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Integrative technology assessment of carbon capture and utilization: a German perspective

碳捕获和利用的综合技术评估：一个德国视角

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Abstract - **Fossil-based energy conversion and energy-intensive industries are sources of a large part of global CO_2 emissions. Carbon capture and storage (CCS) technologies are regarded as important technical options to reduce worldwide CO_2 emissions. However, the discussion on the potential of CCS is highly controversial and focuses on issues such as *technology development, economic competitiveness, environmental and safety impacts,* and *social acceptance*. The paper focuses on these aspects and analyses the potential and the possible role of CCS technologies. When regional considerations are important for evaluation, e.g. in the case of social acceptance, the focus is on the German perspective.**

While there is no lack of technical options for CCS and storage capacities are available, the question arises as to whether and under what conditions CCS could become a key element within the framework of implementing climate protection strategies. To answer this question, an Integrated Technology Assessment is required covering technical, economic, environmental, and social considerations. In order to play a decisive role in climate protection strategies, 5 key criteria are identified: (1) 'demonstration of an industrial scale and commercial availability', (2) 'environmental and safety requirements', (3) 'cost efficiency and economic viability', (4) 'coordination of energy and climate policy', and (5) 'public acceptance'. Given the different analyzes of the 5 key criteria essentials are formulated assessing the potential of CCS technologies as elements of climate protection strategies. Finally, the OECD approach for constructing composite indicators for assessing technologies is used.

Keywords – **CCS, CO_2 utilization, technology assessment.**

I. INTRODUCTION

In order to limit the anthropogenic increase in the average global temperature by 2100 to 2 °C, the concentration of CO_2 in the atmosphere must be restricted to 450 ppmv according to the Intergovernmental Panel on Climate Change (IPCC). To achieve this target, global CO_2 emissions must be cut by 50 % by 2050 compared to levels in 1990. However, global energy consumption is growing year by year and the use of fossil energy carriers is not only continuing, but coal in particular is becoming even more important as an energy carrier globally.

In their analyses on stabilizing global CO_2 emissions, Pacala and Socolow identified strategies ('wedges') to help reduce future CO_2 emissions [1]. A 'wedge' is a strategy or measure to reduce CO_2 emissions, which are forecast to increase in fifty years to 3.67 billion tonnes of CO_2 ($GtCO_2$) per year (= 1 GtC/a). Over 50 years, this represents a cumulative total of approx. 92 $GtCO_2$ (25 GtC). These wedges include energy efficiency, a fuel shift, nuclear energy, wind energy, solar energy, bioenergy, and natural CO_2 sinks, as well as carbon capture and storage (CCS).

Numerous analyses of and projections for the global energy system also emphasize the importance of CCS in strategies for reducing greenhouse gases, e.g. the Stern Report, Energy Technology Perspectives, and the World Energy Outlook [2-7]. The IEA projects an increase in CO_2 emissions in a business-as-usual scenario from 29 $GtCO_2$ per year today to some 62 $GtCO_2$ per year by 2050 [8]. This would be accompanied by an increase in the concentration of CO_2 in the atmosphere to approx. 550 ppm, and by a mean temperature rise of 3 °C to 4 °C. The IEA proposes two scenarios for reducing these emissions, both of which cover the period up to 2050. In the ACT Map scenario, a clear reduction in CO_2 is achieved, saving some 35 $GtCO_2$ per year by 2050 compared to the business-as-usual scenario. This would mean maintaining today's levels of CO_2 emissions in 2050, which would be equivalent to a CO_2 concentration of around 485 ppm. The BLUE Map scenario goes even further, cutting CO_2 emissions in 2050 by 48 $GtCO_2$ per year, representing a reduction of 77 % compared to the business-as-usual scenario.

This would be equivalent to a CO_2 concentration of around 445 ppm in 2050.

In both cases, power generation would make the highest contribution of any sector and CCS would lead to the biggest reductions of any individual measure. CCS would reduce CO_2 emissions in the power sector by approx. 21 % in the ACT Map scenario and by approx. 26 % in the BLUE Map scenario. The results highlight the importance of CCS technology in the global context and show how attractive CCS is if stringent greenhouse gas reduction targets are to be achieved.

Worldwide, industrial processes are responsible for almost 30 % of CO_2 emissions [9], whereby some of these emissions are process-induced. CCS can therefore also help to reduce CO_2 emissions in industrial sectors [10]. The most pertinent sectors are the cement industry, the iron and steel industry, and the production of other metals, as well as industries that process crude oil.

In contrast, the current usage of CO_2 as an industrial gas amounts to approx. 20 Mt/a and as a chemical raw material around 110 Mt/a [11]. The options for utilizing CO_2 in the future would mean that these two areas could contribute to a welcome, albeit limited, direct reduction in carbon dioxide emissions. The interest in utilizing carbon dioxide (CCU) stems primarily from the fact that CO_2 is a potentially recyclable material with an interesting application profile and great potential for the chemical industry. Carbon utilization would also positively affect the evaluation of strategies aiming to reduce CO_2 emissions if product-related CO_2 balances show a reduction in the emission of CO_2. In this way, the greenhouse gas carbon dioxide can be transformed on a limited scale into a raw material for the material value chain [12] (see schematic in Fig. 1).

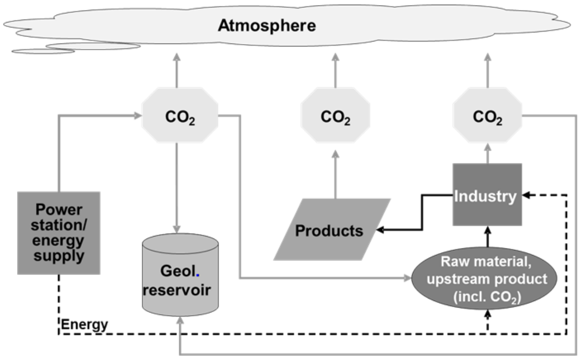

Figure 1: Schematic of carbon capture and storage as well as utilization of CO_2 as a raw material for manufacturing

In this context, capturing carbon dioxide is an important mitigation measure for CO_2 point sources in the energy conversion sector and in industry, and it is the focus of numerous research and development projects throughout the world.

At present, three technology lines are favoured for carbon capture: post-combustion, oxyfuel, and pre-combustion. Although the post-combustion and oxyfuel processes are being tested in smaller test facilities, practical demonstration is still required before first-generation technologies can be implemented on an economic and industrial scale. In the long term, interesting options could replace the currently favoured physical and chemical scrubbing using membranes, as well as carbonate looping, which count as second-generation technologies. For the oxyfuel process, the cryogenic air separation process could be improved (three-column process) and a transition to other oxygen production processes (membranes, chemical looping) is also possible.

For the storage of CO_2, a range of options are being discussed both at the national and European level. These include unused deep underground rock formations containing highly saline fluids (on-shore and under the seabed), depleted natural gas and crude oil fields (enhanced gas and oil recovery, EGR/EOR), and coal seams (enhanced coal-bed methane, ECBM). In national and international research projects, potential storage capacities are being analysed and concepts developed for the long-term and safe trapping of CO_2. With respect to the acceptance of CO_2 storage, strong reservations abound in Germany, as illustrated by the formerly planned on-shore storage facility in Schleswig-Holstein and by the discussion in Lower Saxony. At the moment, neither the general public nor politicians in the north and north-west of Germany appear to be willing to accept potential CO_2 storage sites.

While there is no lack of technical options for CCS and storage capacities are available, the question arises as to whether and under what conditions CCS could become a key element within the framework of implementing climate protection strategies. To answer this question, an Integrated Technology Assessment is required that goes beyond a purely technical evaluation. This paper therefore looks at possible implications that the technology evaluation of carbon capture and utilization could have for energy, climate, and industrial policy. First, we identify 5 key criteria and present assessment results, respectively. In a second step, an overall assessment is made resulting in key conclusions. Finally, the OECD approach for constructing composite indicators for assessing technologies is used.

II. INTEGRATED TECHNOLOGY ASSESSMENT

2.1. OBJECTIVE

The objective of a technology assessment is to determine the importance of a technology in relation to a set of criteria. The set of criteria selected here is rooted in the regulatory framework governing the concept of sustainable development, which has led to the need for the transformation of the energy sector in favour of sustainable technologies and systems. The principle involves investigating the development of energy technologies (and energy systems) in terms of their technical, economic, ecological, and social impacts, and thus evaluating what contribution technologies can make to the transformation of energy systems.

2.2. METHODOLOGICAL APPROACH

The range of methods for technology evaluations is very broad. They include technologically oriented methods (e.g.

risk assessments), economically oriented methods (e.g. cost analyses), politically oriented methods (e.g. voting procedures), systematic considerations (e.g. cost-benefit analyses), and methods based on systems theory (e.g. scenario techniques) [13]. IEK-STE pursues a systems analysis approach here, which focuses on the interdependencies between technologies and their associated fields in the economy, environment, and in society, and is mainly based on quantitative modelling (Fig. 2).

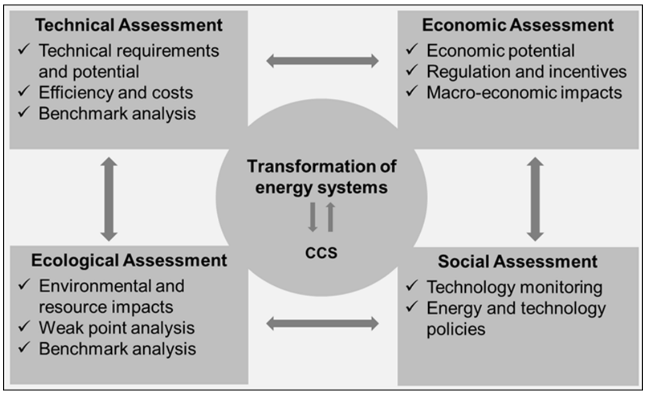

Figure 2: Methodological approach of an Integrated Technology Assessment of CCS

Our approach consists of 5 steps:

1. Criteria selection and indicator identification: Before CCS can play a decisive role in the process of implementing strategies to mitigate climate change, there are a number of key criteria that must be fulfilled. However, simply fulfilling these requirements may not necessarily be enough to guarantee the success of CCS because of the possible development of competing technologies aiming to reduce CO_2 emissions (e.g. renewables, energy efficiency).
2. Indicator level information gathering: Information on the level of indicators may result from own studies. Nevertheless, a literature review necessarily completes the basis.
3. Indicator level quantification and normalization of results: We prefer quantification of indicators as far as possible. Even if this is possible, indicators may have different units, such as ton CO_2, %, or EURO. Using normalization approaches, indicators can be translated to dimensionless ones, therefore facilitating comparison.
4. Indicator weighting: Indicators may have equal or different weights. E.g., environmental indicators may be regarded more important than others, resulting in relatively stronger weights. In other cases, this holds e.g. for economic or societal indicators.
5. Indexing: Combining individual indicators to form a composite indicator for technology assessment methodologically supports decision-making, although this may not be regarded to substitute careful interpretation of any individual indicator result.

III. CRITERIA, INDICATORS, AND INFORMATION GATHERING

3.1. CRITERIA SELECTION/INDICATOR IDENTIFICATION

The challenges affect all areas of an integrated technology evaluation from the technical, economic, and environmental aspects right up to the social aspects. They comprise:

- demonstration on an industrial scale and commercial availability
- environmental and safety requirements
- cost efficiency and economic viability
- coordination of energy and climate policy
- public acceptance

3.2. INDICATOR LEVEL INFORMATION GATHERING

In our case main information is from several chapters of [14] which is based on own studies and extensive literature review.

DEMONSTRATION ON AN INDUSTRIAL SCALE

According to *Markewitz and Bongartz* [15], all three technology lines have great potential to improve efficiency depending on the processes involved, although the energy penalties remain considerable. In all cases, the thermodynamic integration of the carbon capture process is particularly challenging. Interesting options exist in the long term for replacing the currently favoured physical or chemical scrubbing. Alternatives here include the use of membranes as well as carbonate looping. For the oxyfuel process, the cryogenic air separation process could be improved (three-column process), and the transition to other oxygen production processes (use of membranes, chemical looping) is also possible.

Increasing the flexibility of coal-fired power plants with and without carbon capture is one of the main challenges from a technical perspective, because an increasingly volatile feed-in of electricity into the grid will place much greater demands on the flexibility and mode of operation of power plants (e.g. higher load ramps, greater load ranges, more start-up and shut-down cycles). How well CCS power plants will be able to meet these demands is a question that cannot be answered at the moment. From a technical point of view, a basic power plant process with the highest possible efficiency is generally considered essential. The necessary significant increase in efficiencies in the basic power plant process, however, can only be achieved using ambitious live steam parameters (temperature and pressure), which in turn has negative impacts on flexibility.

It is generally assumed that CCS technology will be commercially available from 2020 at the earliest. Against the background of planned fossil-fired power plants worldwide, retrofitting with carbon capture technologies will play a particularly important role. At the moment, post-combustion appears to be the most promising technology line for retrofitting. A big advantage compared to other technology lines is that the modification of the power plant process would not involve too much effort. With respect to timely commercial availability, the current delays in investing in demonstration power plants are counter-productive.

Industrial processes (e.g. iron and steel, as well as cement production and refineries) often involve large CO_2 point sources. There is a range of options for the use of carbon capture for these processes. In the long term, considerable technical potential in Germany is seen specifically for blast furnaces, ammonia synthesis, and clinker production [16].

At present, the global contribution of the industrial utilization of CO_2 to combating climate change is quite low at 130 million tCO_2, but there is potential for improvement. Moreover, the use of CO_2 in the past for organo-chemical and inorganic applications was mainly based on industrial sources, where CO_2 is created as a joint product or an emission. Putting CO_2 to use is becoming more important from an industrial policy point of view, because CO_2 can be used as a cheap raw material, and when large amounts are needed, it can also be obtained from CCS sources. There are many possible ways of using CO_2, which should be analysed in detail with respect to their climatic relevance and their value-added potential. As global carbon emissions are increasing and will continue to do so in future, it can be assumed that the utilization of CO_2 will not replace carbon storage but will supplement it.

The relevance of utilizing CO_2 motivated by industrial policy for climate change mitigation not only depends on the amount itself, but also on the duration of CO_2 fixation [17]. The fixation potential varies widely depending on the use of CO_2 and is calculated based on the combination of small to large quantities and short to long durations of fixation. At the same time, attention should be paid to whether the activation or utilization of CO_2 requires the use of other resources or energy that would interfere with the balance of CO_2. In addition, there is a need to clarify whether the use of CO_2 from CCS sources substitutes another source that would not require geological storage. The best method for analysing the entire energy and CO_2 balance is the life cycle assessment – an established approach for evaluating the environmental impacts of processes and products. However, in practice, conclusions can only be drawn separately for each use of CO_2.

ENVIRONMENTAL AND SAFETY REQUIREMENTS

Carbon capture technologies often lead to amplification of other environmental effects [18]. The rise in other environmental effects is usually triggered by the decline in net efficiency, and the related additional requirements for fuels and chemicals (e.g. scrubbing substances), as well as increased volumes of waste. A detailed analysis of the reasons shows that optimizing the reduction of power plant emissions is in itself not enough to prevent this increase. In particular, the provision of fuel often involves a high proportion of different environmental impacts. If scrubbing substances are additionally used, the human toxicity and ecotoxicity potential rises mainly because of emissions during production. Heavy metal emissions during the dumping of hazardous waste and ash also contribute to increased toxicity. A comparison of the studies shows that the processes of the upstream and downstream chains are often not represented in the same detail as the electricity generation and subsequent carbon capture processes. These processes should therefore be investigated in more detail.

A consideration of the entire life cycle also shows that there may be local or regional environmental effects upstream. While acidification and eutrophication are reduced at power plant sites, they increase in regions where the fuel is extracted and along transportation paths.

Furthermore, a comparison with the overall effects of a region helps to relate different impacts to each other. The desired effect of reducing greenhouse gas emissions is obvious. However, more detailed consideration must be given to emissions promoting acidification and human toxicity, especially for post-combustion plants. The most important method of reducing the majority of environmental impacts is reducing efficiency losses. New technological developments, such as membranes, are promising. Nevertheless, further analyses with a detailed description of the system boundaries and the parameters are required in order to provide robust information on the respective environmental impacts of the different technologies.

Essential safety requirements concern transportation and storage activities. Pipelines are particularly interesting for transporting large amounts of CO_2 over long distances. At present, CO_2 pipelines throughout the world have a total length of more than 4000 km. The transportation of carbon dioxide is state of the art.

The release of large amounts of CO_2 can pose local risks to humans and the environment. As CO_2 is heavier than air under ambient conditions, it can collect in sinks for example, and at very high concentrations (7–10 vol.%) it can pose a life-threatening danger. Comparisons of natural gas and CO_2 pipelines show that the frequency of failures is similar. The purity of the CO_2 stream is particularly relevant for protection against corrosion. Experience with the standards in the USA can only be transferred to the European situation to a limited extent. With respect to impurities, the captured CO_2 stream in power plants is very different to the volumes of CO_2 currently transported in the USA.

Bongartz et al. [19] summarized risk assessments using probabilistic approaches. Frequencies of occurrence were assumed for the different scenarios and used as a basis for determining the ranges of critical CO_2 concentrations. The available studies were used to qualitatively evaluate the categorized transportation risks (e.g. valve leakage, leak, rupture) in terms of frequency and range of critical CO_2 concentrations with the aid of a risk matrix (frequency classes, hazard classes). The findings show that the majority of risks associated with transportation are either insignificant or very small.

Reservoir rocks with the potential for geological storage are mainly sandstones, as they are characterized by sufficient porosities and permeabilities, allowing CO_2 to be injected efficiently into these formations. Overall, four retention mechanisms in the layers of the storage formation facilitate permanent and safe storage: (i) structural retention below an impermeable caprock, (ii) immobilization via capillary binding in pore space, (iii) dissolution of CO_2 in the formation water, and (iv) mineral binding via carbonization.

Near the town of Ketzin on the Havel in Brandenburg, the first continental European field laboratory for CO_2 storage was set up and put into operation as a pilot site in 2004. The pilot site in Ketzin is thus the first and to date the only active CO_2 storage project in Germany. The injection of CO_2 is accompanied by one of the most extensive scientific research and development programmes in the world. The findings on a research scale [20] show that: (i) the geological storage of CO_2 at the pilot site in Ketzin is safe and reliable, and poses no danger to humans or the environment, (ii) a well-thought-out combination of different geochemical and geophysical monitoring methods can detect minute amounts of CO_2 and image its spatial distribution, (iii) the interactions between fluid and rock induced by CO_2 injection at the pilot site in Ketzin have no significant impacts and do not influence the integrity of the reservoir rock or the caprock, and (iv) numerical simulations can depict the temporal and spatial behaviour of injected CO_2.

COST EFFICIENCY AND ECONOMIC VIABILITY

Martinsen et al. [21] use an energy system model to estimate the monetary value of CCS technologies in Germany within the framework of greenhouse gas reduction scenarios (‘system value’ in the following). This value is determined here by the additional avoidance costs that would be incurred if climate change mitigation targets were to be achieved without CCS technologies. It is therefore an implicit measure of the level of willingness of society to pay for refraining from the use of CCS technologies.

The actual present value of the costs avoided by deploying CCS technologies for the period 2005–2050 is approx. $€_{2010}$ 100 billion. The value is calculated by balancing across all sectors (end-use, conversion, primary energy incl. imports). In the end-use sectors (industry, households, traffic and transport, commerce, trade and services), relatively expensive savings measures can be avoided if CCS is implemented in the conversion sector. In the same way, the primary energy sector including imports also plays a role, where most of the additional costs associated with the import of biomass products (e.g. bioethanol) are avoided when CCS is implemented, but additional costs are incurred for fossil fuels, which predominate until 2035. Despite the costs caused by CCS technologies, the conversion sector also contributes to the system value because an additional increase in renewable energy capacity is avoided. Overall, this applies to all sectors but the extent is very different.

The construction of CCS facilities represents an investment with long-term and high capital tie-up. In addition, the projections of the plant costs for CCS power plants still involve uncertainties, despite the continuing development of demonstration facilities. Increased knowledge and ongoing technological development lead to the investment costs of the first commercial CCS plants being predicted as 70–90 % higher than those of conventional plants. The costs for the transportation and storage of CO_2 depend on the quantities to be transported, the transport distance, and the type and location of the geological storage facility, and they vary considerably. In all cases, the costs of capturing CO_2 dominate.

Even high plant utilization gives rise to much higher electricity generation costs, particularly for coal-based CCS plants (lignite: +80 %) [22]. The CO_2 avoidance costs are € 34–38/tCO_2 (lignite), € 41–48/tCO_2 (hard coal), and approx. € 67/tCO_2 for natural gas plants. Only if the price of allowances rises to the same level will the use of CCS power plants during normal operation be cost-effective.

A very low number of full-load hours tends to cause the CO_2 avoidance costs to double. As a result, a relatively high CO_2 price would be necessary to justify operation with a low number of full-load hours.

CCS power plants must be refinanced through the electricity market. Furthermore, the use of CCS power plants can have an effect on the price of electricity on the wholesale market under certain conditions. The price on the electricity market is determined by the costs of the last power plant used, whereby the power plants are used in order of their marginal costs (merit order) and the costs for electricity imports must be considered.

In general, the question arises as to the degree to which potentially higher revenues due to merit order effects cover the additional investment costs for CCS power plants. Owing to the high uncertainties with respect to the additional investment costs, it can be assumed that CCS plants will only become interesting to investors when the allowance price is at least € 40/tCO_2. Development in the area of renewable energy must also be considered. The increased use of renewables will lead to a decrease in the average annual price on the electricity market as long as sufficient ‘cheap’ back-up capacities are available, i.e. power plants with low operating costs. In addition, merit-order effects arise where the use of CCS also dampens the price of electricity. Merit-order effects also tend to boost the level of domestic production. It should be noted that this could cause reciprocal effects. Price effects caused by the increased use of renewable energy will make it more difficult to refinance CCS power plants, and the electricity price effects of CCS power plants will reduce the revenues for renewable energy (which in turn impacts on the level of Renewable Energy Act (EEG) surcharges).

If renewable energy is further integrated into the electricity system, with the current market design (‘energy only’) there is a danger that the power plant capacities of an existing fleet will be potentially underused. In addition to the generation cost effect caused by a low number of full-load hours, the drop in residual demand would lead to a merit order effect. As a result, there would be a short-term cost recovery problem for fossil plants in the installed power plant fleet. Regardless of the possible concrete design of capacity markets, the comparatively high refinancing needs compared to conventional power plants will prevail if capacity revenues are incorporated.

The use of CCS as a CO_2 mitigation measure for industrial plants is technically feasible in principle, but neither demonstration nor commercial CCS plants are currently in operation on the industrial scale. As a result, estimates for plant costs continue to be associated with great uncertainties.

A cost analysis of a cement plant with a capacity of 1 million tonnes of cement per year shows an increase of 32 % in production costs when oxyfuel technology is used [23]. In the case of carbon capture with post-combustion technology, production costs increase by about 100 %. Retrofitting an oil refinery with a capacity of 10 million tonnes of crude oil per year with oxyfuel technology leads to an increase of roughly 15 % in processing costs. This results in CO_2 avoidance costs of about € 55/tCO_2 for the oxyfuel cement plant, and about € 62/tCO_2 for the oxyfuel refinery. Avoidance costs are much higher for the cement plant with post-combustion capture (€ 143/tCO_2).

COORDINATION OF ENERGY AND CLIMATE POLICY

The policy-making process anchoring CCS as a climate change mitigation option in the EU was executed at a remarkable speed [24]. Faced with two options – the mandatory introduction of CCS or the development of a framework for the industrial implementation of CCS – the EU institutions decided in favour of the second option. Between 2005 and 2009, European institutions successfully established CCS as a cornerstone of the EU’s integrated energy and climate policy, developed a legal framework for geological storage, incorporated CCS into the European emissions trading system, and elaborated funding instruments for CCS. This dynamic momentum makes the EU one of the pioneers internationally. Despite this, feedback with respect to the implementation of CCS policy is less positive. The implementation of the CCS Directive reveals the lack of consensus on whether CCS should be used as an option for combating climate change. Today, some European countries, such as Austria, are completely against carbon storage.

The emissions trading system (EU ETS) and the demonstration programme (EEPR, NER300) are instruments that support CCS. However, the majority of companies are hesitant to invest in demonstration projects at the moment. The role of NER300 financing as one of the main instruments supporting CCS demonstration projects in Europe is being increasingly questioned in this context. The instrument attracted criticism from the very beginning because of the uncertainty regarding the price level of allowances. Pessimistic expectations were confirmed by initial experiences trading the allowances. The low price for emissions allowances also ignited discussions on the competitiveness of CCS technology after the demonstration phase. Long-term incentives are decisive for a stable development of low-carbon technologies. Within the scope of these instruments, an EU ETS cap, a carbon tax, and a bonus-malus system are being discussed as part of a carbon standard.

Attitudes towards CCS as a climate change mitigation option have undergone rapid development over the last ten years from initial euphoria to cautious restraint [26]. The development of international cooperation reflects these changes. The recognition of CCS as a potential method for combating climate change with the publication of the IPCC Special Report was accompanied by the establishment of several international organizations and new priorities in existing collaborations. The G8, IEA, and Carbon Sequestration Forum (CSLF) aim to facilitate the timely commercialization and demonstration of CCS.

However, the period between 2008 and 2010 is characterized by the discontinuation of several internationally important CCS projects. This means that the G8’s aspiration of initiating 20 integrated demonstration projects worldwide by 2010 was not met. Despite approaches, such as the recognition of CCS demonstration projects by the CSLF or the creation of the Global Carbon Capture and Storage Institute (GCCSI) in Australia, no international cooperation has succeeded in furthering the demonstration of CCS. A decisive prerequisite has yet to be implemented – the introduction of a sufficiently high CO_2 price in the main emitter countries.

Germany’s CCS Act, for example, shows that there is neither consensus on a national prohibition nor on the demonstration of the commercial application of CCS. The answer to the question of whether CCS is an option for Germany for reducing CO_2 emissions has been pushed into an uncertain future by the Act [27].

Compared to the first bill in 2009, the adopted CCS Act has shrunk to a research law with a theoretical potential for smaller demonstration projects which will probably not be exploited in Germany. If the potential of CCS should be demonstrated for large power plants or for industrial plants, the Act would have to be amended with respect to the storage amounts. In 2017, the CCS Act will be evaluated, and the discussion on CCS could become heated once again.

A minority of explicit political advocates of CCS hope that suitable energy economy and European framework conditions will emerge in future. The advocates include the state governments of Brandenburg, Saxony, and Saxony-Anhalt. In North Rhine-Westphalia, where in 2010 around 54 % of German lignite was mined, the last word has yet to be spoken on lignite policy and thus indirectly on the implementation of CCS.

A clearer picture will emerge over the next few years as to whether the targets for expanding the capacity of renewables will be achieved and how smooth the transformation of the energy system will be [28], what role coal in general and lignite-fired base-load power plants could play, and how emissions trading and its CO_2 prices (EU ETS) will develop. Should it emerge that the EU and its member states are not in a position to implement their extremely ambitious action plan for CO_2 mitigation politically or economically, e.g. because international climate change mitigation goes along with the less demanding willingness of states to act to mitigate CO_2 (bottom-up), the perspectives for CCS could become more clouded. The EU’s CCS policy could also have an impact, e.g. possible additional CCS regulations, making CCS mandatory for new as well as for old power plants. CCS plays a key role in the EU plan for a low-carbon economy in 2050 [29] and the more specific 2050 Energy Roadmap [30], even though commercial application is not expected until after 2030 and

CCS projects are not progressing well in the EU member states.

Another obstacle for CCS is the lack of acceptance for the solution of the ‘back-end’ CCS problem, namely storage. The northern federal states in Germany will pull out all the stops to block even potential storage projects. This problem might be less virulent if CO_2 were to be stored below the seabed (off-shore), particularly within the context of enhanced oil/gas recovery. Research work is being conducted on storage in deep ocean sediments, the safety of such sites, and on the consequences of leaks for the marine environment, which also includes regions off the German coast. It remains to be seen whether a ‘loophole’ [31] will emerge for federal storage projects below the seabed. That CCS opponents take this option seriously is reflected in the coalition agreement of the new state government in Schleswig-Holstein: it wants to ‘preclude’ CCS ‘for the whole of Germany – particularly in the exclusive economic zone.’ [32]. For this reason, should a European CO_2 transportation infrastructure be created, CO_2 could be exported to onshore storage sites in other countries or injected into their deep ocean sediments. The statements issued in response to the legislative compromise indicate an interest in this option in sections of the political and industrial arenas. Assuming that there is interest in carbon capture in Germany and that the respective transportation infrastructure existed, then the acceptance of CO_2 pipelines through the federal states would also have to be ensured – considering the massive opposition to the planned Hürth pipeline in 2008, this represents a huge challenge for politics and society. It may be mastered if CCS were to be considered independently of lignite and if it were to become an integral part of a comprehensive strategy for a low-carbon society that would bring advantages with it for citizens, the economy, and the environment. Within the framework of the Rotterdam Climate Initiative,[1] an attempt is being made to implement this strategy. Germany can learn from this social experiment.

PUBLIC ACCEPTANCE

The acceptance of technologies cannot yet be reliably measured because the population still knows too little about CCS technologies [33]. CCS acceptance research therefore focuses on investigating awareness and knowledge of CCS as well as spontaneous attitudes towards it among the general public. Such studies also concentrate on identifying factors that have an impact on spontaneous attitudes towards the technologies as well as on analysing the impact of information and methods of communication on changes in and the stability of spontaneous attitudes.

With respect to how well known CCS is among the general public, the findings of international and national studies confirm that at least awareness of the concept of ‘carbon capture and storage’ has increased considerably over the course of time. The increasing awareness of the concept of ‘carbon capture and storage’, however, is not accompanied by an increase in knowledge of the technologies. As the findings of international and national studies show, misconceptions about CCS (still) abound among the general public. This can be explained by the fact that lay people often find it difficult to distinguish between environmental problems, such as ozone depletion, global warming, acid rain or smog.

In addition, information on CCS and the communication of CCS should consider the fact that citizens have spontaneous attitudes towards the technologies even though they know little or nothing about CCS. In Germany, these spontaneous attitudes towards CCS are on average (still) mainly neutral, although women are more sceptical of the technologies than men.

The regional differences in spontaneous attitudes before and after the receipt of information demonstrate that citizens of Schleswig-Holstein do not only have more negative attitudes towards CCS than citizens of the region along the Rhine or of the ‘rest’ of Germany, but that the debate surrounding carbon storage in Schleswig-Holstein has already led to the emergence of negative attitudes towards CCS in this region which are not necessarily spontaneous attitudes any more but rather stable opinions. As the present findings also suggest, these negative attitudes in Schleswig-Holstein are mainly related to the fact that citizens here consider the personal risks associated with carbon storage to be much greater than citizens of the other regions.

However, the results also illustrate that spontaneous attitudes towards CCS in all regions are most heavily influenced by the perception of the social benefits of the technologies and that this influence is positive: the greater the social benefits of CCS, the more positive the spontaneous attitudes towards the technologies.

How stable these perceptions of the benefits of CCS are or how easily they can be changed by new information cannot be conclusively analysed using the present findings as a basis. The influence of information on the perception of the benefits of CCS, as well as the influence of the perception of benefits on the stability of attitudes towards CCS, must therefore be systematically investigated in future studies in order to assess the importance of the perception of benefits as an indicator for evaluating the future public acceptance of CCS in Germany.

At the moment, the lack of acceptance for the solution to the ‘back-end’ problem associated with CCS, namely storage, in the northern federal states is blocking all potential storage projects. Policies and legislation on CCS in Germany clearly reflect this negative stance, even if CCS is emphasized as a (necessary) option for energy-intensive and carbon-intensive industries.

3.3. KEY CONCLUSIONS

The preceding deliberations explain the challenges considered to be most important for technology evaluation. What big picture emerges? What is the success factor like as a whole? And how sensitive is the result with respect to the separate challenges?

The greatest success factor applies to the safety requirements for the transportation and storage of CO_2. The assessment of the environmental requirements from a life

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[1] http://www.rotterdamclimateinitiative.nl.

cycle perspective, however, is cause for concern in that the envisaged reduction in the global warming potential may lead to other environmental impacts, such as eutrophication, and thus induce regional shifts in environmental impacts. With a view to public acceptance, no conclusions can be drawn at this point because the public does not yet know enough about CCS technologies. Irrespective of this, the public still forms opinions on CCS technologies, which are characterized by the negative attitudes, e.g. in the northern federal states where potential storage sites are located. This negative attitude is also reflected in the national CCS Act, which does not permit commercial storage of large quantities of CO_2. Implementation on an economic and industrial scale has not yet been demonstrated in Europe despite EU financial incentive systems. As a result, commercial availability is not likely in the near future. Compared to the CO_2 avoidance costs of other large technical options, those of CCS technologies are average, but the electricity generation costs increase rapidly and incentives to invest in the technologies are not enough. The price of CO_2 is currently low and the number of full-load hours is dropping due to the increasing integration of renewable technologies, which means that refinancing the high investment costs is too uncertain in today's market design. With respect to political factors, the outcome of the overall evaluation is negative. The EU appears to be an institutional driving force for CCS technologies, promoting them in its energy, climate, and technology policy. However, this is not as successful as it may appear. Internationally, the euphoria surrounding CCS has dissipated, and CCS advocates in Germany (such as those in individual state governments) can only hope for improvements in future. Should climate change mitigation in Germany prove to be insufficient using the options currently preferred within the framework of the transformation of the energy sector, there may be a re-evaluation of CCS in Germany. Even though none of this can yet provide a decisive answer to the question of whether CCS has a future in Germany or not, the economic climate combined with the political and social balance of power imply that CCS is doomed to failure.

IV. COMPOSITE INDICATOR

Methodologically, an approach used by the OECD for a composite indicator and applied in its technology evaluations is taken here [34]; it combines individual indices to form an overall index.

$$I = \sum_{i=1}^{n} w_i * x_i \qquad (1)$$

$$\sum w_i = 1; \;\; 0 \leq w_i \leq 1 \qquad (2)$$

with I: overall index, x_i: individual index, w_i: weighting factor for index I, and n: number of indices.

4.1. NORMALIZATION AND WEIGHTING

First, each criterion (= individual index) is assigned a success factor *x* on a scale of 1 to 5. The lower the scale value, the worse the technology assessment with respect to the criterion is. Conversely, the higher the scale value, the better the assessment (TABLE 1).

Based on expert interviews at IEK-STE criterion (2) 'environmental and safety requirements' is most successfully fulfilled (rating of 3.00), although 3.00 does not even come close to achieving the maximum, and criterion (5) 'public acceptance' (rating of 1.32) least successfully. Criterion (1) 'demonstration, commercial availability' was also evaluated relatively positively (rating of 2.84), while (3) 'cost efficiency and economic viability' fared poorly with a rating of 1.86.

TABLE 1, EXPERT RATING AND WEIGHTING OF THE INDICATORS

Criterion	Expert rating	Priorities and Weighting			
		Equal	Environment	Economy	Society
1. Demonstration, commercial availability	2.84	0.2	0.125	0.125	0.125
2. Environmental and safety requirements	3.00	0.2	0.5	0.125	0.125
3. Cost efficiency and economic viability	1.86	0.2	0.125	0.5	0.125
4. Coordination of energy and climate policy	2.21	0.2	0.125	0.125	0.125
5. Public acceptance	1.32	0.2	0.125	0.125	0.5

Furthermore, weightings w are introduced to account for the fact that the criteria could affect the overall assessment in different ways. The sum of the weighting factors is always 1. The case where the criteria are weighted equally is analysed as the base case. It implicitly exists whenever – supposedly – weighting is not used. The chosen methodology means that the overall index can have values between 1 and 5. Additionally, cases are introduced, focusing either on environmental, economic, or societal foci by giving them more weight (0.5). In order to fulfil formula 2, in these cases the corresponding criteria have lower weights because of formula 2.

Fig. 3 shows the contribution of individual indices to the results based on different weightings. Observed from different perspectives (equal weighting or weighting foci) the results differ and are not easily comparable. However, the results support the interpretation that the attractiveness of CCS technologies is mainly influenced by criterion 2, 3, or 5, depending on the weighting focus. In case the weighting focus is on environment, then criterion 2 (environmental and safety requirements) is of main importance. In our case, the result is due to the relative optimistic expert rating of criterion (2) 'environmental and safety requirements' (rating of 3.00 of 5.00 maximum).

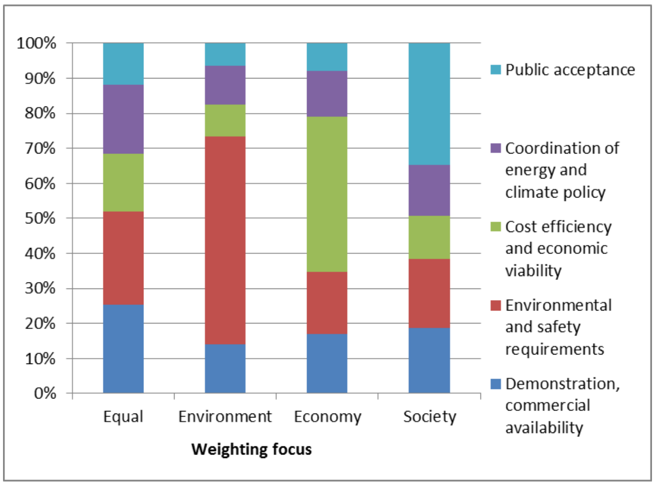

Fig. 3, Relative importance of individual indices based on different weighting foci.

4.2. OVERALL INDEX

In order to fully support the OECD approach of technology assessment a composite indicator was calculated based on formula (1). The calculations result to indices for the four weighting cases (Fig. 4). The CCS technologies indeed are most attractive if the weighting focus is on environmental perspective, followed by the equal weighting concept. The technologies are less attractive if societal concerns are in the foreground. Fig. 4 also shows that the index even in the best case is far less than the possible maximum 5.

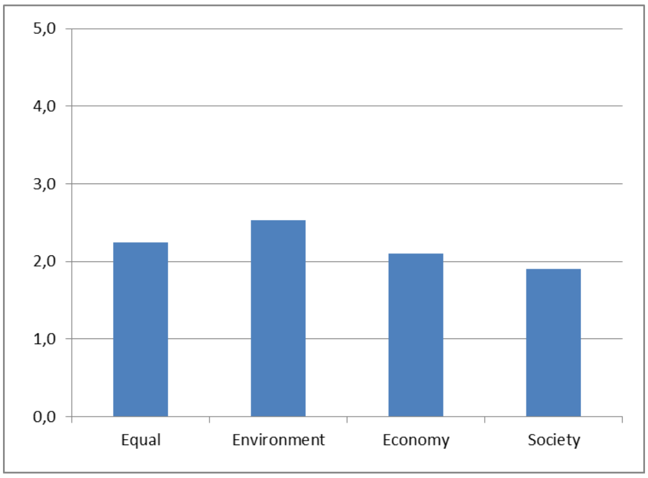

Fig. 4, Composite indicator based on different weightings.

V. CONCLUSIONS

The aim of the paper was to analyze the potential and the possible role of CCS technologies as an option for reducing emission of energy-related CO_2. Methodically, the paper is based on Integrated Technology Assessment, for which the OECD approach of a composite index for assessing technologies is used. The chosen approach needs 5 steps: (1) criteria selection and indicator identification, (2) indicator level information gathering, (3) indicator level quantification and normalization of results, (4) indicator weighting, and (5) aggregation to a composite index.

For this approach, 5 criteria are identified: (1) demonstration on and industrial scale and commercial availability, (2) environmental and safety requirements, (3) cost efficiency and economic viability, (4) coordination of energy and climate policy, and (5) public acceptance. For weighting, 4 cases are tested: (1) equal weighting, (2) environmental focus, (3) economic focus, and (4) societal focus.

The results support the interpretation that CCS technologies may be regarded an attractive option if the focus is on environment. In our case, the result is due to the relative optimistic expert rating of criterion (2) ‘environmental and safety requirements’ (rating of 3.00 of 5.00 maximum). The composite index indeed shows that CCS is most attractive from an environmental perspective, followed by the equal weighting concept. CCS technologies are less attractive if societal concerns are in the foreground. In the case of Germany, it is mainly the level of public acceptance that fails to support CCS.

REFERENCES

[1] S. Pacala and R. Socolow, "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies," *Science*, vol. 305, pp. 968-972, 2004.

[2] IEA, *World energy outlook 2009*: International Energy Agency IEA/OECD, Paris, 2009.

[3] IEA, "Energy technology perspectives - scenarios & strategies to 2050," OECD/IEA, Paris2010.

[4] IEA, *World energy outlook 2011*: International Energy Agency OECD/IEA, Paris, 2011.

[5] IEA, "World energy outlook 2012," IEA, ParisNov 16, 2012 2012.

[6] N. Stern, "Stern review: The economics of climate change," London, http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/stern_review_report.htm, 21.06.20122006.

[7] IEA, "Energy technology perspectives 2012," IEA, Paris2012.

[8] IEA, "Energy technology perspectives - scenarios & strategies to 2050," International Energy Agency IEA/OECD, Paris2008.

[9] IEA, "Energy technology transitions for industry," International Energy Egency IEA/OECD, Paris2009.

[10] J. Gale, "Challenges and opportunities of CO_2 capture and storage for the iron and steel industry," IEA GHG, London2012.

[11] M. Peters, B. Köhler, W. Kuckshinrichs, W. Leitner, P. Markewitz, and T. E. Müller, "Chemical technologies for exploiting and recycling carbon dioxide into the value chain," *ChemSusChem, Special Issue: Carbon Dioxide Recycling*, vol. 4, pp. 1216-1240, 2011.

[12] F. Ausfelder and A. Bazzanella, "Verwertung und Speicherung von CO_2," DECHEMA, Frankfurt2008.

[13] O. Renn. (2010, Methoden und Verfahren der Technikfolgenabschätzung und der

Technologiebewertung. Available: www.elib.uni-stuttgart.de/opus/volltexte/2010/5286/pdf/ren2.pdf

[14] W. Kuckshinrichs and J.-F. Hake, (Eds.), *Carbon capture, storage and use. Technical, economic, environmental and societal perspective*. Dordrecht: Springer, 347 pages, 2015.

[15] P. Markewitz and R. Bongartz, "Carbon capture technologies," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 13-45.

[16] McKinsey, "Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland - Sektorperspektive Industrie," Mc Kinsey&Company, Inc.2007.

[17] T. E. Müller, W. Leitner, P. Markewitz, and W. Kuckshinrichs, "Opportunities for utilizing and recycling CO_2," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 67-100.

[18] A. Schreiber, P. Zapp, and J. Marx, "Environmental aspects of CCS," in *Carbon capture, storage and use*, pp. 147-171.

[23] J. Fleer and W. Kuckshinrichs, "Cost analysis for CCS in selected carbon-intensive industries " in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 173-182.

[24] O. Schenk and J.-F. Hake, "CCS policy in the EU: Will it pay off or do we have to go back to square one?," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 287-309.

[25] ZEP. (2011, Juni 29). *CCS state of play, Dr. Graeme Sweeney, Chairman, ZEP & EVP, CO_2, Royal Dutch Shell*. Available: http://www.zeroemissionsplatform.eu/events/details/136-zepga2011.html

[26] J.-F. Hake and O. Schenk, "International cooperation in support of CCS," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 311-327.

[27] W. Fischer, "No CCS in Germany despite the CCS Act?," in *Cabon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 255-286.

[28] K. Mikulcak, "German government backtracks on the Energy Transition," *European Energy Review, 12 July 2012,*

W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 101-126.

[19] R. Bongartz, J. Linssen, and P. Markewitz, "CO_2 transportation," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 47-65.

[20] M. Kühn, A. Liebscher, S. Martens, F. Möller, T. Kempka, and M. Streibel, "Safe operation of geological CO_2 storage using the example of the pilot site in Ketzin," in *Carbon capture, storag and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 127-143.

[21] D. Martinsen, H. Heinrichs, P. Markewitz, and W. Kuckshinrichs, "The system value of CCS technologies in the context of CO_2 mitigation scenarios for Germany," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 201-220.

[22] W. Kuckshinrichs and S. Vögele, "Economic analysis of carbon capture in the energy sector," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015 *http://www.europeanenergyreview.eu/site/pagina.php?id=3799#artikel_3799*, 2012.

[29] European Commission, "A roadmap for moving to a competitive low carbon economy in 2050," Brussels, Communication from the Commission, COM/2011/0112 final, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT2011.

[30] European Commission, "Energy roadmap 2050," European Commission, Brussels, COM(2011) 885 final, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0885:FIN:EN:PDF2011.

[31] CO_2 Handel. (2011). *Bund schafft sich Schlupfloch im CO_2-Speichergesetz.*

[32] SPD/Grüne/SSW, "Bündnis für den Norden. Koalitionsvertrag 2012 bis 2017," Kiel, http://www.sh.gruene.de/cms/default/dokbin/411/411582.koalitionsvertrag_spd_buendnis90die_grue.pdf2012.

[33] D. Schumann, "Public acceptance," in *Carbon capture, storage and use*, W. Kuckshinrichs and J.-F. Hake, Eds., ed Dordrecht: Springer, 2015, pp. 221-251.

[34] OECD, *Handbook on constructing composite indicators*. Paris: OECD http://www.oecd.org/std/leadingindicatorsandtendencysurveys/42495745.pdf, 2008.