CO_2 Capture and Sequestration in Germany: Status and Perspectives

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1. Introduction

The Kyoto Protocol to the Climate Convention established binding agreements for the reduction of greenhouse gas emissions. With this Protocol developed countries agreed to reduce their emissions to 5.2% below 1990 levels over the period 2008-2012. Many countries are considering various mitigation options because a rapid move towards fossil-free energy carriers is unlikely. In the context of mitigation of climate change CO_2 capture and sequestration (CCS) represents a technological route to neutralize CO_2 emissions whilst continuing to use fossil fuels. Necessarily, CO_2 has to be stored for hundreds or thousands of years. Therefore, CO_2 capture and sequestration is regarded to be an option bridging the gap from a fossil fuel economy to a fossil-free economy. Presently, CO_2 capture technology is under development. Besides biological and ocean sequestration the potential of geological structures suitable for sequestration is being explored.

CO_2 capture is only suitable for large point sources like power plants. In principle there are a lot of technology options capturing CO_2. But actually there is no technology available for commercial operation of large power plants. Thus a lot of R&D effort is still needed with the goal to select the most attractive options and to make them available for commercial operation.

In the past, geological sequestration has attracted comparably less attention but is now starting to become an attractive technical option also in Germany. On the EU level, already the 5th framework program supported research on sequestration. Geological sequestration involves artificial piping or injecting into large geological structures like depleted oil and gas fields, landfills, coal seams, mines and saline aquifers. Storage capacities of saline aquifers alone are likely to be as 1.5 to 8 times as high as will be needed over the next 100 years. On the other hand there are drawbacks, reaching from high costs of CCS to environmental impacts of storage and safety problems for next generations.

The paper concentrates on CO_2 capture at power plants and geological sequestration and on its status and perspectives in Germany. In Germany, CCS is attracting increasing attention by politicians, researchers and economists after some years of thematic restraint. This is due to the increasing awareness, that on the one hand climate protection demands increasing efforts to reduce CO_2 emissions, and that on the other hand no technological option should be banned from a successful mix of technologies and economic incentives without comprehensible reasons. Therefore, the paper presents an overview on the sources of CO_2 in Germany, the electricity supply infrastructure, and storage capacities in different geological structures (chapt. 2) and discusses R&D challenges from a system analysis' perspective (chapt. 3). It describes EU policy with special consideration on R&D activities (chapt. 4) and it summarizes the status and R&D perspectives for CO_2 capture and sequestration in Germany (chapt. 5). Furthermore, it gives an overview on the CCS R&D program of Forschungszentrum Juelich (chapt. 6), concretizing its technology strategy with respect to materials research and process development, and explains how this program fits to EU and German climate change mitigation R&D policies. Moreover, it explains systems analysis' research priorities and describes the role of system analysis for policy advice with regard to CCS in Germany.

KEYWORDS: CO_2 Capture and Sequestration (CCS), CCS Technologies, Geological Sequestration, EU Policy, German R&D Perspectives for CCS, System Analysis, Policy Advice

2. Facts and Figures

2.1 CO_2 emissions

Since 1990 CO_2 emissions in Germany are steadily declining. In 2002 860 mt CO_2 were emitted, which was 16% less than 1990 (**Figure 1**). About 57% of the emissions is due to the end use sectors with industry/commerce (23%), transport (20%) and residential sector (14%). 43% of the total emissions are emitted by the conversion sector (electricity production, refineries etc.), mainly (38%) by the electricity sector, which is favorable for CO_2-capture due to its large point sources.

Figure 2 shows CO_2 neutralization by CCS technologies as part of a strategy for climate protection. Here, CO_2 mitigation measures are defined as measures, which are already part of the German strategy for climate protection. These measures comprise technical measures, e.g. energy efficiency improvements, and economic measures, e.g. ecological taxes. CCS offers technical opportunities to further reduce the impact of fossil-based power production on the atmosphere.

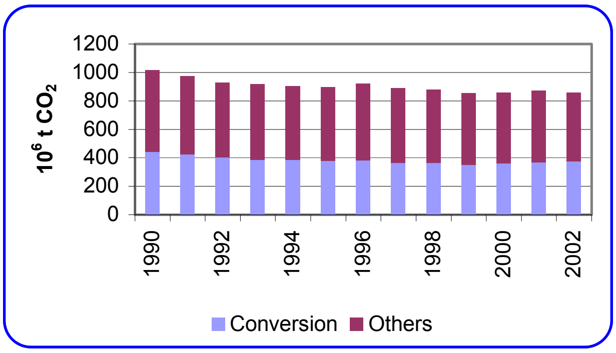


Figure 1: CO_2 emissions in Germany [Source: Ziesing 2004]

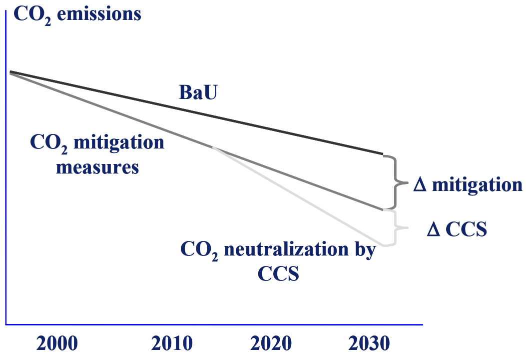


Fig. 2: CO_2 mitigation and neutralization as strategies for climate protection

2.2 Power Plant Capacity and Replacement in Germany

According to current energy forecasts, fossil fuelled power plants will continue to form the backbone of electricity worldwide until far into this century. In Europe (EU-15), the present power plant capacity amounts to about 600 GW, of which approximately 120 GW is installed in Germany.

At present, electricity production in Germany is heavily based on coal and nuclear energy, of which lignite and nuclear supply base-load energy. Approximately 50% (2003: 280 TWh) of the total electricity production is generated by coal fired power plants. The share of gas is 9%. Although the contribution of renewable energies to power supply has increased enormously during the last years due to their promotion by special feed tariffs based on the Renewable Energy Act, its share is relatively small and will remain small even with the ambitious goals in particular for wind energy.

Within the next two decades a large part of generation capacities in Germany will be closed down to two reasons [Hille et al. 2004]:

- Retirement of fossil fuelled power plants at the end of their economic/technical lifetime
- Decommissioning of nuclear power plants due to the Nuclear Power Act that regulates the phasing out of nuclear energy.

Therefore, a significant number of existing plants has to be substituted. Taking into account an excess capacity of 10 GW, and assuming a constant or slightly declining power demand and an operating time of 300,000 full-load hours, new power plants will be required earliest between 2010 and 2015 [Markewitz et al. 2002a]. Until 2030 then 40-50 GW have to be reinvested in Germany. For Europe 300,000 MW are required [Markewitz et al. 2002b].

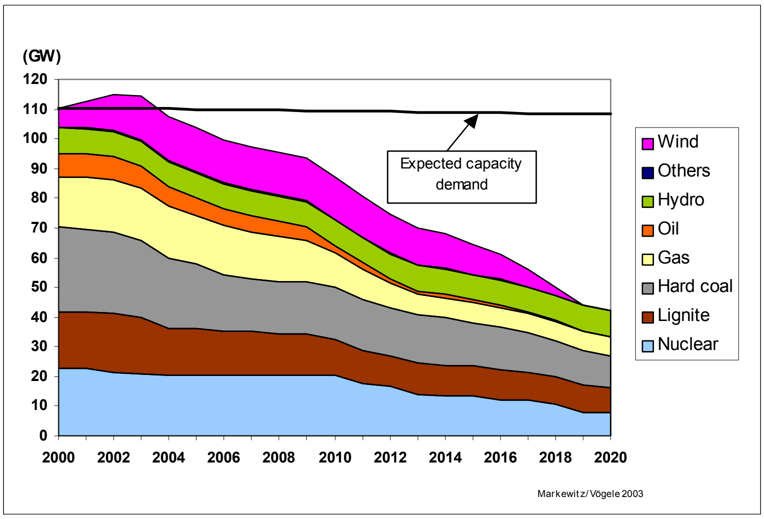


Fig. 3: Power plant mortality and capacity gap in Germany

The phase between the year of earliest requirement of new plants and 2030 may be regarded as a "window of opportunity" for CCS in Germany. Due to several reasons a prerequisite for any economic success of CCS in Germany is to install the technology within the reinvestment cycles of the power sector. This allows to implement new power plant concepts (like pre-combustion), which might be more suitable for CO_2 capture than conventional existing power plant concepts. If CO_2 capture technologies and new power plant concepts are not commercially available within the timeframe of reinvestment, more attention has to be put on retrofitting strategies.

2.3 Capacities for Storage of CO_2 in Germany

In Germany potential capacities for storing CO_2 amount to 41 Gt (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR), which equals roughly 100 years of CO_2 emissions of fossil power plants. Potential capacities comprise exhausted gas fields, deep saline aquifers, and coal seams, that cannot be economically exploited (**Table 2**).

Option	Capacity Mt	Advantage	Disadvantage	Research
Gas reservoirs	2,560[1)]	• EGR • Storing properties known • Long-term impermeability	• Impermeability/Safety of old drillings • Disturbance of gas extraction?	Experiments, numerical models and simulation of gas fields for further possibilities for EGR
Aquifers	33,000[2)]	• Widely distributed • Long term fixation of CO_2 in carbonates	• Conflict with geothermal energy recovery? • Conflict with Water Balance Act?	Potential, capacity, Experiments, leakages, speed of reaction
Coal seams	5,500[3)]	• Proximity to large emittors • ECBM	• Low injection rates due to low permeability • Conflict with future use of deep coal seams	Adsorption characteristics for CO_2 and methane, mechanical characteristics, increase of expected low injection rates
Total	41,000			

1) including reserves 2) effective capacity uncertain 3) effective capacity very uncertain

Table 2: Options for storing CO_2 in Germany [Kretzschmar 2003, COORETEC 2004, own considerations]

Further technical possibilities, i.e. oil fields and coal or salt mines are not regarded as future options in Germany, either because its technical insignificance or because safety reasons. Alternatives, such as dry-ice storage, storage in the ocean, and others do not appear to be reliable in the long term not technical feasible.

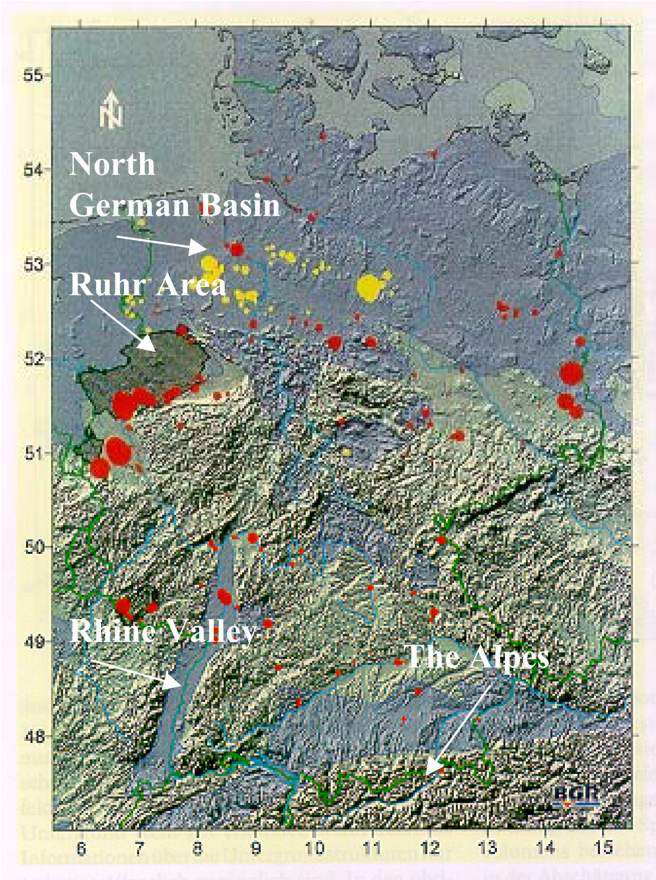
Taking into account criteria as storage capacity, storage safety, and technical and scientific experience exhausted gas fields provide the most favorable conditions for CO_2 storage in Germany [COORETEC 2004]. They are well explored and have already been exploited and the tightness of the overlying strata has been demonstrated. The possibility of enhanced gas recovery (EGR) should be given priority in research.

Due to their wide area and considerable thickness, deep salt-water-bearing aquifers represent the greatest storage potential, although this potential has not yet been explored in detail and is not yet quantifiable.

The property of coal of preferentially absorbing CO_2 rather than methane could be applied for CO_2 storage while at the same time obtaining seam gas (enhanced coal bed methane, ECBM). The application of this procedure still requires considerable R&D efforts.

Figure 4 shows a map of Germany with its main CO_2 point sources and storage options. Large point sources are located in the middle of Germany in west/east direction, nearby the North Sea and in

South-West-Germany. Gas reservoirs as the most favorable options in Germany are located in the North German Basin, whereas coals seams are located in the Ruhr Area and the Saar Area.



red: sources, blue: deep aquifers, black: coal seams, yellow: gas fields

Figure 4: CO_2 point sources and potential storage options in Germany [May et al. 2003]

3. R&D Challenges from a System Analysis' Perspective

Energy policy and the energy sector decide on the possible deployment of CCS technologies in Germany. Therefore, to be successful in a societal perspective R&D has to take into account framework conditions set by energy-economic considerations as well as by energy/environmental policy.

From an energy sector's perspective the window of opportunity for a necessary capacity substitution beginning earliest in 2010-2015 reaching to 2030 is an important framework condition. In the case CCS technologies are not competitive at that time, a power supply infrastructure will be build up without CCS and will be established for the future. R&D for CO_2 capture as well as for CO_2 sequestration are the more successful the sooner competitive technologies exist for this window of opportunity. With respect to CO_2 capture R&D for retrofit technologies for power plants may also be of interest.

The neutralization of CO_2 as a part of a strategy for climate protection has to be regarded an environmental benefit of CCS. To present the problem in its entirety it is necessary to study other environmental impacts as well. An important question is whether there is a trade-off between CO_2 neutralization and other environmental impact categories. From an environmental policy's viewpoint a full assessment of environmental impacts has to be worked out, covering all life cycle stages.

4. EU policy

With the 5th and 6th Framework Program the European Union promoted several studies on CO_2 capture and storage in geological structures. **Table 3** gives an overview about the projects and funds. The most important integrated projects of the 6th Framework Program of the European Union dealing with CCS are ENCAP, CASTOR and In-situ R&D Laboratory for Capture and Sequestration of CO_2. The overall EU funding of these projects amounts to 15 Mill € and total costs are approximately 40 Mill €. The CASTOR project addresses capture and storage of CO_2 with cleaner fossil fuel plants. The overall goal is to develop all of the innovative technologies needed to capture, at the post-combustion stage, transport and store CO_2. The goal of the ENCAP-project is to develop new pre-combustion CO_2 capture technologies and processes for power generation. It aims at technologies which meet a target of at least a 90% CO_2 capture rate and a reduction in the costs of capture of 50% compared to present. The in-situ laboratory project is addressed to potential public concerns about the safety and environmental impact of geological storage. The project aims at developing this basis by injection of CO_2 into a saline aquifer. It involves intensive monitoring of the fate of the injected CO_2 using a broad range of geophysical and geo-chemical techniques.

Study	Focus	EU Budget	EU Program
AZEP	Pre-combustion capture	3.4 Mill €	5th FP Research Capture
GRACE	Membranes	2.1 Mill €	5th FP Research Capture
ENCAP	Pre-combustion capture	*)	6th FP Research Capture
CASTOR	Post combustion capture	*)	6th FP Research Capture
GESTCO	Geological Storage of	1.9 Mill €	5th FP Research Sequestration
SACS I, II	Monitoring	1.2 Mill €	5th/6th FP Research Sequestration
RECOPOL	ECBM in Poland	1.7 Mill €	5th/6th FP Research Sequestration
Weyburn	Monitoring	1.2 Mill €	5th FP Research Sequestration
Nascent	Natural CO_2-reservoirs	1.9 Mill €	5th FP Research Sequestration
In-situ R&D Laboratory	Geological Storage	*)	6th FP Research Sequestration

*) Preliminary estimate by EU-commission: 15 Mill €

Tab. 3: EU CCS Initiatives

5. R&D perspectives in Germany

5.1 The BMWA R&D Initiative: COORETEC

Against the background of more stringent climate protection goals, R&D must also be focused on new technological processes in the sense of a precautionary concept. Even if from the present perspective these solutions will probably only become acute in the distant future, nevertheless, in view of the long lead and developing times, specific research activities should already be started today in order to have suitable options for future challenges.

The German Federal Ministry of Economics and Labour (BMWA) has taken the initiative on a new research and developing concept for realizing low carbon and zero emission power plants on the basis of fossil fuels (COORETEC: CO_2 REduction TEChnology). In order to draw up the new research concept, the Ministry has called upon all those involved, such as manufacturing industry, electricity utilities, and research institutions, to take part in order to summarize the state of the art in power generation technologies, also with respect to future development options and potentials. Approximately hundred experts from all areas of energy technology and energy research are involved in this initiative.

The COORETEC R&D-concept is based on two pillars. These are efficiency improvement of conventional technologies and the development of zero emission power plants. **Table 4** contains a short list of achievable efficiency improvements and also of the time when the respective technology will become available from the present perspective, as estimated by experts. To achieve the goals the COORETEC concept contains a detailed R&D roadmap.

Of the power plant processes currently available, the steam cycle process and the natural gas combined cycle process have achieved commercial acceptance. This can be attributed to the gradual development over a period of decades which has contributed to significantly improved efficiency and the associated CO_2 reduction. Not least due to the extensive operating experience, these two processes are ahead of all other power plant concepts in fulfilling the criteria of economic efficiency, availability and reliability. There is still considerable potential for increasing efficiency, and exploiting this potential must be given highest priority in R&D work. Of the remaining power plant processes, from the present perspective the IGCC process has by far the greatest priority with respect to development and funding. Furthermore, it also has decisive advantages over other plant processes such as pressurized pulverized combustion or pressurized fluidized bed combustion, currently largely pursued at the level of basic research, should be encouraged in an appropriate framework.

Against the background of more stringent climate protection goals, R&D must also focus on new technological approaches to meet the future challenges. This includes for example to focus R&D on hybrid power plants whose potential efficiency is very high and also capture of CO_2 in power plants. The combination of CO_2 capture possibilities and their integration into the power plant process should be the subject of future R&D activities. The development of suitable membranes (CO_2, O_2, H_2) could represent a key technology. All these measures for CO_2 capture are only meaningful if the subsequent fate of the CO_2 can be satisfactorily clarified. Future activities should therefore pay equal attention to CO_2 capture and also possibilities of further CO_2 treatment.

	Power plant process	*Today implemented*	Year of order 2010	2020	2025+
Steam cycle power plant					
1	Conventional process (Hard coal)	*47*	51	53	53+
2	CO_2-Capture from flue gas (MEA or other similar solvents)	Commercially not available	33 ... 37	39 ... 43	39+ ... 43+
3	Combustion with O_2 (Cryogenic separation, condensation of H_2O from flue gas)		38 ... 41		
4	As process Nr. 3, but air separation with membrane	Commercially not available		50+ (Demo)	
Gas combined cycle					
5	Conventional process (Natural gas)	*58*	62	65	70+
6	CO_2-Capture from flue gas with MEA or from gaseous fuel with methanol	Commercially not available	48 ... 52	51 ... 55	56 ... 60+
7	Combustion with O_2 (Cryogenic separation, condensation of H_2O from flue gas)	Commercially not available		61+ (Demo)	
Combined cycle process (Coal)					
8	Conventional process (IGCC)	*45 ... 48*	50 ... 52	54 ... 57	62+
9	CO_2-Capture from coal gas with methanol	Commercially not available	42 ... 46	47 ... 50+	50 ... 55+
10	Gasification and combustion with O_2 (based on air separation by membranes, condensation of H_2O from flue gas)	Commercially not available		53+ (Demo)	58
11	Pressurized pulverized coal combustion including combined cycle (without CO_2-capture)	Commercially not available			53+ (Demo)
12	Pressurized fluidized bed combustion (2. Generation.) (without CO_2-capture)	Commercially not available			53+ (Demo)
13	Externally fired combined cycle (without CO_2-capture)	Commercially not available			53+ (Demo)
Hydrid process					
14	High temperature fuel cell, use of waste heat in combined cycle, further option: coal gas from coal gasification	Commercially not available			60+ (Coal) 70+ (Natural gas)

Remark: Range of values are reflecting different assessments of the COORETEC working groups 3 and 4

Table 4: Potential efficiencies and availability of future power plant technology [COORETEC 2004]

5.2 The BMBF/DFG Initiative: Special Program on "Geo-Technologies"

Whereas the BMWA Initiative concentrates on electricity and fossil-fuelled technologies, the Special Program of the Federal Ministry of Education and Research (BMBF) and the German Research Association (DFG) focuses on the use of geological formations to store CO_2 [Bundesanzeiger 2003]. It aims to assess technologies to store CO_2 in underground formations as well as to develop exploration und monitoring technologies and to force prototypes for deployment.

In particular, the Program explains research demand to

- Evaluate rock layers for storing CO_2 under consideration of short-term and long-term safety aspects, especially storing capacities of deep aquifers, of oil and gas reservoirs, and of deep coal seams.
- Further develop injection and monitoring technologies, including the development of numerical models to forecast underground diffusion of CO_2 and to assess potential risks for groundwater and sea water (for more detailed information see Sproink in this volume).

5.3 The Energy R&D Program of the Helmholtz Association (HGF)

The Helmholtz Association (HGF) represents 15 German scientific-technical and biological-medical research centers. These centers have been commissioned with pursuing long-term research goals on behalf of the state and society. Helmholtz Centers perform research in strategic programs in six core fields: Energy, Earth and Environment, Health, Key Technologies, Structure of Matter, Transport and Space. The HGF's Research Centers concentrate their efforts where they can introduce their specific competence and so make essential and indispensable contributions. The R&D programs of the six core fields are evaluated by national and international experts every five years. With focus on the energy field the evaluators found power station research to be the most important program for solving energy problems faced in the coming five to ten years. On a time scale above 10 years they recommended research to be extended in key work areas, such as computer simulation, alternative fuels, and membrane technology for carbon dioxide filters.

6. FZJ R&D Program on CO_2-capture

Coming from the reviewer's recommendations the Forschungszentrum Juelich initiated an R&D program on CO_2 capture. The activities started at the beginning of 2004 and cover a broad spectrum of R&D topics (**Table 4**) concentrating on CO_2 capture.

		IWV	STE
Materials and processes for CO_2 capture	Development of porous and mixed conducting ceramic membranes and suitable manufacturing methods		
	Measurements of selectivity, permeability and flow rates		
	Development of REDOX-systems for N_2/O_2 separation		
	Hot gas cleaning, behavior of material under oxyfuel and gasification conditions		
System analysis for CO_2 capture and sequestration	Process analysis (on capture)		
	Energy systems research (on CCS)		
	Life Cycle Assessment (on CCS)		

IWV: Institute for Materials and Processes in Energy Systems; STE: Program Group Systems Analysis and Technology Evaluation

Table 4: R&D topics of Forschungszentrum Juelich on CO_2 capture and sequestration

6.1 Materials and Processing

One main topic of the FZJ research activities is the development of materials for porous and mixed ceramic membranes, which can be applied for CO_2 capture. Membranes could play a key role in the context of CO_2 separation. FZJ has a great tradition in designing and analyzing new materials for such energy technology applications (e.g. fuel cell, photovoltaic). There is also great experience in measurement techniques. Another R&D focus is to investigate the behavior of material under oxyfuel and gasification conditions .

6.2 System Analysis

Current energy supply infrastructures are not designed to capture and store large amounts of CO_2. Large investments in capture and storing technologies are necessary if CCS is regarded to be a part of the technology mix for climate protection. Although the FZJ Program concentrates on materials and processing for CO_2 capture, from a system analysis' perspective it is necessary to study storing of CO_2 as well. Therefore, system analysis of FZJ contributes to the scientific basis for the strategic decisions by concentrating on three items (**tab. 4**):

- **Process Analysis on CO_2 Capture**
  Process analysis covers the analysis and evaluation of power plant concepts with CO_2 capture. One goal of this analysis is to provide material scientists with references and data about the specific operating conditions (temperatures, pressures), which are important for material development. Another goal is to calculate efficiency losses and costs for the investigated power plant concepts and setting of benchmarks.

- **Evaluation of CCS in the Context of the German Energy System**
  CCS is one option to reduce CO_2 emissions significantly. Strictly speaking, it neutralizes CO_2 emissions. However the realization of CO_2 capture, transport and sequestration needs high investments. Developing a cost effective national mitigation strategy should cover all energy sectors like conversion and the end use sectors (industry, residential, transport) (**Fig. 5**).

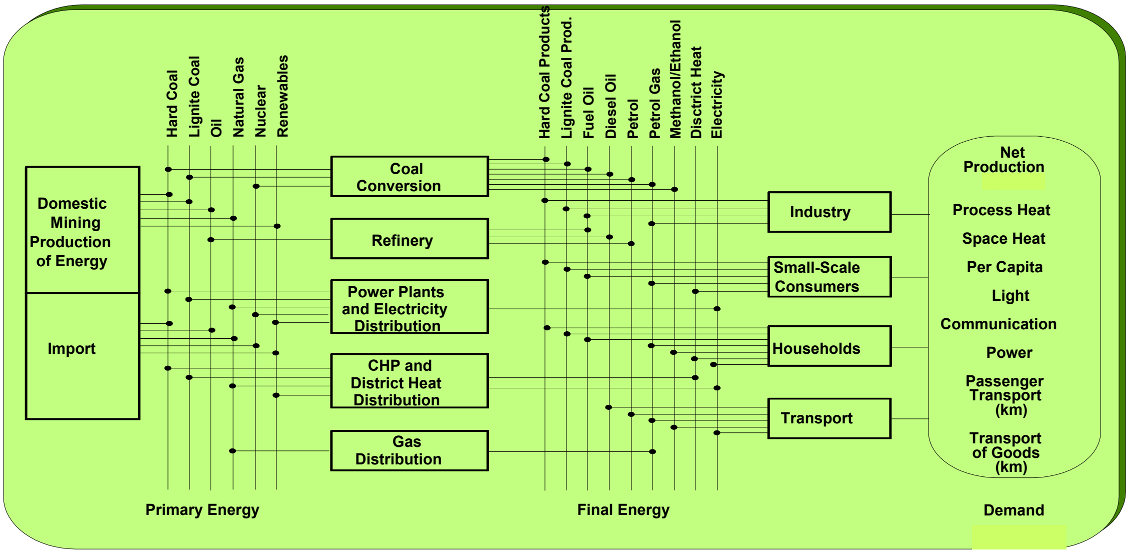


Fig. 5: Energy system flow chart

Because of this background it will be analyzed what are the most cost efficient mitigation strategies to reduce greenhouse gas emissions. The analysis will be done by using an energy system model, which considers the interdependences of the network of the national energy system. In this context different cost effective scenarios will be developed also with respect to different policy strategies (e.g. role of coal and renewable energies). The scenarios will show the role of CCS in the context of national mitigation strategies varying the energy political frame. Furthermore, the analysis enables a comparison of CCS with other mitigation options covering the conversion as well as the end use sectors.

Usually, national energy system models are working on a high aggregated level. Thus, detailed analysis work has to be done for the electricity sector. Introduction of CCS will be a long term process, and its wide-spread application will commence slowly. Based on the existing detailed power plant stock and assuming technical lifetimes for power plants, mortality lines for the German power plant stock will be developed. Before the background of capital turn over time dependent substitution of old power plants and the windows of opportunities for CCS technologies can be shown. The analysis enables a statement when CCS technologies have to be available. Also retrofitting aspects will be part of the analyses.

There are different options of CO_2 sequestration like aquifers or old oil and natural gas fields, which are usually not located nearby the power plants. Thus requirements of a suitable infrastructure have to be taken into account.

- **Environmental Assessment**
  For an environmental assessment, LCA is a widely accepted approach. Methodologically, an LCA covers all life cycle stages of products or service units. Ideally, an LCA represents the full life cycle from extraction of natural resources over electricity conversion to CCS (cradle to grave, **fig. 6**). It balances energy and material flows (inventory analysis) and assesses life cycle environmental impacts (impact assessment).

An LCA of CCS has to regard some specific aspects. On the one hand known LCA concepts have to be adapted to the peculiarities of CCS, i.e. energy conversion technologies and transports of CO_2 via pipelines. On the other hand the LCA methodology has to be further developed to assess specific environmental and safety aspects in particular for storing of CO_2. The ongoing research e.g. on seismic activities, leakage probabilities and volumes, and groundwater pollution has to be integrated into the LCA methodology. Additionally, the long time-scale of storing CO_2 raises the question of weighting future risks and uncertainties against present benefits. Of course, this is not a CCS specific question. To make matters worse, CCS technologies for power plants are not commercially available, yet, and therefore only have an R&D status, so that an LCA has to be performed as an R&D accompanying effort.

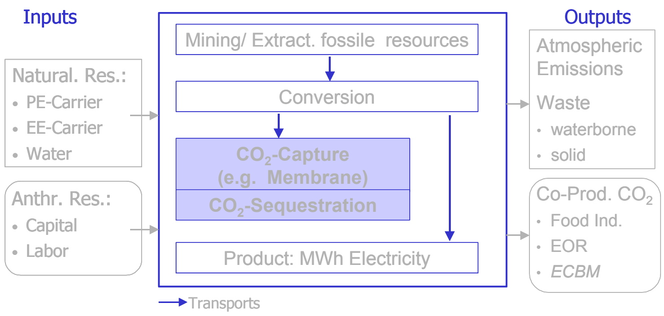


Fig. 6a: Aggregated process chain for electricity production including CO_2-sequestration (i.e. post-combustion)

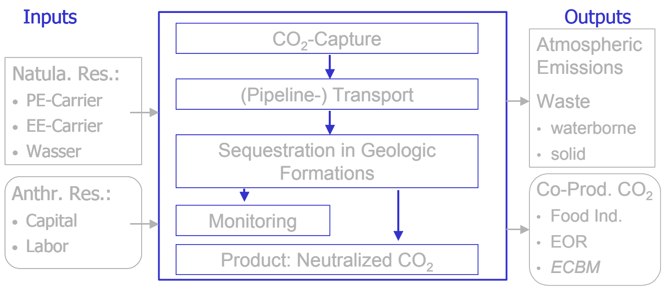


Fig. 6b: Process chain for the part of CO_2-sequestration (i.e. post-combustion)

7. Conclusions

For CCS there might be a „Window of Opportunity“ in Germany due to several aspects:

- If drastic climate protection measures become necessary, “non-conventional” climate protection measures might be necessary as well. In this sense, CCS is regarded to be a non-conventional technical measure.
- Power production in Germany depends heavily on fossil fuels. This sector can contribute to further reductions of CO_2 emission.
- For power production capacity replacement is required, earliest in 2010-2015, then rapidly growing. This offers the opportunity to build up a CCS infrastructure within the investment cycle of the power sector.
- In principle, exhausted gas fields, deep saline aquifers, and coal seams are available for CO_2 storage.

To make the “Window of Opportunity” a success story from a societal perspective, R&D has to take into account framework conditions set by energy-economic considerations and energy/environmental policy. Therefore, R&D on CCS has to regard the following (simple) aspects:

- CCS has to be demonstrated a reliable technology for fossil-based power supply. Therefore, demonstration projects will become necessary in the future.
- The vintage structure of power production capacity may require both new integrated technology and retrofit techniques.
- To be competitive with other CO_2 reduction/neutralization measures the specific cost of CCS must considerably decrease.
- From an ecological viewpoint, total environmental impacts covering all stages of the life cycle of CCS must be minimized, instead of exclusively concentrating on CO_2 emission.

The European Union and Germany promote R&D for capture and storage as well. In Germany, the work of the Helmholtz Association and the competence of its member Forschungszentrum Juelich are concentrated in an own R&D program, covering technology development on CO_2 capture and system analysis on capture and sequestration as well. The focus of materials and process development for capture technology in this program is on development of porous and mixed conducting ceramic membranes and suitable manufacturing methods, development of REDOX-systems for N2/O2 separation, and analysis of the behavior of material under oxyfuel and gasification conditions.

From a system analysis' perspective materials and process development for CO_2 capture is accompanied by an evaluation in the context of the German energy system and by a full environmental assessment of neutralizing CO_2, including transport and storage. Optimally, this research is done for different technology routes. The results of this topics are useful and necessary as a scientific basis for far-reaching strategic decision-making for politicians and also for other stakeholders.

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