hand, one of the

"realistic" scenarios, even the lowest storage scenario would have offered sufficient place for sequestration over decades.

Deriving a conservative storage potential for Germany's neighbouring countries showed that most existing estimates might be highly overestimated. But even when taking the conservative estimates, the remaining storage potential (49 Gt) corresponds to the sum total of CO_2 emissions of the analysed countries at that time (47.6 Gt). Of these, the most promising formations are located offshore in the North Sea near Norway (21 Gt) and the UK (15 Gt). Since, however, neither source-sink matching has been performed nor have limiting factors such as costs or a lack of public acceptance been considered, the "practical capacity" might be much lower. It should also be mentioned that, after publishing the results, additional studies were undertaken in particular in Norway and in the UK, where detailed storage atlases were developed. In the Netherlands, more detailed analyses of the gas fields were undertaken with regard to their possible subsequent use as CO_2 storage facilities.

6.4 Cluster 3: Additional or Extended Assessment of Individual Issues

Additional papers complement the articles presented above with research questions that could not be considered in the respective research project or which arose as additional questions following previous articles. In contrast to the first two clusters, the order of the papers described here is not determined chronologically, but by thematic reasons. Furthermore, research questions and methodology are summarised in one paragraph each.

Detailed analysis of the potential CCS infrastructure needed for the state of North Rhine-Westphalia

- Paper N-3 breaks down the main research question from paper P-5 (the potential future role of CCS in Germany) to the state of North Rhine-Westphalia (NRW), where nearly 50% of Germany's CO_2 emissions from large stationary sources are caused. Its *research question* was how many coal-fired power plants might be retrofitted with CO_2 capture and what infrastructure this would necessitate. The analysis was based on the NRW energy and climate strategy envisaged at that time, the main contribution of which would have been the successive replacement of old fossil-fired power plants by highly efficient new ones. The 2020 climate target would thus be achieved, but in order to also reach the 2050 target, all these power plants would have to be retrofitted with CCS. Additionally, the possible CO_2 capture from primary industry was roughly analysed in order to utilise synergy effects with the power plant industry.

  Methodologically, this meant setting up a (simple) reinvest model and analysing which power plants would have to be newly built at which time and which of these power plants could be retrofitted with CCS or built directly as new CCS power plants. A cluster analysis identified individual "CO_2 clusters", encompassing power plants and industrial sites. An infrastructural analysis served to estimate the necessary CO_2 storage capacities (onshore, offshore or transport to Dutch sites) and determine a possible pipeline network between the identified clusters and possible storage sites and their gradual construction.

  The *results* show that the NRW strategy would have required the retrofitting or construction of some 30 GW of CCS power plant capacities within ten years. Together with CO_2 capture in large industrial plants, 180-195 Mt CO_2/year would have had to be transported over a distance of 550 to 1,330 km across Germany or the Netherlands to storage sites. The paper questioned whether it would have been possible to quickly make up to 11 large trunk lines available and equip the corresponding storage sites in such a short time. It should be noted that the final report presented the possible infrastructures in much more detail than this conference paper.

- Subsequently, paper P-7 *questioned the conditions* under which parts of the quantities of CO_2 determined in the clusters in NRW could be stored onshore or offshore in the Netherlands or delivered by a CO_2 trunk line from the Netherlands to the large Utsira formation in the Norwegian part of the North Sea. The author's *methodological approach* used an inventory analysis for capturing and transporting CO_2 from NRW to the Netherlands, while the main part of the text consisted of identifying and assessing the inventory of Dutch sources, sinks and pipeline routes and their costs using a geographical information system combined with a bottom-up least-cost energy model based on the MARKAL-NL-UU tool. The price for the transit of CO_2 through the Netherlands was assumed to be EUR 7.5/t CO_2.

  The Dutch authors' *results* show that a European offshore pipeline to the Utsira formation may be cost-effective after 2020 under two preconditions: First, CO_2 permit prices increase from EUR 43/t CO_2 in 2020 to EUR 60/t CO_2 in 2030, remaining at this level up to 2050; and, second, the included CO_2 quantities from NRW (55 Mt CO_2/year) are actually available. In this case, up to 2.1 Gt CO_2 could be stored in Utsira by 2050. If the CO_2 quantities from NRW (and Belgium) are not available, or if onshore or near offshore deposits are used, a trunk line to Utsira would only be cost-effective ten years later, and less than 1.3 Gt CO_2 from the Netherlands could be stored there by 2050.

CCS in industry using the example of the cement industry in China

- Several of the previous papers had already pointed out the importance of CCS for emissions from *primary industry*, but its possible CO_2 reduction potential was only considered as a complement to the electricity sector (papers P-1, P-2, P-4, P-6, N-3). However, it was necessary to look at primary industry in its own right, and the cement industry served as a good sample case to carry out a more detailed analysis of its possible contribution to GHG reduction targets (paper P-8). This industry shows the highest CO_2 emissions of primary industry, and creates about 5% of global CO_2 emissions. Since about half of the world's cement production takes place in China, it made sense to carry out the analysis using China as an example. The *main research question* was to assess the potential role of CCS as one of several CO_2 mitigation technologies in the cement industry. *Methodologically*, this meant developing exploration scenarios for the cement demand, combining them with varying use of mitigation technologies and analysing their CO_2 avoidance cost.

  The *results* revealed a very high potential for energy efficiency improvements in cement production with CO_2 avoidance cost below zero. They might save up to 43-72% of CO_2 emissions, depending on the chosen scenario. Much higher cost savings, but less CO_2 reduction potential (7-14%), result from clinker substitution by blast furnace slag, fly ash and limestone. The use of alternative fuels to coal is just at the beginning of its development, and might save up 17-21%. The paper assumed that CCS could be applied to up to 50% of cement production in the long term, in particular to reduce processinherent CO_2 emissions. However, CCS's high energy penalty implies high CO_2 avoidance costs (EUR 34/t CO_2 for oxyfuel combustion and EUR 52/t CO_2 for post-combustion). Even if these were to decrease over time, as in the electricity sector, financial incentives would still be necessary for the implementation of CCS.

Public perception of CCS in Germany

- While papers P-1, P-2 and P-4, and the study on which paper P-6 is based analysed the position of certain stakeholders in the CCS debate, the question of the public's perception was still missing as part of the integrated assessment's social dimension at that time. Especially during the peak of the CCS discussion, there was considerable public opposition to the first pilot projects in Germany, as well as in other countries such as the Netherlands (Brunsting et al. 2011). While some studies on the perception and acceptance of CCS had already existed at that time, no one had investigated whether there were different perceptions of the public with regard to the different steps of the CCS chain. The *research question* of paper P-9 was therefore, on the one hand, to evaluate possible differences in the perception of CCS with regard to the type of source, transport or storage of the separated CO_2 and, on the other hand, to determine the factors that influenced the perception of CCS within a certain scenario based on additional variables.

  Methodologically, this entailed developing hypotheses for the three steps of the CCS chain as to how modifications in the respective configurations (e.g. CO_2 capture from industry instead of from power plants) could change public attitudes towards CCS. This was followed by an experimental approach designed to test these hypotheses. Such an approach enabled the research team to combine the presentation of selected information with a measurement of its perception. The experiment was carried out using an online survey representatively selecting 1,830 participants from Germany, with each participant receiving questions regarding one of 18 possible combinations of sources (coal-fired power plant, biomass power plant, industry), transport issues (pipeline, no specification) and sinks (saline aquifer, EGR, depleted natural gas field). The evaluation consisted of analyses of variance and linear regression models. The author's contribution was the development of the research question and the discussion of the results in the context of the on-going energy policy discussion of CCS in Germany.

  The *results* showed that when people were first informed about CCS, their perception of CCS was neutral or slightly positive (with a mean evaluation of 4.3 on a response scale of 1 = negative to 7 = positive). Considering all findings from the regression analysis, the rating of the respective source turned out to be the most important predictor. While CCS for biomass power plants was rated slightly better than CCS for industrial applications, the latter was rated slightly better than CCS for fossil power plants. The two scenarios that combined coal as the CO_2 source with storage in saline aquifers obtained the most negative average responses (3.8 and 3.9).

6.5 Cluster 4: Meta-Analysis of the Status of Past and Current Research

Research question

In light of the early systems-level analyses of CCS using the articles outlined in the first two clusters, the question arises as to how the research landscape has developed since when those papers were written. Is the relevance of multi-dimensional evaluations or related approaches (and thus the view from various perspectives) now state of the art, or is the focus still very limited to technical questions? Even though development on the technical side is highly relevant and successfully on-going (for example, with regard to second and third-generation CO_2 capture processes that consume fewer resources) and should certainly continue to be a research focus in the future, the high expectations for the application of CCS described in Chapter 4 have not yet been fulfilled. A number of studies and articles have tried to explain the reasons for this failure and identified, among others, the absence of business cases, public awareness, and acceptance, a lack of social and policy support, and the delayed commercial availability of CCS (paper P-10).

In order to look at the possible role of CCS from the perspective of research, the *main research question* of paper P-10 was to explore whether research in CCS was prepared to meet the obvious mismatch between expectations and actual deployment of CCS in the power sector. Is research pressing forward and capable of delivering 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) failing to be addressed in reality, since either only technical research is conducted or no interdisciplinary research is taking place?

Methodologies

The *main methodological approach* to answer these questions was to conduct a meta-analysis on published peer-reviewed papers in the field of CCS. Applying bibliographic coupling (Jarneving 2007) as a part of bibliographic analysis allowed the research front of CCS to be explored. This frontier is formed by papers that share citations (Persson 2014). By creating links between those papers that share citations, a network evolves, containing clusters that may gather around topics or a particular focus. Boyack and Klavans (2010) found that bibliographic coupling represents the research front more accurately than other citation approaches.

In order to be able to apply bibliographic coupling for CCS, several methodological steps had to take place. The first step was the conceptualisation of a keyword search in order to select the basic paper set. Second, from the keywords specified in the paper set, key topics and methods had to be identified. The third step was to determine the final paper set (consisting of 4,271 papers) by removing those papers to which the bibliographic coupling could not be applied (e.g. if no references were given) from the basic set. Fourth was the actual bibliographic coupling. The fifth step entailed using a network analysis tool to depict and explore the resulting clusters of papers. Finally, it was necessary to develop a method to analyse the resulting large amount of papers, to discuss the content of each cluster, and to derive conclusions on the topics addressed in the clusters and their connections with each other. During this process, the author carried out both the conceptual work and the discussion of the content, while the paper's co-author was responsible for the technical questions of the bibliographic coupling.

Results

The analysis resulted in a paper network consisting of 3,879 papers that spread over 12 main clusters containing between 97 and 850 nodes. Figure 7 summarises them in seven meta-clusters (MC). In contrast to meta-clusters A-C considering research on technologies, meta-clusters D-G deal with the circumstances of their implementation, particularly by exploring issues of public perception, policy, regulation, market development, macroeconomic issues, or the overall systems perspective.

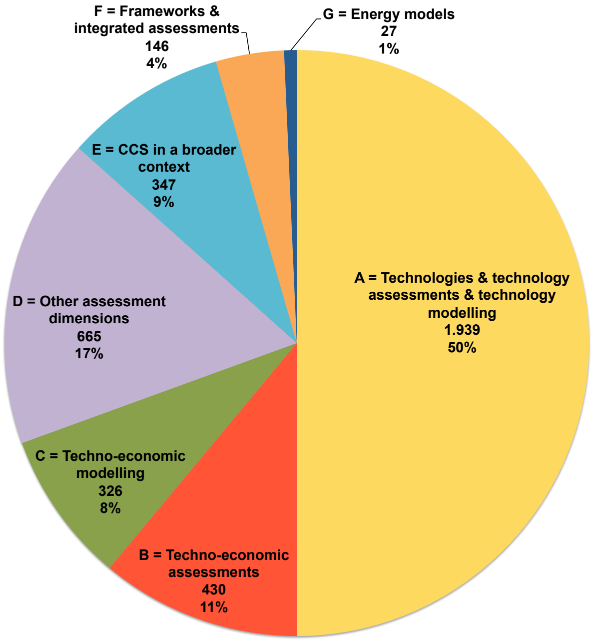

Figure 7: Summarising meta-clusters (MC) of the overall paper network, their number of nodes, and their share as a percentage of the total number

Source: Paper P-10

The distribution between the clusters is as follows:

- The research front was, on the one hand, dominated by technical research (69% out of 3,879 papers).
  - The largest group of papers (MC A, 50% = 1,939 papers) referred to technologies or technological issues such as geological storage, the development of technologies and processes, the thermodynamics of CO_2, the transport of CO_2, or technology models. Strongly related to these are
  - Techno-economic assessments (MC B, 11% = 430 papers), pursuing a cost-optimal design of processes, and
  - Techno-economically optimising models (MC C, 8% = 326 papers), focusing, for example, on optimal source-sink matching or the retrofitting of power plants.
  - These groups also identified and included recent technological developments as described in the excursus in Section 4, as there are new capture options (49 papers), cost assessments of advanced pre-combustion and post-combustion technologies (108 and 30 papers, respectively), and various applications of CCS in primary industry.
- On the other hand, 31% of the research front represented non-technical issues, which was indeed more than previously expected. They included papers on
  - Other assessment dimensions than costs (MC D, 17% = 665 papers), primarily including studies on public perception (300 papers), policy issues and regulation (90 papers), or socio-technological issues (50 papers). With 38 papers, environmental assessments are far less represented than initially expected.

- CCS in the broader context (MC E, 9% = 347 papers), for example 120 papers embedding a techno-economic assessment into broader questions of energy market developments on a regional, national or supranational level.
- Frameworks and Integrated Assessments (MC F, 4% = 146 papers), mostly developing and applying models and assessment frameworks from a systems-analytical perspective. With ten papers, multi-criteria assessments are rather poorly represented.
- CCS included in energy models (MC G, 1% = 27 papers).

The analysis also showed that some issues do not arise in current research, e.g. the assessment of the uncertainty of storage capacity potentials or the consideration of aspects of social acceptance in models and assessments.

It is worth noting that the topics referred to in the second group of clusters (D-G) correspond to the analysis of barriers for the implementation of CCS that predominantly refer to these issues. Therefore, research is advancing and trying to meet the challenges faced by CCS. However, it is particularly important to scrutinise whether the proportion of papers that both consider the CCS implementation in a broader context (MC E, 9%) and assess CCS from a holistic perspective (MC F, 4%) may be too low to assess the challenges posed by widespread deployment of CCS as envisaged in the roadmaps presented in Section 4.

7 Synthesis and Conclusions

When the results of the four research clusters are combined, the following answers to the overall research questions emerge:

1 | **What role could the application of CCS in the power sector play from a holistic perspective in a decarbonised, technologically open energy system? How would conceivable CCS paths look like (e.g. technologies, infrastructures, development periods, investments)?**

It is not possible to give a general answer to this question. With regard to the topics addressed in this thesis, it is important to make a distinction between Germany on the one side and the EU and large emerging coal states on the other.

Germany

Even in a technology-open energy system like the one in Germany, there are certain perspectives and incentives for the development of technologies. Accordingly, individual technologies cannot develop arbitrarily and independently of one another. In particular, German energy policy encompasses several long-term targets including the massive deployment of RE sources, the rise of combined heat and power (CHP) plants, and the increasing implementation of efficiency measures (adopted in the “Energiekonzept 2010” and updated several times later (BMWi 2010)). Therefore, as the analyses of the papers in Cluster 2 showed, the potential for CCS in Germany is limited alone for structural reasons (systems compatibility). Nevertheless, a rollout of CCS in limited amounts would have been theoretically possible. At the same time, however, additional challenges working against CCS included late large-scale availability, economic conditions, as well as ecological and social issues.

The social factor was the most decisive factor at that time, as society, insofar as it was affected by the transport or, in particular, the storage of carbon dioxide, did not accept CCS in Germany. Accordingly, CCS in the power sector was no longer a politically feasible option in the power plant sector in Germany. On the other hand, the acceptance analysis showed that CCS is seen as neutral to rather positive as long as people are not affected directly. In line with the generally negative image of coal use in Germany, CCS is viewed least positively for coal-fired power plants. Accordingly, the potential future use of CCS for the energy-intensive industry could play a more positive role. However, even in this field there are no system analytical assessments yet.

The analysis for the state of NRW, which at the time did not focus on the expansion of RE sources, but on the continued operation of fossil power plants, revealed the infrastructure requirements that a pure CCS strategy would have. In this case, a massive expansion up to 11 large CO_2 pipelines and the exploration and provision of several storage facilities between 2020 and 2030 would have been necessary to capture and store up to 200 Mt CO_2/year. In particular because of the late large-scale availability of CCS, but also because of the massive opposition of people who would have been affected by pipelines of several hundred kilometres in length, this strategy was not pursued any further.

The European Union (EU)

Even though Germany’s energy policy goals, in particular the deployment of RE sources, have historically developed in the way that they have due to the strong anti-nuclear movement in the 1980s, other EU countries are similarly committed to the above-mentioned strategies, in particular the expansion of renewable energy sources and the implementation of energy efficiency measures. With regard to other low-carbon technologies to be used, however, the EU leaves the choice to its individual member states – CCS technology and nuclear energy are two of the six strategic energy technologies of the EU SET (Strategic Energy Technology) Plan.

Hence, the potential future role of CCS at the European level can not easily be assessed at present. However, it can be assumed that, due to similar energy systems structures and available portfolios of CO_2 mitigation options as those within Germany, there will also be restrictions on the expansion of CCS. At the same time, however, other influencing factors would also have to be taken into account. The European Commission particularly highlighted shortcomings in 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 EU (EC 2013). While no CCS-based power plant is in operation at present, three large-scale facilities (Caledonia Clean Energy in the UK, Ervia Cork CCS in Ireland, and Hydrogen 2 Magnum in the Netherlands) are in the early development phase. Each of them is designed to capture 2-3 Mt CO_2/year (Global CCS Institute 2019). The evaluation of storage potentials of European neighbouring countries showed that, even when making conservative estimates, sufficient capacities should be available.

Apart from these plans, however, the focus in Europe is mainly on the application of CCS in industry and the development of a corresponding supranational transport and storage network in the North Sea (SCCS 2012). Just as the quantities of CO_2 potentially captured in NRW would be piped through the Netherlands to a central European trunk line starting in the harbour of Rotterdam and going to the Sleipner storage field in the Norwegian North Sea, so could CO_2 from other European countries. This would have two advantages: The trunk line would be more fully utilised, which should lead to lower individual costs, and acceptance problems in individual countries with regard to CO_2 storage could be avoided there. One disadvantage, however, is that countries would have to set up respective national transport structures up to the trunk line. Accordingly, the idea of the trunk line has been taken up in specific terms, but with regard to industry rather than power plants. In March 2019, for example, the "Northern Lights" infrastructure project submitted a PCI ("Project of Common Interest") funding proposal to the EU with the goal of linking energy systems from seven different EU countries, and storing the captured CO_2 emissions from various industrial plants off the Norwegian coast (Sandberg 2019).

India, China, South Africa

In contrast to Germany or other European countries, however, CCS in major coal-consuming countries would not directly compete with a low-carbon energy strategy focused on RE sources and energy efficiency. Instead, such countries – in particular India and China – are interested in simply being able to cover the rapidly growing energy consumption. This is why investments are being made in all available technologies, including coal-fired power plants, nuclear power plants or renewable energy sources. But these countries are also increasingly committing themselves to the long-term climate protection goals of the international community, which sooner or later may require the introduction of CCS, at least a retrofitted system (the IEA sees 91% of the need for retrofitting in China and 8%

in India (IEA 2017)). Against that background, CCS could help here to shape a more climate-friendly energy system.

In this case, however, it is important to note the preconditions that would need to be fulfilled. Any possible CCS strategy, whether it is for power plants or energy-intensive industry, depends on careful consideration of the different interests and challenges, in particular a reliable assessment of the CO_2 storage potential, appropriate economic conditions and improvements in the efficiency of the capture processes. The IEA also sees a key challenge in converting theoretical storage capacities into “bankable practical storage facilities” (IEA 2016). As long as these countries suffer from a considerable lack of energy, strategies that focus on additional energy consumption may not have first priority. This might be part of a public debate that has not yet started due to the very low public awareness of CCS. Since this thesis deliberately avoided comparisons with other low-carbon technology options for these countries, systems-analytical studies would also be necessary to identify the complex energy system with all its restrictions and dependencies before the potential future role of CCS can be determined.

These expectations have at least not yet been fulfilled with regard to the “China CCS Roadmap” (ADB 2015) released in 2015, the aim of which was “to inform the PRC’s[5] decision makers on the technical, economic and policy dimensions of deploying CCS over a timeframe and at a scale to enable the cost-effective achievement of the PRC’s emissions reduction targets.” System-analytical aspects beyond this are not included.

2 | What are the key determinants of the high expectations for CCS in the electricity sector?

The IEA’s 2009 CCS technology roadmap and other roadmaps and scenarios seem to have been based on a straightforward implementation of CCS, which at least for the countries analysed here contradicts the role and the respective challenges discussed above. This is why it assumed a much faster implementation of CCS than what reality currently allows. In the IPCC’s early Special Report on CCS (IPCC 2005), which was crucial for much of the later work on this topic, only technical issues were considered without looking at the implications that a rollout of CCS would have from a more holistic point of view. Learning from 20 years of experience, the CCS scene still only sees stable policies and financial support as key challenges (IEA 2016; IEAGHG 2017). The analyses carried out within this thesis suggest that many more determinants other than missing financial support are responsible for this discrepancy:

- Although there have been lots of advances in research, which not only concern CCS in power plants, several challenges have been reported at international GHGT conferences. These particularly include the costs of post-combustion, which are still too high (“the high-costs for retrofitting existing power and chemical plants, and the high operational costs for carbon capture advanced configurations, either by themselves, or combined with novel solvents”) (IEAGHG 2019). Moreover, according to Rubin et al. (2015), the incremental capital cost for post-combustion capture increased in the past. Only concurrent lower annual capital charge factors and higher assumed capacity factors led to the fact that PC power plants with CCS showed slightly lower LCOE than

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[5] PRC = People’s Republic of China

described in the IPCC report ten years ago (IPCC 2005). Therefore, one reason for overly high deployment rates resulting from the energy models might also be that overly high learning rates have been used from the start.

- CCS is now also compared with other low-carbon technology options, which was not the case in the past. One example for this is the explicit exclusion of RE and efficiency strategies when assessing CCS strategies for the UK, since these options "could not deliver sufficient [GHG] reductions soon enough" (Gough and Shackley 2006). In particular, the ever-increasing cost advantage of renewable energy sources is now viewed critically and "a dramatic increase in wind and solar deployment and a corresponding fall in the LCOE" is observed, even if the system costs – as in this thesis – have not yet been taken into account (IEAGHG 2019). The fact that this development was not considered at an early stage, at least in sensitivity analyses, is probably also one reason why CCS was promoted as a bridging technology towards a renewable age. But also after the massive cost decrease of RE, a "no CCS for power" strategy seems inconceivable for cost reasons and due to the technical challenges of system integration (IEA 2016).
- Besides the overly high learning rates for capital and the operating costs of CCS, underestimated learning rates for renewable energy sources could also be a reason for energy models to propose CCS as a cost-optimal solution. These often economically optimising energy models are usually the basis for technology roadmaps for the IEA as well as for the EU. They could be responsible for the fact that the spread of CCS in the electricity sector was massively overestimated and competing technologies underestimated. Creutzig et al. (2017) have shown this in detail using the example of photovoltaics in comparison to CCS. Accordingly, the learning rates for CCS and competing technologies underlying the energy models so far should be reviewed and sensitivity analyses should be carried out with adapted learning rates.
- In addition to comparisons with competing technologies, however, the other perspectives considered in this thesis were also either insufficiently or completely excluded in the potential assessments of CCS. These included, in particular, questions of the necessary structural fit of CCS to existing energy systems (system compatibility), additional energy consumption (which represents a problem not to be underestimated, especially for the emerging countries), or additional water consumption (which is highly problematic in particular for dry countries such as India or South Africa, as papers P-1 and P-4 have described), or the total GHG reduction rates of only 59-87% for the most relevant technology paths while assuming a CO_2 capture rate of 90%, and partly increasing other environmental impacts. Besides that, CCS could potentially conflict with meeting development targets such as reducing poverty and inequality, providing electrification and increasing resilience to the impacts of climate change. Finally, various stakeholders should have been involved in the discussion from the outset, or at least prospective studies should have been carried out on the possible acceptance or rejection of CCS.
- In the course of the CCS Global project, which papers P-1 – P-4 are based on, the experts and decision-makers from India, China and South Africa made it abundantly clear that a stronger commitment from the industrialised world in terms of technology demonstration, cooperation and transfer to developing countries and emerging economies would be required alongside national actions and analysis. This might be another

important prerequisite for the success of CCS in these countries, as provided for in the roadmaps.

- One factor not responsible for the small number of projects, but the basis for roadmaps and scenarios are the unexamined assumptions of CO_2 storage potential. Most of the publications on CCS under analysis here took sufficient storage potential for granted or referred to literature sources that had suggested large theoretical storage capacities that in practice (considering the effective potential) will be most likely emerge as being considerably smaller. One critical analysis of storage potential was the work of the British Geological Survey (BGS) done for India, which explicitly included the uncertainty of existing estimates (paper P-1).
- Nevertheless, even in research, technical aspects predominated, while more holistic technology assessment studies including a broader set of criteria are rare, as the bibliographic analysis in Cluster 4 showed. In addition to the studies presented in this thesis, one of the earliest technology assessment studies in Germany was a 2007 study by the Office for Technology Assessment of the German Bundestag (Grünwald 2008, 2009). The assessment of CCS options for the UK also appeared quite early, but also with the same shortcomings mentioned above (Gough and Shackley 2006).

The analysis of these key determinants leads directly to the next research question, which addresses solutions to these challenges.

3 | Have the approaches and methods used so far as basis for policy advice been suitable for the assessment of complex low-carbon technologies? If not, what possible options are available to be able to assess a technology in a future-oriented way?

As illustrated in the course of the former research question, the usual way to assess a technology is to use individual techno-economic assessments and cost-optimising macroeconomic energy models as the basis for roadmaps. Since important issues discussed above have not been taken into account, this approach might no longer be sufficient for policy advice. However, the EU's Impact Assessment, which in general was explicitly intended to ensure that EU initiatives and decisions were "prepared on the basis of transparent, comprehensive and balanced evidence" (EC 2009), did not take into account the constraints when assessing the impacts of CCS, partly due to the fact that it only assessed the Directive on Geological Storage and not CCS as a whole (EC 2008). Particularly in the energy sector, in view of the challenges of becoming climate-neutral by 2050 at the latest, severl aspects will come together that can only be addressed by systems analysis:

- The energy system in a complex system with hundreds of moving parts;
- The energy sector (as well as other sectors) is exposed to complex challenges with partly contradictory objectives (for example, climate protection and, resource issues);
- The need for action in the short to medium term creates a high degree of dynamism;
- In contrast to the past energy system with relatively few types of power plants, storage facilities and transport infrastructures, great technological diversity has arisen with technologies that are not yet fully ready for the market;
- Last but not least, the *Energiewende* has made a major social impact, which can be seen in many different questions of social acceptance.

A more integrative and intertemporal systems-analytical view is therefore necessary, not only for policy advice. This thesis took up this in the following aspects:

- The analytical focus was extended from a techno-economic assessment to a holistic assessment, taking into account different indicators from technological, economic, ecological and social perspectives.
- Instead of examining current conditions only (for example, the current costs of a technology), this thesis took a long-term perspective with a time horizon of 2050, so that dynamics of future development could be taken into account.
- CCS was evaluated not only as a standalone technology, but also in comparison with competing technologies, particularly from an economic and ecological point of view.
- Finally, the thesis analysed a technology with respect to a complex system environment in which it is embedded. This also made it possible to include structural issues relating to the entire system (for example, an increasing share of renewable energy sources, which leads to a lower capacity factor of conventional power plants).

In addition to the methods applied here, policy advice should be supplemented by the following further activities:

- Elements of multidimensional technology assessments should be integrated into both Integrated Assessment Models (IAM) and pure energy models, since these analyses form the basis for national, European or international transformation pathways. Although techno-economic data such as learning rates of technologies, efficiencies, etc. are already taken into account, ecological or social aspects should also be integrated appropriately. Arvesen et al. (2018) have demonstrated one way of doing this, for example, for the integration of life cycle assessment results into an IAM. Another challenge would be the consideration of social acceptance or technical risks such as CO_2 storage, which in principle also represent costs of implementation. One long-term goal might be to couple a conventional MCA with IAM or energy models.

- Particularly with regard to the evaluation of CCS, issues of CO_2 storage capacities might be considered during (multi-criteria) assessments, studies on public perception, and in particular IAMs and energy models (papers P-2, P-10). One issue, for example, might be to consider the uncertainty of storage capacity potentials and the different characterisation factors according to the “techno-economic resource-reserve pyramid for CO_2 storage capacity” (Bachu 2007). At the very least, the considerable distinction between theoretical and effective storage potential should be taken into account in such evaluations.

- Last but not least, greater public participation and comprehensive public discussion of various future technology paths and their advantages and disadvantages would be likely to lead to greater acceptance.

All these challenges show that CCS requires a more complex evaluation than being “simple and pragmatic”, as the CCS lobby posits: “climate change mitigation policies could be driven by ideological perspectives that are unfavourable to CCS rather than pragmatic approaches that CCS could fulfil. There could also be a lack of commitment due to a combination of economic declines coupled with increasing nationalism at a time of economically demanding policies” (IEAGHG 2019).

8 Outlook on Future Research

Finally, this Section looks at further fields of research regarding the assessment of CCS. From a methodological point of view, this means addressing at least two challenges:

- Coupling broader technology assessment approaches with IAMs and pure energy models as proposed in the previous section.
- Conducting sensitivity analyses with existing models to simulate the effects of different expectations of cost reductions (expressed by learning rates) on model results regarding the resulting technology mix.

Additional fields of application where CCS might be evaluated according to the recommended approaches include

- Assessing the implications of a possible future retrofit of China's and India's coal-fired power plants
  As mentioned above, retrofitting of coal-fired power plants with CCS would mainly affect China and India, where lots of power plants were installed in the 2010s. It therefore becomes necessary to analyse the implications of such retrofitting on costs (economic viability), environment (additional energy consumption, emissions from various environmental categories), social aspects (consequences of additional coal mining) and infrastructure issues. The possible retrofitting with CCS should concurrently be compared with other options such as the increased expansion of renewable energy sources.

- Scrutinising the possible role of CCS in energy-intensive industries.
  These industries include the steel, cement, chemical, glass, and pulp and paper sectors. While some papers of this thesis have already researched the industrial applications of CCS with varying intensity (see papers P-1, P-2, P-4, N-3, P-8) and the use of CCS in industry has also been recommended, there is still disagreement with regard to the extent to which CCS is needed. One viewpoint is that the deep decarbonsation of industry will not be possible without CCS at all, due to process-induced CO_2 emissions, which might not be avoided in time by alternative processes (IEA 2016, 2017; IEAGHG 2019). Another point of view is that there are indeed alternative processes that are already being tested in demonstration projects, for example, using hydrogen-based direct reduction (HDR) in steel production instead of using coke (Vogl et al. 2018). One key question, similar to what was discussed years ago about electricity production, is whether the application of CCS could actually be implemented faster than alternative processes, and under what conditions. This is also a classic case for the need of a far-sighted comprehensive technology assessment.

- Assessing the possible role of CCS with regard to hydrogen production
  For some years now, hydrogen has been the focus of alternative concepts in the energy, transport and industrial sectors. In particular, it is a central source for synthetic fuels and alternative industrial processes (see above). Various sides are therefore beginning to develop hydrogen strategies and roadmaps, and it is becoming apparent that considerable quantities of green hydrogen could be required in the next decade. The key question is the production of hydrogen. "Decarbonised" hydrogen can be produced both by electrolysis based on electricity from renewable energy sources ("green hydrogen"), by steam reforming from natural gas ("blue hydrogen"), and by coal gasification ("grey hydrogen"). The latter two options, however, require the use of CCS. For

example, hydrogen imported from Australia is to become part of Japan's low-carbon energy strategy, which is to be produced in Australia on a large scale from coal and the application of CCS (Kamiya et al. 2015). However, a comprehensive technology assessment will be necessary to compare such fundamentally different strategies.

- Assessing the implications of storing CO_2 in solid state instead of gas
  In view of the low level of acceptance of underground CO_2 storage and the infrastructure required, other options for CO_2 storage are increasingly being discussed. These include the storage of CO_2 in solid state instead as gas that is primarily discussed. Cooling down CO_2 to lower than minus 78°C yields dry ice that would require huge ice deposits and permanent cooling over hundreds of years. Another option is mixing CO_2 with water and discharging it as carbonic acid CO_2 into basalt rock, where it would form carbonates, as demonstrated in Hellisheiði, Iceland (Reykjavik Energy 2018). But such options are not per se better than storage in saline aquifers and have their own advantages and disadvantages that also have to be weighed and evaluated against each other.
- Assessing the role of CCS with regard to the potential need of negative emission technologies (NET)
  One speaks of the achievement of "negative emissions" if CO_2 is removed from the atmosphere and subsequently stored in a permanent way. NET such as biomass and CCS (BECCS) or direct air capture and CO_2 storage (DACCS) might become necessary to an enormous extent in the future according to the Intergovernmental Panel on Climate Change (IPCC). The resulting storage of CO_2 could take on completely different dimensions than storing CO_2 captured from power plants or industry. As Viebahn et al. (2019) have noted, using DAC as an example, there is a significant need to perform systems analyses to assess these and other NET technologies, including their effects on energy consumption and resource consumption – including requirements for the construction of infrastructure systems (transport, storage). Since climate models have quantified the need for negative emissions, the results of any technology assessment should also be linked with such climate models to make decisions more reliable from the outset.

9 Author’s Papers Used in this Thesis

Peer-reviewed

P-1 **Viebahn, P.**; Vallentin, D.; Höller, S. (2014): Prospects of Carbon Capture and Storage (CCS) in India’s Power Sector – An Integrated Assessment. Appl Energ 117(2014)62–75. https://doi.org/10.1016/j.apenergy.2013.11.054

P-2 **Viebahn, P.**; Vallentin, D.; Höller, S. (2015): Prospects of Carbon Capture and Storage (CCS) in China’s Power Sector – An Integrated Assessment. Appl Energ 157(2015)229-244. https://doi.org/10.1016/j.apenergy.2015.07.023

P-3 Höller, S.; **Viebahn, P.** (2016): Facing the uncertainty of CO_2 storage capacity in China by developing different storage scenarios. Energy Policy 89(2016)64–73. https://doi.org/10.1016/j.enpol.2015.10.043

P-4 **Viebahn, P.**; Vallentin, D.; Höller, S. (2015): Integrated Assessment of Carbon Capture and Storage (CCS) in South Africa’s Power Sector. Energies 8(12)14380-14406. https://doi.org/10.3390/en81212432

P-5 **Viebahn, P.**; Nitsch, J.; Fischedick, M.; Esken, A.; Schüwer, D.; Supersberger, N.; Zuberbühler, U.; Edenhofer, O. (2007): Comparison of Carbon Capture and Storage with Renewable Energy Technologies Regarding Structural, Economic, and Ecological Aspects in Germany. Int. J. Greenhouse Gas Control 1(1)121–133. https://doi.org/10.1016/S1750-5836(07)00024-2

P-6 **Viebahn, P.**.; Vallentin, D.; Höller, S. (2012): Integrated Assessment of Carbon Capture and Storage (CCS) in the German Power Sector and Comparison with the Deployment of Renewable Energies. Appl Energ 97(2012)238–248. https://doi.org/10.1016/j.apenergy.2011.12.053

P-7 Van den Broek, M.; Ramírez, A.; Groenenberg, H.; Neele, F.; **Viebahn, P.**; Turkenburg, W.; Faaij, A. (2010): Feasibility of Storing CO_2 in the Utsira Formation as Part of a Long Term Dutch CCS Strategy: An Evaluation Based on a GIS/MARKAL Toolbox. International Journal of Greenhouse Gas Control 4(2)351–366. https://doi.org/10.1016/j.ijggc.2009.09.002

P-8 Wang, Y.; Höller, S.; **Viebahn, P.**; Hao, Z. (2014): Integrated Assessment of CO_2 Reduction Technologies in China’s Cement Industry. Int. J. Greenhouse Gas Control 20(2014)27–36. https://doi.org/10.1016/j.ijggc.2013.10.004

P-9 Dütschke, E.; Wohlfarth, K.; Höller, S.; **Viebahn, P.**; Schumann, D.; Pietzner, K. (2016): Differences in the public perception of CCS in Germany depending on CO_2 source, transport option and storage location. Int J of Greenhouse Gas Control 53(2016)149–159. https://doi.org/10.1016/j.ijggc.2016.07.043

P-10 **Viebahn, P.**; Chappin, J.L. (2018): Scrutinising the Gap between the Expected and Actual Deployment of Carbon Capture and Storage – A Bibliometric Analysis. Energies 2018, 11(9), 2319. https://doi.org/10.3390/en11092319

Reviewed by the editor

N-1 **Viebahn, P.** (2011): Life Cycle Assessment for Power Plants with CCS. In: D. Stolten and V. Scherer (Eds.), Efficient Carbon Capture for Coal Power Plants. Weinheim: WILEY-VCH. https://www.wiley-vch.de/en/areas-interest/engineering/chemical-biochemical-engineering-10cg/general-introductory-chemical-engineering-10cg0/efficient-carbon-capture-for-coal-power-plants-978-3-527-33002-7

N-2 Höller, S.; **Viebahn, P.** (2011): Assessment of CO_2 Storage Capacity in Geological Formations of Germany and Northern Europe. Energy Procedia 4(2011)4897–4904. https://doi.org/10.1016/j.egypro.2011.02.458

N-3 **Viebahn, P.**; Esken, A.; Fischedick, M. (2009): Energy-Economic and Structural, and Industrial Policy Analysis of Re-Fitting Fossil Fired Power Plants with CO_2 Capture in North Rhine-Westphalia/Germany. Energy Procedia 1(1)4023–4030. https://doi.org/10.1016/j.egypro.2009.02.208

10 References

ADB (2015): Roadmap for Carbon Capture and Storage demonstration and deployment in the People's Republic of China. Mandaluyong: Asian Development Bank.

Arvesen, A.; Luderer, G.; Pehl, M.; Bodirsky, B. L.; Hertwich, E. G. (2018): Deriving life cycle assessment coefficients for application in integrated assessment modelling. Environmental Modelling & Software 99111–125. doi: 10.1016/j.envsoft.2017.09.010.

Bachu, S. (2007): Carbon Dioxide Storage Capacity in Uneconomic Coal Beds in Alberta, Canada: Methodology, Potential and Site Identification. Int. J. Greenh Gas Con 1(3)374–385.

BMWi (2010): Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung vom 28.09.2010. Beschluss des Bundeskabinetts. Berlin: Bundesministerium für Wirtschaft und Energie für die Bundesregierung. http://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5. Last access: 22 July 2014.

Boyack, K.; Klavans, R. (2010): Co-Citation Analysis, Bibliographic Coupling, and Direct Citation: Which Citation Approach Represents the Research Front Most Accurately? Journal of the American Society for Information Science and Technology 61(2010)2389–2404. doi: 10.1002/asi.21419.

Brunsting, S.; Upham, P.; Dütschke, E.; De Best Waldhober, M.; Oltra, C.; Desbarats, J.; Riesch, H.; Reiner, D. (2011): Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage. Int. J. Greenh Gas Con 5(6)1651–1662. doi: 10.1016/j.ijggc.2011.09.012.

Bullinger, H.-J. (1994): Technikfolgenabschätzung (TA). Technologiemanagement — Wettbewerbsfähige Technologieentwicklung und Arbeitsgestaltung. Springer Vieweg.

Creutzig, F.; Agoston, P.; Goldschmidt, J. C.; Luderer, G.; Nemet, G.; Pietzcker, R. C. (2017): The underestimated potential of solar energy to mitigate climate change. Nature Energy; London 217140. doi: http://dx.doi.org/10.1038/nenergy.2017.140.

Deutscher Bundestag (2019): Technikfolgenabschätzung (TA). Ausschuss für Bildung, Forschung und Technikfolgenabschätzung (ABFTA).

EC (2008): Accompanying document to the Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the geological storage of carbon dioxide - Impact Assessment. SEC(2008) 54/2. Brussels: European Commission.

EC (2009): Impact Assessment Guidelines. SEC(2009)92. Brussels: European Commission.

EC (2013): Consultative Communication on The Future of Carbon Capture and Storage in Europe. No. COM(2013) 180 final. Brussels: European Commission.

Ewers, J.; Renzenbrink, W. (2005): Stocktaking and Classification of the Different CO_2 Reduction Technologies. VGB PowerTech Journal 85(4)46–51.

Fenn, J.; Blosch, M. (2018): Understanding Gartner's Hype Cycles. Gartner Research. https://www.gartner.com/en/documents/3887767. Last access: 15 September 2019.

Global CCS Institute (2019): Overview on CCS projects as of 2 November 2019. Canberra: Global CCS Institute. https://co2re.co/FacilityData. Last access: 2 November 2019.

Göttlicher, G. (2004): The Energetics of Carbon Dioxide Capture in Power Plants. NETL, US Department of Energy English Translation of "Energetik der Kohlendioxidrückhaltung in Kraftwerken. VDI Progress Reports Series 6 No. 421".

Gough, C.; Shackley, S. (2006): Towards a Multi-Criteria Methodology for Assessment of Geological Carbon Storage Options. Climatic Change 74(1–3)141–174.

Grubler, A.; Wilson, C.; Bento, N.; Boza-Kiss, B.; Krey, V.; McCollum, D. L.; et al. (2018): A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3(6)515. doi: 10.1038/s41560-018-0172-6.

Grünwald, R. (2008): Treibhausgas – ab in die Versenkung? Möglichkeiten und Risiken der Abscheidung und Lagerung von CO_2. No. 25. Studien des Büros für Technikfolgen-Abschätzung beim Deutschen Bundestag. Berlin: Edition Sigma. https://www.tab-beim-bundestag.de/de/publikationen/buecher/gruenwald-2008-120.html. Last access: 5 October 2019.

Grünwald, R. (2009): CO_2-Abscheidung und -Lagerung im Überblick: Technik, Potenziale, Risiken, Kosten und Regulierung - A Review of Carbon Dioxide Capture and Storage Technology, Potentials, Risks, Costs, and Regulation. GAIA - Ecological Perspectives for Science and Society 18(3)211–220.

Heinemann, N.; Wilkinson, M.; Haszeldine, R. S. (2017): Comment on “Facing the uncertainty of CO_2 storage capacity in China by developing different storage scenarios” by Samuel Höller and Peter Viebahn. Energy Policy 109228–229. doi: 10.1016/j.enpol.2017.06.066.

Hendriks, C. (1994): Carbon Dioxide Removal from Coal-Fired Power Plants. Dortrecht, Boston, London: Kluwer Academic Publishers.

IEA (2009): Technology Roadmap: Carbon Capture and Storage. Paris: International Energy Agency.

IEA (2016): 20 Years of Carbon Capture and Storage. Accelerating Future Deployment. Paris: International Energy Agency.

IEA (2017): Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations. Paris: International Energy Agency.

IEA (2018): World Energy Outlook 2018. Paris: International Energy Agency.

IEAGHG (2017): GHGT-13 Conference Summary. Cheltenham: International Energy Agency Greenhouse Gas R&D Programme.

IEAGHG (2019): GHGT-14 Conference Summary. Cheltenham: International Energy Agency Greenhouse Gas R&D Programme.

IPCC (2005): Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. (B. Metz, O. Davidson, H. de Coninck, M. Loos, and L. Meyer, Eds.). Cambridge, New York: Cambridge University Press.

IPCC (2011): Special Report on Renewable Energy Sources and Climate Change Mitigation. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2014a): Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, US: Cambridge University Press.

IPCC (2014b): Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2018): Summary for Policymakers. In: Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above preindustrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Genf, Schweiz: Intergovernmental Panel on Climate Change.

Jarneving, B. (2007): Bibliographic coupling and its application to research-front and other core documents. Journal of Informetrics 1(4)287–307. doi: 10.1016/j.joi.2007.07.004.

Kamiya, S.; Nishimura, M.; Harada, E. (2015): Study on Introduction of CO_2 Free Energy to Japan with Liquid Hydrogen. Physics Procedia, Proceedings of the 25th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2014 6711–19. doi: 10.1016/j.phpro.2015.06.004.

Martínez Arranz, A. (2016): Hype among low-carbon technologies: Carbon capture and storage in comparison. Global Environmental Change 41(2016)124–141. doi: 10.1016/j.gloenvcha.2016.09.001.

Moriarty, P.; Honnery, D. (2019): Ecosystem maintenance energy and the need for a green EROI. Energy Policy 131229–234. doi: 10.1016/j.enpol.2019.05.006.

Persson, O. (2014): The intellectual base and research fronts of JASIS 1986–1990. Journal of the American Society for Information Science 45(1)31–38. doi: 10.1002/(SICI)1097-4571(199401)45:1<31::AID-ASI4>3.0.CO;2-G.

Reykjavik Energy (2018): The CarbFix2 project. https://www.carbfix.com/carbfix-2011-2014. Last access: 27 July 2019.

Rubin, E. S.; Davison, J. E.; Herzog, H. J. (2015): The cost of CO_2 capture and storage. International Journal of Greenhouse Gas Control, Special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO_2 Capture and Storage 40378–400. doi: 10.1016/j.ijggc.2015.05.018.

Sandberg, P. (2019): Northern Lights - A European CO_2 transport and storage network. VdZ-Seminar ‘Contributions to Decarbonising German and European Industries’, 11 June 2019, Düsseldorf.

SCCS (2012): Central North Sea – CO_2 Storage Hub: Enabling CCS deployment in the UK and Europe. Edinburgh: Scottish Carbon Capture & Storage.

Teske, S. (Ed.) (2019): Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. Springer International Publishing. https://www.springer.com/gp/book/9783030058425. Last access: 8 July 2019.

Teske, S.; Sawyer, S.; Schäfer, O.; Pregger, T.; Simon, S.; Naegler, T. (2015): energy [r]evolution - a sustainable world energy outlook 2015. 100% renewable energy for all. No. 5. Brussels: Greenpeace International, Global Wind Energy Council, SolarPowerEurope. http://www.greenpeace.org/international/en/publications/Campaign-reports/Climate-Reports/Energy-Revolution-2015/. Last access: 25 July 2019.

UNFCC (2018): The Paris Agreement. United Nations Framework Convention on Climate Change. UN climate change annual report. Bonn, Germany. https://unfccc.int/annualreport. Last access: 25 July 2019.

Viebahn, P.; Scholz, A.; Zelt, O. (2019): The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. Energies 12(18)3443. doi: 10.3390/en12183443.

Viebahn, P.; Vallentin, D.; Höller, S.; Esken, A.; Pietzner, K.; Luhmann, H.-J. (2010): RECCS plus: comparison of renewable energy technologies with carbon dioxide capture and storage (CCS). Update and expansion of the RECCS study 0329967/07000285. Final report. Final Report on Behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Wuppertal: Wuppertal Institut.

Vogl, V.; Åhman, M.; Nilsson, L. J. (2018): Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production 203736–745. doi: 10.1016/j.jclepro.2018.08.279.

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