Chapter 14

Systems Analysis of CCS Scenarios

The previous chapters discussed the technological basis of CCS and presented ecological and economic comparisons with renewable energy options; we now move on to analyse the significance of CCS for energy supply and climate policy in the overall context. After reviewing the general factors influencing the implementation of CCS we analyse a range of scenarios to show which of the future perspectives for CCS are plausible and sensible. The analysis is based on the German energy system, but some aspects are also in principle applicable to other countries, especially those planning similarly large power station replacement programmes.

14.1 CCS in the Energy Economy

The role of CCS in the energy economy as a whole is influenced by many factors. This chapter begins with an overview of these, starting by taking a more fundamental look at the compatibility of CCS with other climate protection measures.

14.1.1 General Factors Affecting CCS

Alongside technical, ecological and economic considerations, the availability of alternatives and social acceptance, the future role of CCS will be determined above all by the potential demand for power generation capacity over the period under consideration. From the energy economy perspective, the relationship between power station replacement demand and technological availability of CCS is the decisive factor that determines the limits of general applicability of CCS.

Initial rough estimates of the theoretical (demand-side) limits of CCS are found in Fig. 14-1. The starting point for the analyses here is a scenario where – under conditions otherwise identical to the reference scenario – all new fossil-fuelled power stations built after 2020 are fitted with CO_2 capture and storage.[1]

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[1] Reference scenario from Energiereport IV in EWI and Prognos (2005).

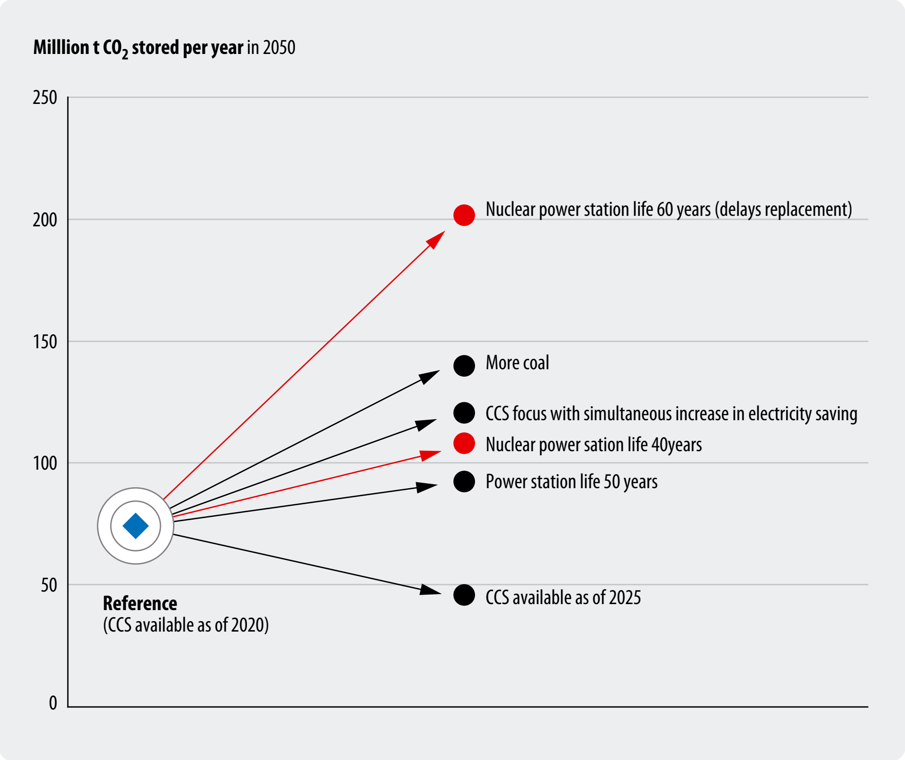

Fig. 14-1:
The main factors influencing future CO_2 capture and storage in Germany (analysis for 2050)

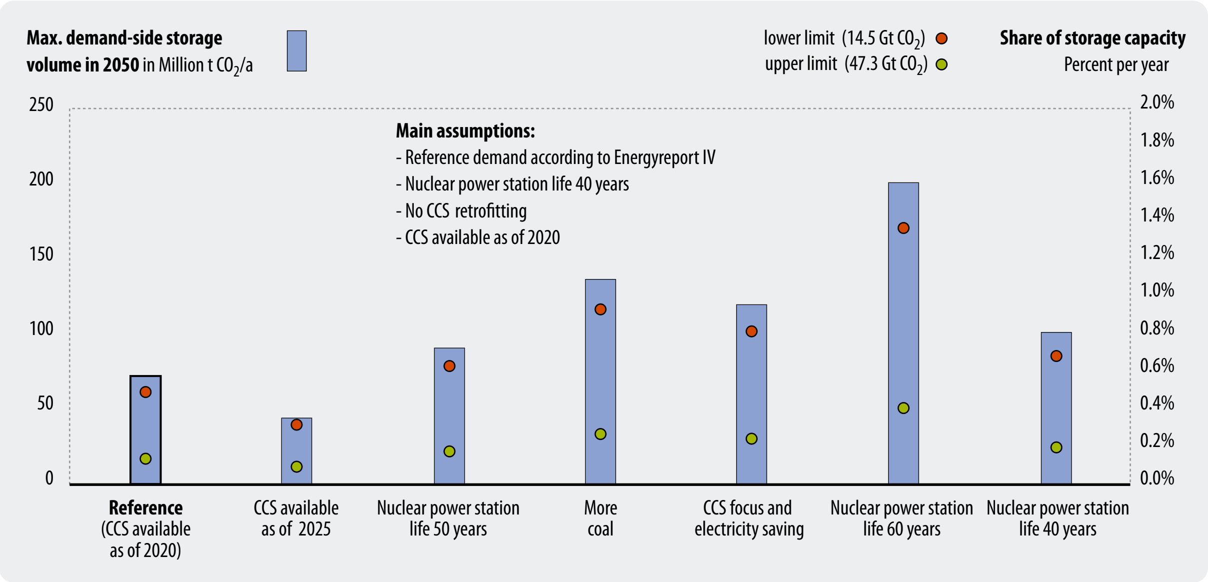

Fig. 14-2: Relationship between possible storage demand and available capacity

Taking this approach we find an annual storage demand of 73.1 million t CO_2 for the reference case. Various factors could influence this theoretical figure. A considerable proportion of power generation capacity will have to be replaced by 2025, so a five-year delay in getting CCS ready for implementation would (if we for the moment exclude the question of retrofitting) reduce the storage demand to 47.8 million t CO_2. Increases of the amount of CO_2 to be stored could result in particular from a change in the power station mix (larger share of coal compared to the reference case) but also from any change in the assumptions about nuclear power plant operating life that would delay the need to replace capacity. Increasing the operating lives of the fossil-fuelled power stations themselves (from 40 to 50 years) would have a comparable effect because it would also delay the need to replace capacity.

If we compare the resulting annual storage quantities (between just under 50 million t CO_2 and 200 million t CO_2) with the minimum and maximum figures for available storage capacity in Germany (see chapter 7), we find that capacity problems are not to be expected, at least where CCS is used as part of a transitional strategy.[2] This applies under the provison that the identified storage capacities also turn out to be viable – i.e., sufficient long-term stability, ecologically compatible, exploitable at acceptable cost. It also assumes that power stations can be connected to suitable sinks (through new CO_2 infrastructure) with enough capacity to allow storage during each power station's whole operating life.

Fig. 14-2 shows the respective shares of available storage capacity represented by annual storage demand, while Fig. 14-3 shows the corresponding static ranges for the storage capacity.

If we take the lower capacity figure as our measure, by 2050 the projected annual storage volume will have filled only between 0.3 % (best case) and 1.4 % (worst case) (Fig. 14-2).

The situation becomes even clearer when we consider the resulting static ranges. If we calculate the static range for the lower storage capacity figure we find – depending on the scenario – a possible storage period of 72 to 305 years (Fig. 14-3). As the figures show, the possible implementation of CCS in power stations will be largely determined by the need to replace increasingly ageing power stations, which is already enormous today. In this context the question of retrofitting CCS in existing power stations is highly significant and will be addressed in the next section (14.1.2). Equally significant is the potential expansion of CO_2 capture to include hydrogen production. Section addresses this aspect in greater detail in quantitative scenario analyses.

14.1.2 Power Station Retrofitting

There are two possibilities for retrofitting CO_2 capture in existing coal-fired power stations. Firstly, post-combustion CO_2 capture from the flue gas, e.g. by means of monoethanolamine scrubbing (MEA), and secondly, converting the combustion process to function with pure oxygen (oxyfuel). Both involve considerable infrastructure changes within the power station. In the case of MEA scrubbing the main factors are the considerable additional space required for the flue gas scrubbers and the column for regenerating the scrubbing solution

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[2] For the calculations here we set the ***lower limit*** of national storage potential at **14.5 Gt CO_2** (sum of *minimum* capacity estimates for exhausted oil and gas fields and saline aquifers). For the ***upper limit*** we added together the *maximum* capacity estimates for oil and gas fields and saline aquifers, and also included deep coal seams (ECBM, enhanced coal bed methane recovery) to arrive at a total capacity of **47.3 Gt CO_2** (cf. Table 7–5).

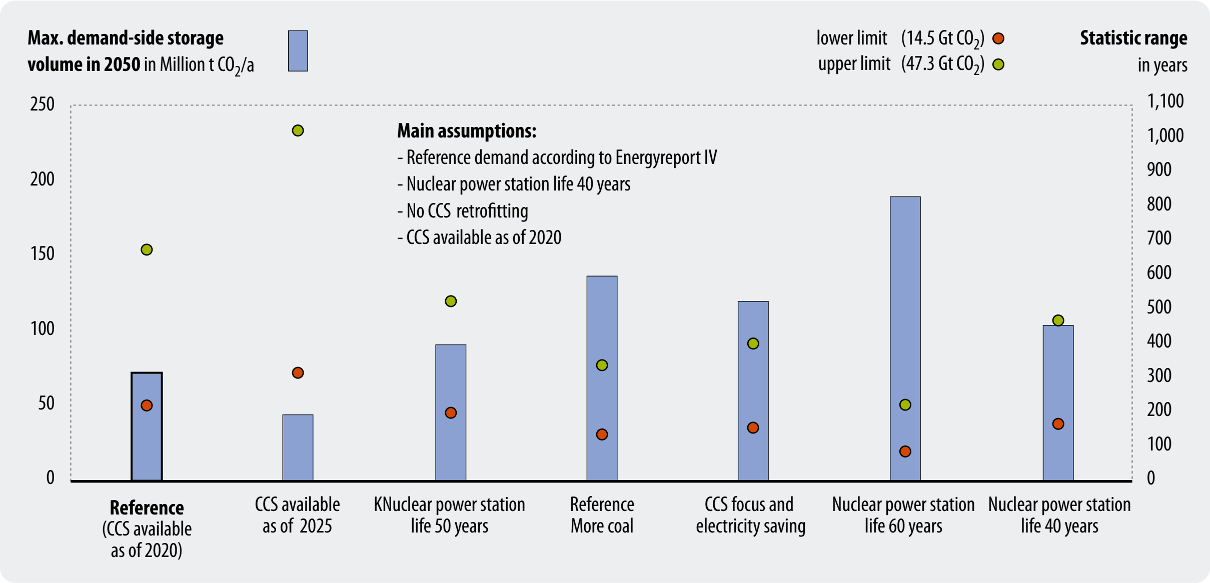

Fig. 14-3: Static ranges of storage capacity for different power generation scenarios

(plus space for storage facilities required for the MEA). Additionally, it is still unclear how much further purification of the flue gas will be required for the process to function properly. For example, if amine scrubbing is used for CO_2 capture, the SO_2 and NO_x concentrations must be reduced further than required by the legal emission limits. Surplus oxygen after combustion also has a disruptive effect, but developing more stable solvents to replace conventional MEA could permit higher residual O_2 concentrations.

In the case of retrofitting as an oxyfuel power station an air separation facility is needed to supply pure oxygen. Such a conversion would also involve major rebuilding of the furnace, for example to allow the possibility to recirculate CO_2 from the waste gas (as required to control the temperature of combustion).

During the retrofit procedure power stations can only operate at limited or zero outputwith corresponding financial losses. Because of the large losses in efficiency involved, retrofitting only makes sense in power stations that have a high level of efficiency to start with. So from today's perspective (especially if we consider the residual operating life required to amortise the additional investment) retrofitting is probably only conceivable for power station new builds that are part of the forthcoming capacity replacement programme (Fischedick et al. 2006). For coal these include power stations operating comparable to the reference power station (with an electrical efficiency of 46 %) and potentially also power stations using new 700°C steam technology with conversion efficiency of possibly more than 50%.

Retrofitting must also take account of possible effects on plant operation performance. In the case of post-combustion CO_2 capture in a conventional power station probably no negative effects on dynamics and control are to be expected, because the effects of MEA scrubbing will be comparable to the flue gas desulphurisation scrubbers that are normally already fitted. In the case of pre-combustion capture in an IGCC process, CO_2 capture represents a major process between gasification and gas turbine, which requires closely regulated interconnection of the different steps of the process. Because the steps cannot be operated independently of one another, CO_2 capture can be expected to have a system-relevant impact that does not fundamentally exclude retrofitting but does at least place restrictions on it. In comparison to pre- and post-combustion concepts for CO_2 capture, dynamics and control in an oxyfuel power station are influenced little or not at all by CO_2 capture. After combustion in pure oxygen the waste gas consists largely of CO_2 and H_2O, and rather than separating the CO_2 from the gas mixture the steam is separated out by condensation. The combustion and steam processes are largely separate.

There is growing research into the question of retrofitting power stations and the possibilities of implementing preparatory measures (capture-ready plant). Work is already under way, for example in the Dutch CATO programme, and studies for a capture-ready concept are currently also being prepared by the Canadian Clean Power Coalition and Sask Power for a 350 to 450 MW coal-fired power station. In Germany RWE Power is planning to build an IGCC plant with CO_2 capture by 2014 and also intends to work on retrofitting concepts (in cooperation with BASF and Linde). In the Netherlands there is already discussion about making capture-ready design obligatory for new power stations.

In terms of energy and climate policy retrofitting could be of great importance if current power station construction plans (without carbon capture) are implemented in full, and sooner or later a clear conflict with ambitious climate protection goals arises.

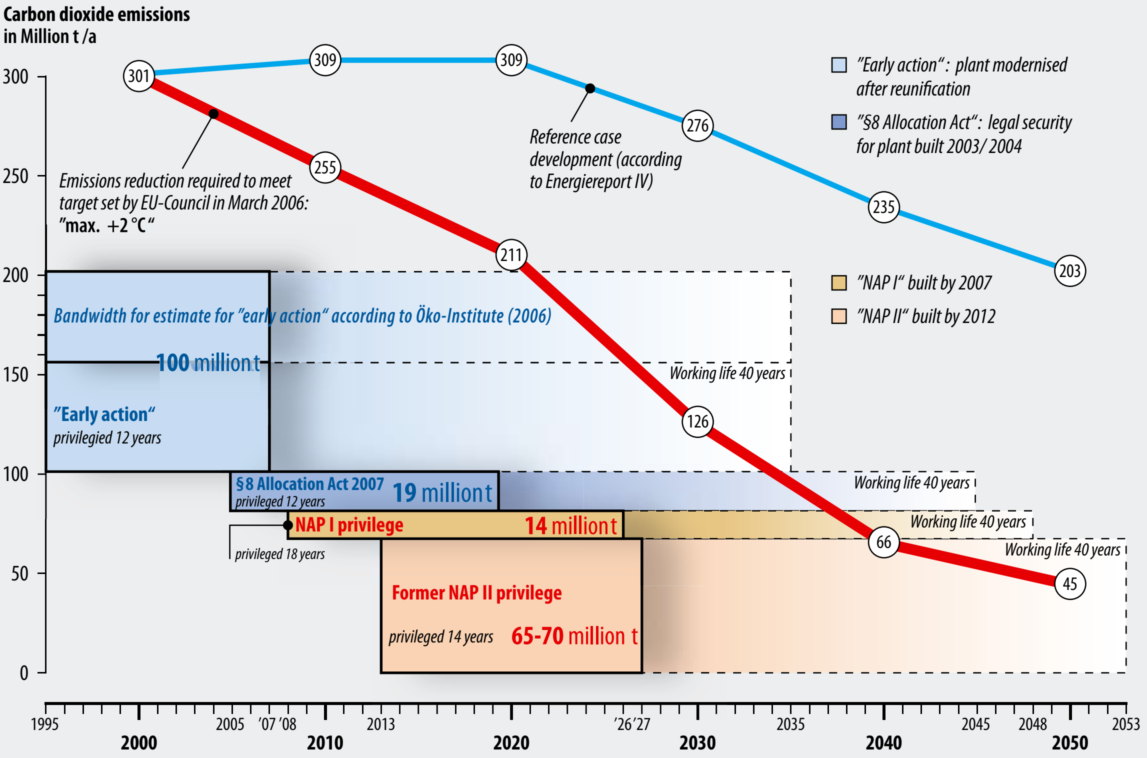

Fig. 14-4: Emissions from existing and planned power stations in relation to two emissions reduction trajectories in Germany (WI calculations)

The forthcoming investment programme doubtlessly contains many opportunities. It offers good prospects for economic and employment policy, represents sensible industrial policy, and will boost the German economy with respect to export markets. But it also represents a great opportunity for ecological modernisation. If we start from the existing plans for up to thirty-two power stations with an installed capacity of about 18 GW, and assume initially that these will merely replace existing power stations (with the same fuel but considerably worse fuel efficiency) we find a considerable theoretical CO_2 saving of 24 %.[3]

On the other hand, the announced new builds represent structural decisions with implications that extend far into the future and must therefore be examined for conflicts with future developments. This applies in particular to long-term responses to the climate policy challenge. The sum of all construction projects could thus prove incompatible with such goals, and even if new power stations are considerably more efficient than the existing ones they replace, the problem will remain. In times of climate change even 'much better' may prove to be 'not good enough'. Or put another way, for climate protection not only the 'class of plant' but also the simple 'mass of plant' is relevant.

If we compare the new build plans with specific goals for CO_2 emissions (see Fig. 14-4) the potential conflict is obvious.

The figure shows that by the third decade of this century the new power stations already planned today will be coming into conflict with climate protection goals. Put another way, if all the power stations were to be built as planned, we would already have decided today that it will not be possible to apply a restrictive (but necessary) climate protection target to the power station sector that is proportionate to other sectors' targets. Consequently other sectors would have to be treated more strictly than the electricity generating sector if the overall target is to be met, and it is doubtful whether that could be sustained politically.

The general situation changed recently. In former years the NAP II privilege allowed more plans for new builds. After cancellation of the privilege the number of new builds will strongly depend on the developments of the European emissions trading scheme.

As already mentioned, the conflict stems in the first

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[3] 18 GW is a rather conservative figure. Various sources cite plans involving up to 40 GW.

place from the volume of planned new capacity. But this could be reduced considerably by targeted electricity saving measures (which are generally also very attractive in broader economic terms) and a further diversification of the range of renewables (see section 14.2). Assuming the power stations are built, it may prove necessary to retrofit them with CO_2 capture in the medium term. It would therefore be logical to equip today's new power stations with the possibility of retrofitting for CO_2 capture and storage (capture-ready). Corresponding incentive regimes are not yet in place, but they would be conceivable and are currently under discussion especially at the European level.

14.1.3 Compatibility of CCS with Other Climate Protection Measures

From the perspective of energy economics it is also relevant to know which fields of application CCS technologies relate to today and in the future and how they stand in relation to other climate protection strategies regarding compatibility with them and whether conflicts will arise.

Applications for CCS

Because of the high costs and infrastructure investment involved, CO_2 capture and storage is most obviously an option for the centralised structure of large power stations. It is not yet clear to what extent CO_2 capture and storage will remain restricted only to these central point sources or whether in future the many small-scale sources (e.g. fuel cells for stationary domestic supply, vehicles) could be included directly or indirectly (e.g. gasification prior to capture, CO_2 capture from the atmosphere).[4]

CCS for decentralised structures is possible at least indirectly through the introduction of a hydrogen economy where hydrogen would be produced centrally, distributed through new or existing pipeline systems (e.g. the natural gas pipeline network) and used locally, for example to generate electricity or heat or to power vehicles. On the one hand this would expand the length of the process and thus imply additional energy losses but on the other hand (pure) hydrogen applications in particular would allow high conversion efficiency rates. To what extent and in what applications and timeframes introducing a hydrogen economy makes sense and would lead to a rational energy balance remains to be investigated.

Compatibility or conflict

A further question that arises in any analysis of energy economics is the compatibility of CCS with other climate protection options. Table 14-1 provides an overview of compatibility testing of CCS with the climate protection strategies that play a decisive role in the NaturschutzPlus scenario (BMU 2004). The matrix identifies the possible negative interactions and (potential) positive synergies; it thus represents one of the main starting points for the process of defining scenarios described in section 14.2, and begins to address whether CCS stands in conflict with the expansion of renewables or represents a bridge to reaching that goal.

According to Table 14-1 the greatest competition is with the expansion of centralised renewable electricity generation (wind offshore, import of renewables). Compatibility problems arise above all with respect to decentralised combined heat and power. Synergy possibilities and combined solutions appear possible with respect to hydrogen production. For geothermal there are still open questions to resolve. Here there would seem to be both the possibility of competition and the potential to exploit synergy effects because both cases involve the use of underground structures. However, the number of potential CO_2 sinks is limited. Other conflicting interests could arise if compressed air storage gains in importance, for example to balance out fluctuations in electricity generated from renewables. Conflicting interests with natural gas storage are obvious, because in some cases deep aquifers are already used today.

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[4] Given that the CO_2 produced by combustion weighs more than three times as much as the carbon in the mineral oil, capture in the vehicle is a problematic option and would automatically impact negatively on the energy balance.

Table 14-1: Interaction matrix for CCS (basic assumption: available from 2020/2025) and other relevant climate protection strategies (focus on electricity generation and fuel production, geographical scope: Germany)

Assumption CCS availability from 2020/2025					
Technology/ strategy	**Availability**	**Synergy potential with CCS**	**Conflict potential with CCS**	**Potentials**	**Conclusion: conflicting development?**
			Fossil and nuclear electricity generation		
Efficient centralised electricity generation	Immediately (700°C plant from 2015)	Efficiency increases create leeway for CCS	Efficiency reduction; in combination with renewables high flexibility required, probably not provided by CCS power stations (due to additional components)	Significantly reducing over time	
Centralised public and independent CHP	Immediately		Normally gas-fired power stations due to high electricity-to-heat-ratio (smaller CCS incentive), high equipment investment for independent operators (space requirement critical)	Replacement of existing power stations	
Decentralised CHP	Immediately	Via hydrogen fuel supply (best prospects with use of fuel cells)	CCS not practicable for decentralised applications (high costs	Significant expansion (16 % share of electricity generation in 2050), later with fuel cells	(Yes)
Nuclear power	Immediately			No new builds – phase-out	Yes – but public acceptance more important
			Electricity generation from renewables		
Hydropower	Immediately			Maximum capacity installed	No
Wind energy (onshore)	Immediately		Intermittent renewables require high flexibility which is probably not provided by CCS power stations	Maximum capacity installed (but onshore repowering)	No
Wind energy (offshore)	2010		see above	Large contribution long-term, contribution of wind to total renewable electricity generation 33 % (of which > 2/3 offshore)	Yes
Imported renewables	From 2025			Share rising long-term (65 TWh in 2050, 13 % share of electricity generation by 2050)	Yes – strong conflict with CCS regarding date of deployment
Photovoltaics	Immediately		Intermittent renewables require high flexibility which is probably not provided by CCS power stations	Limited mid-termimportance in Germany	(No)
Biomass	Gasification from 2015	Double dividend with CCS (negative emissions), multi-fuel use possible e.g. with co-combustion of biomass in power stations or combined gasification	Due to fuel logistics usually smaller plants, especially with CHP (< 20 MW)	High importance of biomass	Consider combined concepts
Geothermal (heat, electricity)	From 2015	Synergy projects possible (cf. RWTH project)1)	Conflicts conceivable, especially with heat supply, CCS at 800 m and deeper open question	Cautious estimate:14.5 TWh in 2050 corresponds to just over 3 %	

Technology/ strategy	**Availability**	**Synergy potential with CCS**	**Conflict potential with CCS**	**Potentials**	**Conclusion: conflicting development?**
			Electricity generation from renewables		
Electricity saving	Immediately			High, saving in 2050 about 20 % compared with reference development	Yes – but efficiency technologies available earlier
Wärmeeinsparung	Immediately			In buildings very high (e.g. passive house standard compared to current German buildings standard ("EnEV")	(Yes – compared to CCS-H2, but efficient technologies are available earlier)
			Fuel supply		
Biofuels				Limited use of biofuels (111 PJ in 2050[2])	No
Hydrogen (fuel, feed into natural gas network)		Low-CO2 hydrogen can be imported (CO2 separation at borehole), hydrogen production in IGCC plants, (combined cycle multi-purpose concepts)		Limited quantities of hydrogen in scenario (189 PJ in 2050) on basis of electricity from renewables	Think about combined concepts
Mineral oil		Enhanced oil recovery creates favourable economic framework			International first step for CCSS
Natural gas		Capture of CO2 as natural gas impurity			International first step for CCS
			Storage systems		
Compressed air stores	In principle immediately, intense research under way		Competition for suitable geological storage formations, which are also of fundamental interest for compensating intermittent renewable contributions		(Yes)
Thermal energy stores (seasonal)	In principle immediately, intense research under way		Competition for suitable geological storage formations, seasonal stores are fundamentally of great importance for renewable heat storage		(Yes)

1 Integrating CO_2 in reflux water in geothermal projects (deep geothermal at depth of e.g. 1,500 m) – calcite formation

2 Very restricted use in NATP I scenario (largely in stationary applications), in NATP II scenario 300 PJ (here no use of renewable H_2), a comparable order of magnitude is also found in the UBA fuel scenario.

14.2 Scenario Analyses: Assessment of the Strategic Importance of CCS

The results of calculations in models are highly dependent on the assumptions on which the models are based. This applies in particular to the fundamental economic data of the available alternatives and the development of fuel prices. In the following we examine scenarios for Germany in order to elucidate – without the distractions of optimisation models – the strategic importance of CCS for reaching ambitious climate protection goals.

14.2.1 Storylines for Political Relevant CCS Scenarios

In the light of the interaction matrix described above (Table 14-1) and earlier studies dealing with ways to meet ambitious climate protection targets – as already presented in scenario studies conducted for the Federal Environment Ministry and the Federal Environment Agency (UBA 2006b, BMU 2004, WI/DLR 2002) – this study identifies three different scenarios[5] (name of scenario in brackets):

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[5] Target: 80 % reduction in CO_2 emissions by 2050 compared to reference year 1990.

- **CCS as the main element of a climate protection strategy** with maximum application of CCS technologies, whereas development of renewables is derived from the reference trend **(CCSMAX)**
- **Avoidance of CCS as a result of** great success in increasing efficiency and through the ambitious expansion of technologies for using renewable energy as described for example in the NaturschutzPlus scenarios (BMU 2004, 2005) **(NATP)**
- **CCS as a bridge to renewable energies** in a scenario where increases in efficiency and expansion of renewables cannot be sufficiently mobilised to achieve the climate protection goal on their own in the envisaged time frame **(BRIDGE)**

Rather than developing completely new scenarios we based our work on the NaturschutzPlus scenario (modified and adapted to current conditions) (BMU 2004; UBA 2006b) and the reference forecast from the EWI/Prognos Energiereport IV.[6] All three scenarios either state a climate protection goal to be achieved by 2050 or else examine whether such a goal is achievable. The goal is specified by the NaturschutzPlus scenario: 242 million t CO_2 emissions in 2050. The scenarios are also shaped by specific storylines, which are described below. The principal results of the scenarios are described in the following.

CCS as the main climate protection strategy (CCSMAX scenario)

If CCS is chosen as the main strategic pillar of climate protection this can function on two different levels:

- *Central electricity generation* (largely condensation power plant). The driving forces here are that existing structures could be maintained (including operator structures), that coal (as the fossil fuel with the greatest reserves) could continue to be used, and that this option could represent an industrial policy model for other countries with significant coal reserves.
- *Central hydrogen production* (on the basis of coal gasification). Low-emission electricity generation alone will not be enough to achieve the required reduction in CO_2, and in the transport sector biofuels – alongside improving efficiency – can make only a limited contribution to climate protection. So here the driving force for expanding the CCS option would be to diversify the range of different fuels to include hydrogen for reasons of security of supply.

Because of the structural preconditions (strong focus on large-scale power station technology) it is logical to develop the scenario on the basis of the existing Energiereport IV (i.e. a 'business-as-usual' approach) with the goal of meeting comparable climate protection targets (80 % emissions reduction goal).

When expanding CCS, the existing age structure of the power stations initially has a restrictive effect, but it must also be taken into account that a hydrogen system cannot be established at the drop of a hat. Conceivable steps would be first to launch the system with a centralised supply for major consumers (e.g. airports), establishing 'stand-alone systems' and starting to feed into the natural gas network to certain shares. Then the successive creation of the first mixed gas structures could follow (including necessary modifications of application technology for mixed gas), and finally a gradual move (in both the temporal and geographical sense) to full-blown hydrogen systems.

CCS as a bridge to expanding renewables (BRIDGE scenario)

In this scenario CCS is understood as a complementary technology for a climate protection strategy that ultimately aims to further expand renewables and increase energy efficiency, but cannot implement these in the required intensity due to conflicts of interests and insurmountable obstacles.

In contrast to the idea of using CCS exclusively as a back-stop technology (a technology that is only applied when other measures fail to have sufficient effect), this development strategy integrates CCS as a strategic element from the outset and regards it as necessary for meeting the climate protection target in time. The foremost questions to be analysed here are firstly the extent to which the necessary expansion of renewables and the implementation of energy efficiency measures (including the expansion of decentralised CHP) can be spread over a longer period and secondly whether CCS can turn out to be a longer-term complementary and transitional option (compatible with the expansion of renewables) for the technologies that are strongly expanded in the NATP scenario.

14.2.2 Definitions and Parameters for the Scenarios

The required demographic and economic data for all the scenarios are taken from EWI and Prognos (2005), with modifications only with respect to the development of transport volume, where figures from UBA (2006) were used (Table 14-2). However, the reference development used here was determined on the basis of the 2005 situation. This means that for the near future (based on 2010) a number of deviations from the energy data in Energiereport IV arise. In all the scenarios the agreed phase-out of nuclear power is completed on schedule.

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[6] In the course of an investigation of fuel strategies for the Environment Agency (UBA 2006b) the climate protection strategies developed for the Federal Environment Ministry (BMU 2004) were modified to account for changes in conditions (e.g. population trends) in accordance with the EWI/Prognos Energiereport IV.

Table 14-2: Demographic and economic data for the scenarios

Data	**1996**	**1998**	**2000**	**2002**	**2005**	**2010**	**2020**	**2030**	**2040**	**2050**
Population (million)	81.94	82.11	82.21	82.41	82.41	82.41	81.39	79.42	77.30	75.12
Employment (million)	37.27	37.62	38.75	38.67	38.76	38.92	38.95	37.50	37.00	35.80
Households (million)	37.30	37.60	38.15	38.76	39.15	39.67	40.02	39.72	39.20	38.50
Housing units (million)	36.10	36.80	37.06	37.27	37.60	38.20	39.80	40.85	39.50	38.50
Housing space (million m^2)	3,080	3200	3,281	3,347	3,450	3,615	4,010	4,406	4,560	4,510
Heated industrial space (million m^2)	1,310	1,385	1,458	1,465	1,485	1,514	1,539	1,500	1,480	1,432
GDP (€1,000 million. 2000)	1,870	1,934	2,030	2,050	2,110	2,306	2,691	3,050	3,355	3,600
Cars (million)	41.00	41.70	42.84	44.52	44.83	46.96	50.60	51.90	52.38	52.09
Passenger transport (1,000 million passenger-km)			1,169	1,186	1,220	1,285	1,433	1,511	1,560	1,536
Goods transport (1,000 million t-km)			490	496	535	607	748	843	918	980
Ratios										
Household size	2.20	2.18	2.15	2.13	2.11	2.08	2.03	2.00	1.97	1.95
Living space/head (m^2)	37.6	39.0	39.9	40.6	41.9	43.9	49.3	55.5	59.0	60.0
Size of housing unit (m^2)	85.3	87.0	88.5	89.8	91.8	94.6	100.7	107.9	115.4	117.1
Cars/household	1.10	1.11	1.12	1.15	1.15	1.18	1.26	1.31	1.34	1.35
Useful area/employee (m^2)	35.1	36.8	37.6	37.9	38.3	38.9	39.5	40.0	40.0	40.0
GDP/head (€2000)	22,822	23,554	24,692	24,875	25,603	27,982	33,062	38,403	43,402	47,923
Passenger transport/head (km)			14,219	14,391	14,804	15,593	17,606	19,025	20,181	20,447
Goods transport/head (km)			5,960	6,018	6,492	7,366	9,190	10,614	11,876	13,046
Index (2000 = 100)										
Population	99.7	99.9	100.0	100.2	100.2	100.2	99.0	96.6	94.0	91.4
Employment	96.2	97.1	100.0	99.8	100.0	100.4	100.5	96.8	95.5	92.4
Households	97.8	98.6	100.0	101.6	102.6	104.0	104.9	104.1	102.8	100.9
Housing units	97.4	99.3	100.0	100.6	101.5	103.1	107.4	110.2	106.6	103.9
Housing space	93.9	97.5	100.0	102.0	105.2	110.2	122.2	134.3	139.0	137.5
Heated useful area	89.8	95.0	100.0	100.5	101.9	103.8	105.6	102.9	101.5	98.2
GDP	92.1	95.3	100.0	101.0	103.9	113.6	132.6	150.2	165.3	177.3
Cars	95.7	97.3	100.0	103.9	104.6	109.6	118.1	121.1	122.3	121.6
Passenger transport	0.0	0.0	100.0	101.5	104.4	109.9	122.6	129.3	133.4	131.4
Goods transport	0.0	0.0	100.0	101.2	109.2	123.9	152.7	172.0	187.3	200.0
GDP growth (%/a)		1.68	2.42	0.49	0.96	1.78	1.54	1.25	0.95	0.70

Until 2030: according to EWI and Prognos (2005); WI projection through 2050
Transport and number of cars according to UBA 2006

The overall economic and energy data in the NaturschutzPlus I and II scenarios developed by BMU (2004) – which serve as the basis for our NATP scenario – are largely based on the year 2000. In the meantime considerable changes have occurred both in the energy market and in the development of renewables. Compared with the reference development presented by the Enquete Commission (expert commission of the German Bundestag) in 2002 (Enquete 2002), the energy market reference forecast for 2030 ('Energiewirtschaftliche Referenzprognose 2030') in Energiereport IV (EWI and Prognos 2005) already reaches quite different conclusions regarding probable trends. But even this relatively new study, based largely on data from 2002, does not include the latest energy price rises and the sharp increase in recent years in the contribution of renewables to electricity generation and liquid fuels. Upcoming power station new builds are included as per known planning of the electricity companies.

Table 14-3: Primary and final energy consumption and gross electricity generation in the three scenarios, itemised by energy source

	Total energy supply (PJ/a)						Electricity generation							
	Primary energy		Final energy		Renewables primary		Gross generation (TWh/a)				Installed capacity (GW)			
Year/ scenario	Total	of which fossil	Total	of which electricity	(PEV)	(END)	Total	Renewables	Nuclear	Fossil	Total	Renewables	Nuclear	Fossil
2005	14,238	11,833	9,118	1,836	658	572	613	62	163	387	131.2	26.9	21.3	83.0
2020														
CCSMAX	12,980	11,556	8,800	1,886	1,097	892	591	112	30	449	139.4	40.9	4.3	94.2
BRIDGE	12,565	10,861	8,531	1,796	1,377	1,072	575	127	30	418	144.3	51.3	4.3	88.7
NATP	12,071	10,174	8,291	1,710	1,570	1,230	551	159	30	362	147.7	61.1	4.3	82.3
2030														
CCSMAX	12,375	11,068	8,403	1,853	1,300	1,084	581	145	0	436	142.5	49.1	0.0	93.4
BRIDGE	11,699	9,957	7,977	1,746	1,742	1,392	559	168	0	391	147.5	61.2	0.0	86.3
NATP	10,534	8,237	7,689	1,638	2,297	1,886	529	265	0	264	158.4	87.1	0.0	71.3
2050														
CCSMAX	12,483	10,837	7,309	1,782	1,646	1,392	569	197	0	372	146.2	63.8	0.0	82.4
BRIDGE	10,419	8,010	6,523	1,598	2,409	2,002	542	245	0	297	148.3	74.2	0.0	74.1
NATP	8,122	4,696	6,025	1,512	3,426	2,881	534	384	0	150	158.3	111.5	0.0	46.8

The **NATP scenario** describes a development that gradually continues the expansion of renewables already initiated through energy policy and increasingly links it with growing contributions from more efficient energy conversion (CHP) and use (efficiency measures). It describes the short- to medium-term effects of the German government's current energy policy and projects this favourable framework into the future. It abides by the German government's climate protection goals and the agreed targets for expanding renewables. The required instruments remain effective in their current state (e.g. Renewable Energies Act, CHP Act, tax breaks, obligation to blend biofuels) or are strengthened (energy efficiency promotion in the heat market). Earlier and current studies (BMU 2004, 2006) have shown that the growth dynamic initiated in renewables must be maintained at least at the current extent for the foreseeable future if energy policy in this field is to successfully meet its goal of making renewables competitive in the energy market without further subsidies.

By consistently continuing to expand renewables until 2050 – and assuming a successful mobilisation of potential efficiency improvements in energy conversion and use – the NATP scenario leads to a clear reduction in use of fossil fuels and thus to a considerable reduction in CO_2 emissions. It largely follows the lower reduction path shown in Fig. 14-4. In 2050 about 240 million t CO_2/a will still be emitted, which represents a reduction of 76 % from the figure for the reference year 1990. Here the application of CCS technologies is not necessary for climate protection. This scenario is the archetype of an ambitious climate protection policy based on the strategies of efficiency and expanding renewables and thus serves as a yardstick for assessing the CO_2 emissions that have to be avoided by means of CCS in other scenarios.

We updated the original NaturschutzPlus scenario on this basis with 2005 as the baseline for all energy data.[7] The potential for improving efficiency in the electricity, heat and transport sectors and the combined heat and power subsegment was reassessed using the latest data. The most important alterations in these areas relate to expected short-term electricity consumption, and to the amount of electricity and heat currently actually produced by CHP and the perspectives for short-term expansion there. The figure for gross electricity generation taken as the starting point here – 613 TWh/a in 2005 (comparison 2000: 571 TWh/a) – is considerably higher than that used by BMU (2004). Electricity generated from fossil fuels in CHP has remained stagnant for about ten years at about 50–53 TWh/a. Recently, however – stimulated by rising electricity prices and trading in CO_2 certificates – a slight increase has been noted again. For 2005 we take 53 TWh/a as a staring point. Thanks to the favourable framework offered by the Renewable Energy Sources Act there is also about 10 TWh/a CHP electricity from biomass (including biogas).

The **CCSMAX scenario** continues current energy policy – on the basis of the energy market reference forecast by EWI and Prognos (2005) – and leads to a certain

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[7] When the work was conducted some of the data for overall energy supply in 2005 were still provisional.

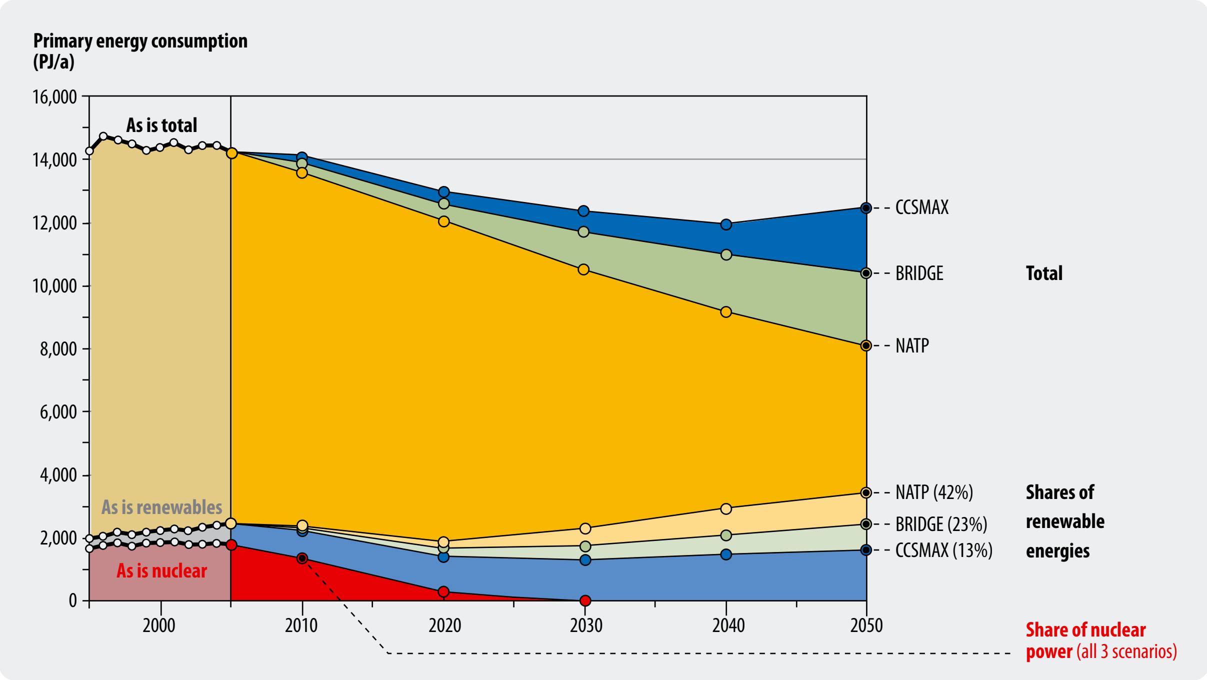

Fig. 14-5: Primary energy trends in the three scenarios showing the shares of nuclear and renewables

degree of progress in trends to increase dissemination of efficiency and renewable energy technologies. But the progress is far from being sufficient to meet existing climate protection goals. The scenario thus models a climate protection policy that will be inadequate in the medium term; one that would necessitate the use of CCS technologies from about 2020 if the 2050 climate protection target is to be met in time after all. It models from the demand side the maximum CCS contribution that the German energy supply system could require by 2050. It was assumed that development of efficiency and renewable energy technologies would not fall behind the levels assumed in the reference development.

Compared to the reference development, the **BRIDGE scenario** defines an accelerated climate protection policy that boosts efficiency and renewable energy strategies in comparison to the reference case. But because from the outset major players in energy policy and the energy business do not expect these two strategy elements to be enough to meet the 80 % emissions reduction target, CCS technologies are included here from about 2020 as part of an overall strategy for meeting climate protection targets.

Table 14-3 summarises the main data for overall energy supply – and in particular for electricity generation – based on the above assumptions. Fig. 14-5 shows structural differences in primary energy supply between the scenarios and the shares of different energy sources.

Even in the reference case, primary energy consumption shows a slight downward trend, (which is replicated in CCSMAX) because it is assumed that the trend for continuous improvements in energy productivity can more than compensate the growth in energy services (expressed by growth in GDP). In the longer term falling population in Germany also has an effect. But only the NATP scenario exploits the great potential of structural technical efficiency improvements. Here only the economically viable options are considered at any particular time. Both the other scenarios assume that structural and institutional impediments will to differing degrees impede effective exploitation of these potentials.

In both scenarios *with* CCS the reduction in primary energy consumption slows after 2020 because of the increasing use of primary energy for low-CO_2 production of electricity and hydrogen. In the CCSMAX scenario this actually causes use of primary energy to rise again after 2040. So in this scenario the use of fossil energy in 2050 (10,837 PJ/a) is only 9 % less than today (11,830 PJ/a). In the BRIDGE scenario use of fossil primary energy falls considerably (by 33 %) and in the NATP scenario even further (by 60 %). Given that GDP grows by 75 % between 2005 and 2050, primary energy intensity falls in the NATP scenario to 34 % of today's value by 2050. That does not yet, however, reach the structural technical limits, which the Enquete Commission puts at a mean value of approx. 25 % ('Factor Four') (Enquete 2002). So there is still further potential for reduction especially in the transport sector and in utilisation of electricity.

The contribution from renewables increases in all scenarios. But measured against the speed of growth of the past five to seven years future growth slows significantly

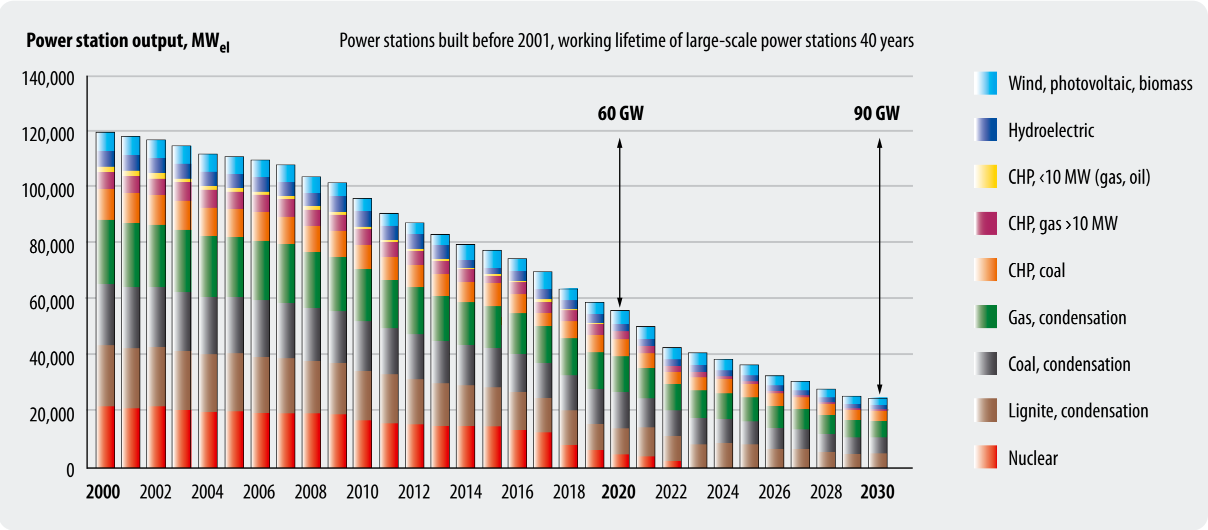

Fig. 14-6: Remaining output of power stations built before 2001 in Germany, itemised by type

in the CCSMAX scenario, reaching only 2.5 times today's value in 2050. That corresponds with a policy that allows existing funding instruments to expire in the foreseeable future and neglects to establish them in the first place in some fields (e.g. heat supply). In the other extreme case, the NATP scenario, the current speed of growth of renewables is maintained over the coming decades. How quickly the relative shares of renewables grow, will depend strongly on the development of primary energy consumption. In the NATP scenario in 2050 their contribution in absolute terms (3,426 PJ/a) is double that of the CCSMAX scenario, but their share (42 %) is more than three times higher.

14.2.3 Scenarios for Developing CCS Technologies in the Electricity Sector

The intensity of structural change in electricity generation is largely defined by the necessity of replacing ageing fossil-fuelled power stations. The decision to phase out nuclear power, the continuing growth in renewables and the development of electricity consumption also influence this transformation.

Fig. 14-6 shows the capacity retirement line for German power stations in the twenty-first century. If we assume that a large-scale power station has a working lifetime of forty years we can calculate the consequential replacement demand from the capacity retirement line. Of the power stations built before 2000, a total of 60 GW will have to be replaced by 2020: approx. 35 GW fossil-fuelled power stations (including approx. 8 GW in CHP plant), 8 GW plant using renewables and 18 GW nuclear power. By 2030 altogether 90 GW or 75 % of installed capacity in 2000 will have to be replaced.

In conjunction with the expansion of renewables and the expansion of CHP (especially decentralised), both of which are aims of energy policy, the potential 'market' for CCS power stations is defined. However, whereas renewables and CHP already profit from the pre-2020 structural changes, which affect more than half of existing power station capacity, CCS plant will not be ready for this market (that being the assumption in the scenarios under consideration). The potential market volume for CCS plant could expand if it is possible to retrofit CCS technologies in fossil-fuelled power stations built between 2005 and 2020.

In electricity consumption too, a small reduction already occurs in the reference case (see Table 14-3).[8] But in the CCSMAX scenario for 2050 final demand for electricity is only 3 % less than the value for 2005 (and thus as high as consumption in 2000). Partial exploitation of potential for electricity savings in the NATP scenario increases the savings to 18 %. In all the scenarios production and supply of hydrogen using renewable energy begins in 2030, which requires in the CCSMAX scenario in 2050 an additional 22 TWh/a of electricity (in BRIDGE: 31 TWh/a; in NATP: 47 TWh/a).

In the electricity sector the interdependence with renewables is especially great because they already have a share of more than 10 % and current growth is most dynamic of all in that sector. But in the CCSMAX scenario electricity from fossil fuels still dominates in 2050 with a share of 65 %. In the BRIDGE scenario both energy sources are almost equally involved (fossil 56 %), while in the NATP scenario renewables (72 %) clearly outweigh fossil fuels.

The following assumptions were made when determining installable CCS capacity in the electricity sector:

- Commercial application begins in 2020, all large-scale power stations have a working lifetime of 40 years.

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[8] However, the reference case is based on data from 2000 when gross electricity generation was 571 TWh/a (without pumped storage), and doesn't include the relatively steep increase to 2005.

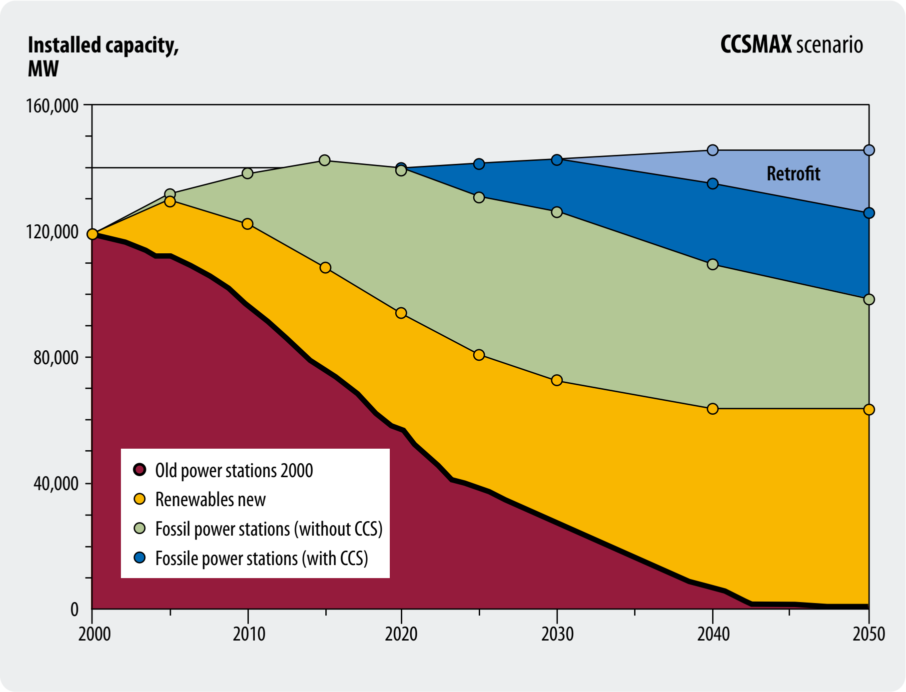

Fig. 14-7:
Installed output in the CCS-MAX scenario: old power stations, new renewable energy plant and new fossil-fuelled power stations with and without CCS

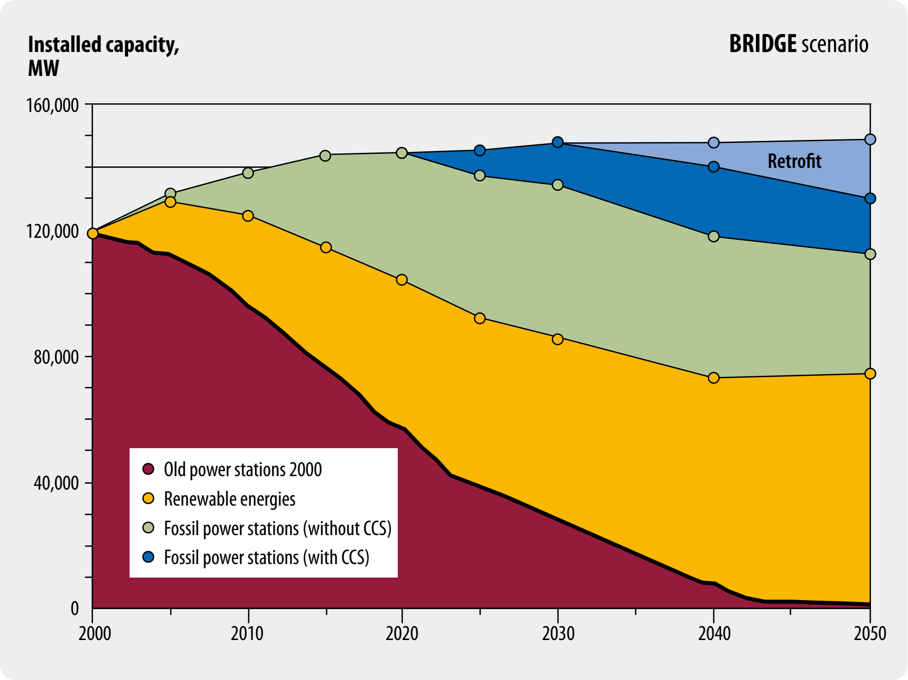

Fig. 14-8:
Installed output in the BRIDGE scenario: old power stations, new renewable energy plant and new fossil-fuelled power stations with and without CCS

- From then on 90 % of new condensation power stations and 50 % of large cogeneration plants (CHP) will be equipped with CCS technologkies.
- New power stations built between 2005 and 2010 will be replaced by new CCS plant between 2045 and 2050.
- New power stations built between 2011 and 2020 (large condensation power stations, large cogeneration plants) will be retrofitted with CCS technology after 2030, in the same proportions as new builds.
- The parameters of power stations without and with CCS are taken from chapter 12; only the direct CO_2 issions are considered;[9] in all scenarios fossil-fuelled power stations without CCS have the same parameters.

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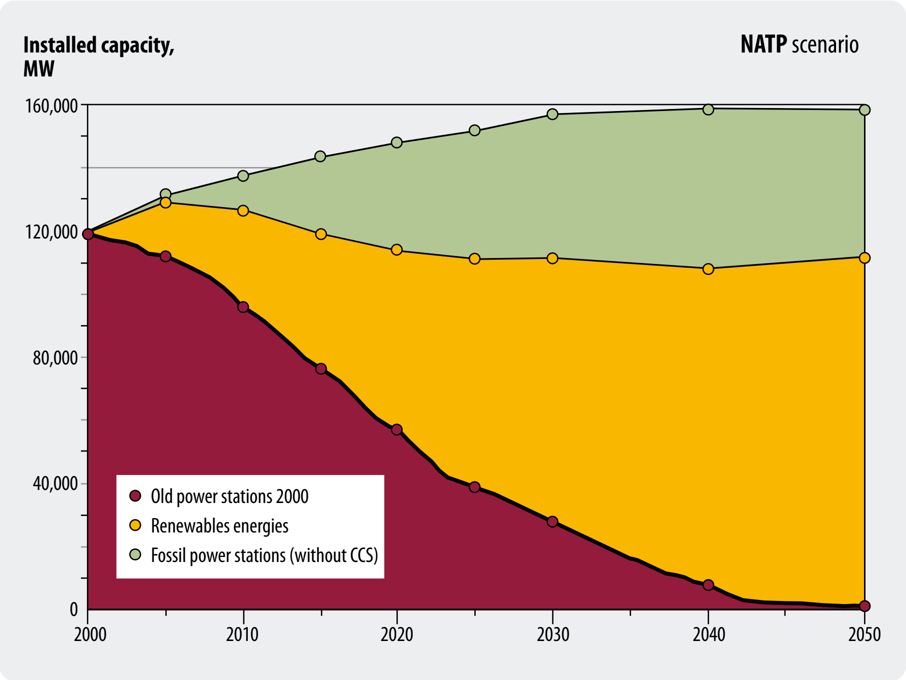
[9] So *indirect* CO_2 emissions (from upstream processes) and other greenhouse gases (e.g. methane) are not included here. The LCAs in chapter 10 show, however, that these emissions assume significant dimensions.

Fig. 14-9:
Installed output in the NATP scenario: old power stations, new renewable energy plant and new fossil-fuelled power stations without CCS



- Renewables and cogeneration plants will be expanded in the dimensions described above.

Fig. 14-7 to Fig. 14-9 show the output curves of the different power station types in the three scenarios (see also Table 14-3). In Fig. 14–7 and Fig. 14–8 the upper segment represents installed CCS capacity divided into new and retrofitted plant. By 2020 42 GW (CCSMAX), 36 GW (BRIDGE) or 30 GW (NATP) of new fossil-fuelled large scale power station capacity – which cannot initially be equipped with CCS technology – will already have to have been installed. On the basis of the assumed conditions the following maximum CCS capacities can be installed by 2050:

- **CCSMAX:** 47 GW (of which 7 GW coal, 14 GW lignite, 27 GW natural gas; power station structure until 2030 taken from Energiereport IV [EWI and Prognos 2005])
- **BRIDGE:** 36 GW (14 GW coal, 8 GW lignite, 14 GW natural gas)

The installed capacity of all renewables – currently 27 GW – rises through expansion measures to between 64 GW (CCSMAX) and 112 GW (NATP). Apart from biomass and thermal storage in conjunction with solar thermal and geothermal power, their capacity utilisation may fluctuate depending on conditions. The fossil-fuelled power station capacity required in the CCSMAX scenario rises slightly until 2020 before returning to about today's level with a figure of about 83 GW. It falls slightly until 2050 in BRIDGE to reach 74 GW and falls strongly in NATP to 47 GW. These figures also include a growing trend towards fossil-fuelled CHP capacity (currently 18 GW, in 2050 in CCSMAX 31 GW, in BRIDGE and NATP 36 GW).

To reflect the different power station structures the scenarios model a broad range of possible investment strategies. As a consequence the power station load factors are different too. In 2050 in the CCSMAX scenario 228 TWh/a of electricity are generated from CCS power stations (40 %) and in the BRIDGE scenario 146 TWh/a (27 %).

Fig. 14-10 and Fig. 14-11 show how these data fit into the overall generation structure. The CCSMAX scenario demands extremely fast growth of CCS technologies if the opportunities offered by power station replacement

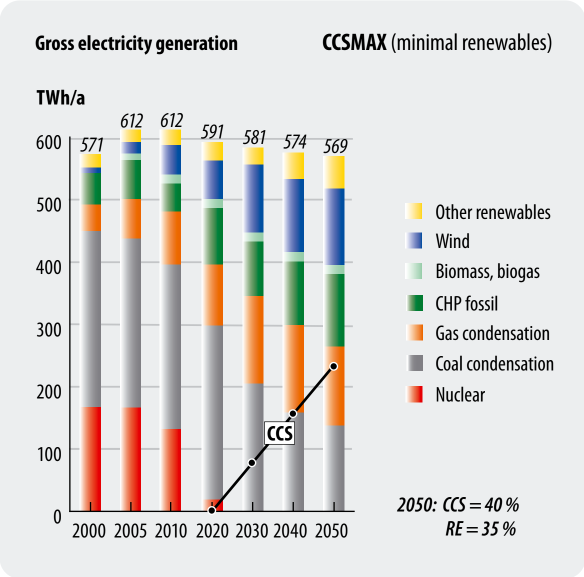


Fig. 14-10: Structure of gross electricity generation of CCSMAX scenario RE = renewable energies

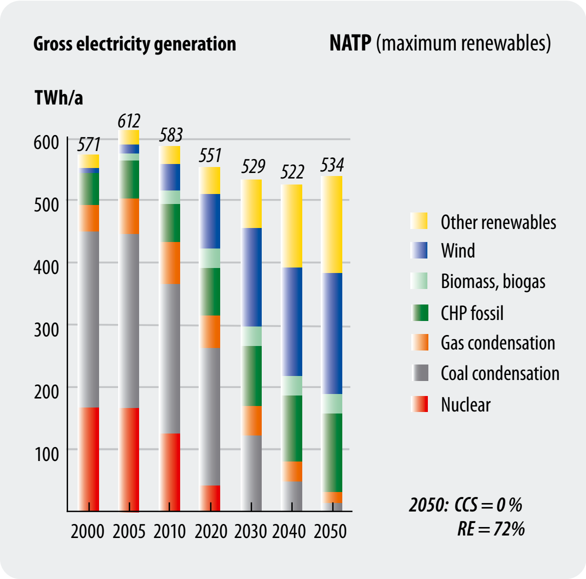


Fig. 14-11: Gross electricity generation in the NATP scenario

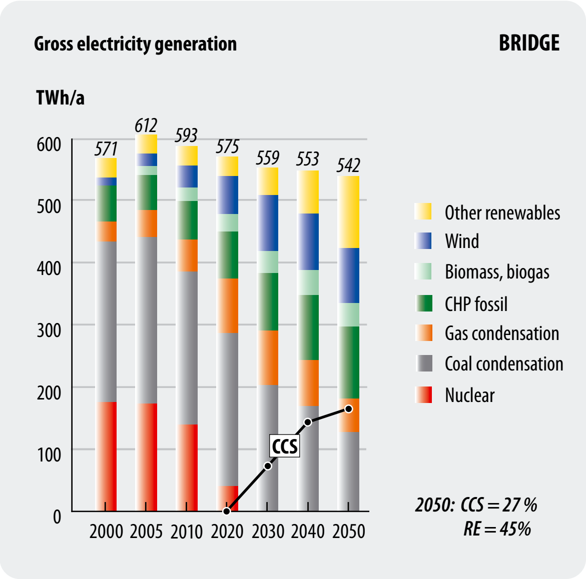


Fig. 14-12: Gross electricity generation in the BRIDGE scenario

demand are to be used to the full. Between 2020 and 2050 an average of 1,600 MW CCS power station capacity would have to come on stream every year (or after 2030 to be retrofitted). In BRIDGE it would be less at 1,200 MW/a, but still considerable.

In all three scenarios between 72 % and 75 % of electricity in 2050 is generated with low or no emissions with different shares in the two technology categories (Fig. 14-10 to 14-12). Because of the differences in total amount generated, the respective absolute amounts vary between 384 TWh/a (NATP: 72 % renewables + 0% CCS out of total 534 TWh/a) and 425 TWh/a (CCSMAX: 35 % renewables + 40 % CCS out of total 569 TWh/a).

Fig. 14-11 clearly shows the effects of the investment strategies on CO_2 emissions from electricity generation. By 2020 the combination of ambitious efficiency measures and continuing expansion of renewables in the NATP scenario leads to a clear fall in CO_2 emissions that more than compensates for the phasing out of nuclear power. The assumed smaller contribution of the efficiency and renewables strategy in the BRIDGE scenario leads to a fairly stable level of emissions between

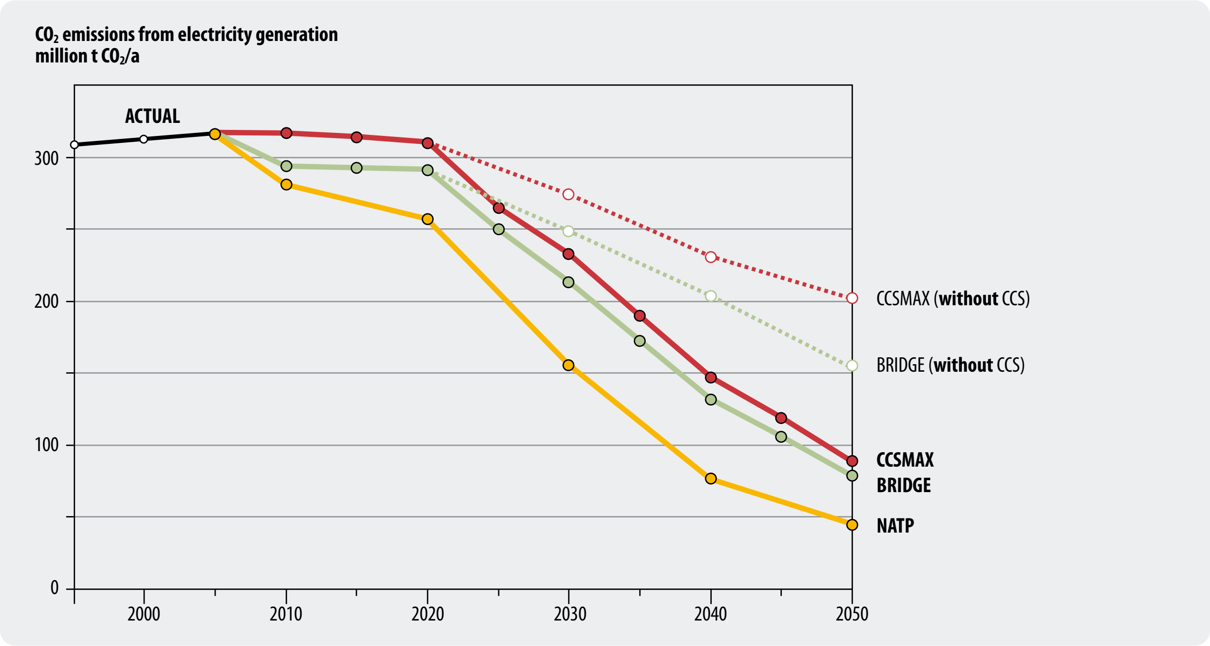


Fig. 14-13: CO_2 emissions from electricity generation in the scenarios (broken line = without introdution of CCS technologies; CHP electricity generation with credit for heat supply)

2010 and 2020 when the impact of phasing out nuclear power is greatest. In the CCSMAX scenario today's level of emissions is maintained until 2020. In comparison to the efficiency and renewables strategy in the NATP scenario, the CCS deployment scenarios achieve comparable gradients of CO_2 reduction after 2020, but are unable to make good the deficit that has accumulated before 2020. The NATP scenario achieves the lowest emissions figure for the electricity sector, with just 45 million t CO_2/a. By contrast, the CCSMAX scenario has 90 million t CO_2/a and the BRIDGE scenario 80 million t CO_2/a. In the BRIDGE scenario the CO_2 emissions avoided through application of CCS in electricity generation are 76 million t/a; in the CCSMAX scenario the figure is 113 million t/a.

Theoretically the NATP scenario could also be combined with a CCS strategy after 2020 to achieve similarly low emission values in 2050. But to do that the expansion of renewables would first have to be accelerated hard until 2020 and then drastically reduced again to free capacity for increased construction of CCS power stations. Under the conditions of these scenarios there would be no reason to do that because by that point – especially through their dynamic expansion – renewables (apart from photovoltaic) would have become almost completely competitive on the electricity market. So it is then unlikely that in this scenario CCS technologies would be able to gain any worthwhile foothold in electricity supply. If the expansion dynamic of renewables continued as in NATP it would at least in theory be possible to install about another 15 GW of CCS capacity by 2050. But this would have to occur primarily in cogeneration plants and in power stations with low load factors, so that only 40 TWh/a of CCS electricity could be generated. That would be an absolutely unattractive market niche.

If renewables are expanded more slowly from the outset – as proposed in the BRIDGE scenario – and at the same time progress on efficiency is slow, CCS technologies would have greater chances of establishing themselves in the German electricity market after 2020. In this scenario the market volume for CCS technologies is around 47 GW. For 2050 this results in a relatively balanced mix of electricity from renewables (245 TWh/a), CCS electricity (146 TWh/a) and conventionally generated electricity from fossil fuels (150 TWh/a). In this case CCS technologies could compensate for less than ideal development of renewables and efficiency technologies and thus ensure a tolerably low level of emissions from electricity generation (80 million t/a in 2050). Table 14-4 shows the situation in 2050 after introducing CCS for electricity generation.

Table 14-4: Effects of applying CCS in electricity generation in the CCSMAX and BRIDGE scenarios in 2050

	Avoided CO_2	Captured CO_2	Extra primary energy required
	million t/a	million t/a	PJ/a
CCSMAX	**112.8**	**156.9**	**382**
from coal	16.7	21.9	44
from lignite	65.9	96.4	225
from natural gas	30.3	38.6	112
BRIDGE	**75.5**	**103.6**	**241**
from coal	27.8	36.5	74
from lignite	33.4	48.8	114
from natural gas	14.4	18.3	53

14.2.4 Scenarios for Developing CCS Technologies in the Hydrogen Sector

Even with great success, emission-reducing measures in the electricity sector alone will not be sufficient to reduce total emissions far enough to meet the 80 % climate protection target. Similarly comprehensive measures are also required in the heat and vehicle fuels sectors. If we wish to apply CCS technologies here too, one obvious option is generating hydrogen from fossil primary energy while retaining the CO_2. Questions of resources and cost mean that only coal gasification comes into consideration.

The quantities of hydrogen to be produced in the scenarios were selected so as to ensure that the overall climate protection goal for 2050 was achieved for the German energy system (i. e. NATP emissions level, 240 million t CO_2/a). The following assumptions were made:

- The overall efficiency of coal gasification with CO_2 capture is 65 %, the plant load factor is 7,800 h/a. The CO_2 capture rate is 88 %, so CCS hydrogen is thus still burdened with CO_2 emissions of 0.017 million tCO_2/PJ_{H2} (in relation to the coal used that means 0.011 million tCO_2/PJ_{th}).
- CCS hydrogen only substitutes oil products (heating oil, petrol and diesel). So 0.055 million t CO_2 can be avoided for every PJ of hydrogen used (if natural gas is replaced the substitution effect sinks accordingly and amounts to just 0.039 million t CO_2/PJ_{H2}).
- In all the scenarios a baseline of 300 PJ/a is reached in 2030; this requires 16.5 GW_{th} gasification output and 460 PJ/a of coal, with which 310 PJ/a of crude oil can be substituted.

The quantity of H_2 required in 2050 in the CCS scenarios varies depending on the assumed reduction in final energy demand through increases in user efficiency and the assumed expansion of renewables. Table 14-5 summarises the main data.

Table 14-5: Application of CCS in hydrogen production in the CCSMAX and BRIDGE scenarios in 2030, 2040 and 2050

	Hydrogen	Coal required	Gasification output	CO_2 reduction*)	CO_2 captured	Extra primary energy required*)
	PJ/a	PJ/a	GW_{th}	million t/a	million t/a	PJ/a
2030						
Both	300	462	16,5	17	37	152
2040						
CCSMAX	1,000	1,538	55	55	125	502
BRIDGE	700	1,077	38	38	87	351
2050						
CCSMAX	3,440	5,290	188	189	429	1,725
BRIDGE	1,800	2,770	99	99	224	904
*) Substitution for mineral oil						

In order to achieve the set goal of reducing CO_2 emissions to 242 million t CO_2/a in the BRIDGE scenario, about 60 % of the oil demand in 2050 would have to be replaced with 1,800 PJ/a hydrogen; in the CCSMAX scenario it would have to be 95 % (3,440 PJ/a hydrogen). The contribution made by hydrogen in this scenario would also influence the use of fossil feedstock in the chemicals industry, which would then have to partially switch to natural gas or synthesis gas produced by coal gasification. But these interactions cannot be investigated in any greater detail here. A move to substitution of natural gas is not sensible because of the small substitution effect, or would cause relatively high CO_2 avoidance costs. The additional quantities of coal required amount to 27 % (BRIDGE) to 42 % (CCSMAX) of total primary energy demand in 2050.

The expansion of gasification capacity would have to occur exceptionally quickly, with 1,650 MW_{th}/a having to be constructed between 2020 and 2030. In the period 2040 to 2050 this construction rate would have to rise to 6,100 MW_{th}/a in the BRIDGE scenario and to the very considerable figure of 15,000 MW_{th}/a in the CCSMAX scenario. So one minimum precondition for implementing this strategy would be for commercial coal gasification plant to be set up on a large scale from 2020 without major teething or acceptance problems and for hydrogen production and CO_2 capture and storage to operate at high load factor.

A second significant criterion is that a hydrogen infrastructure would need to follow this growth. Although the share of hydrogen in final energy demand in 2040 is relatively small in CCSMAX (14 %) and BRIDGE (10 %), by 2050 in the CCSMAX scenario hydrogen would already be the predominant final energy type (with 47 %). From today's perspective that appears to be a great obstacle (UBA 2006). But a share of 29 % (= 1,900 PJ/, including 100 PJ/a renewable hydrogen), as required in the BRIDGE scenario to meet the climate protection target, appears achievable by 2050 in terms of infrastructure.

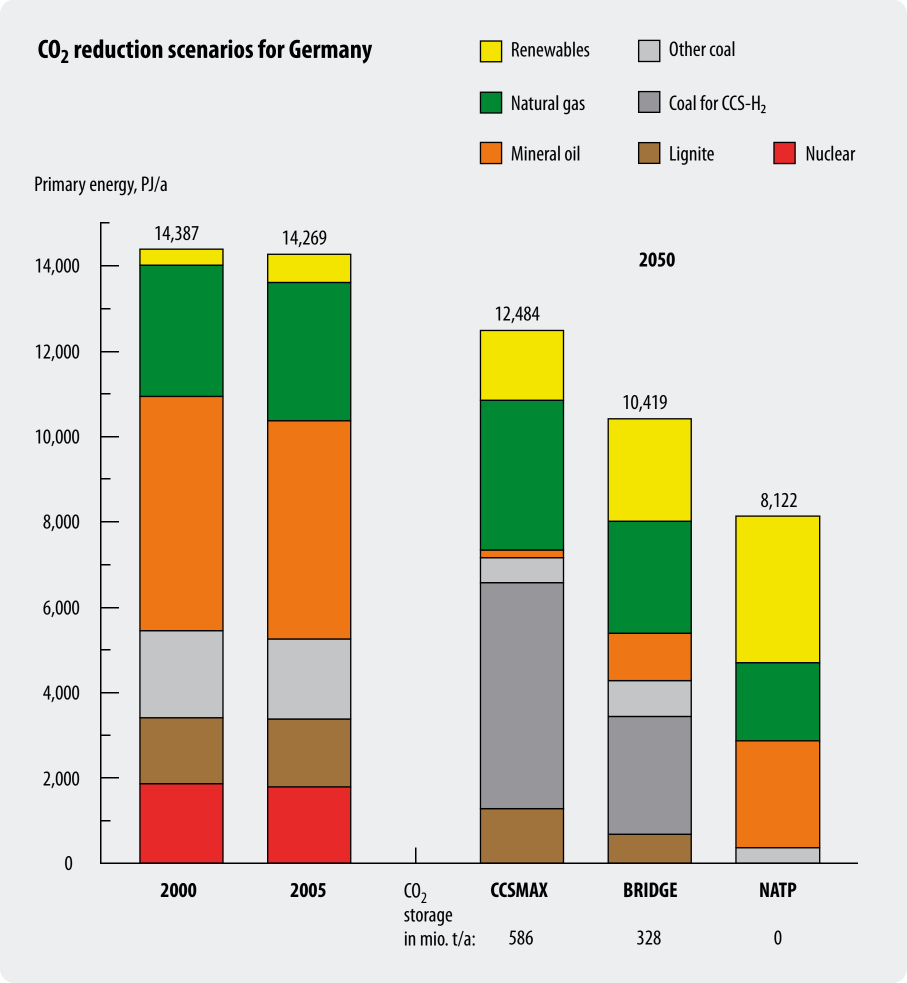
14.3 Conclusions of the Scenario Analysis for Germany

In our overall analysis we found very different structures for primary energy supply in Germany in 2050. The CCSMAX scenario represents an energy future strongly shaped by coal, indeed to speak of a 'renaissance of coal' would not be exaggerated. Here coal represents 47 % of primary energy, plus another 10 % lignite. Together with natural gas (whose quantities in this scenario are about the same as today) the share of fossil primary energy is 87 % – which is higher than today's 83 % (Fig. 14-14).

In the BRIDGE scenario, too, fossil fuels still predominate with a total of 77 %. Here coal with 35 % is no longer the predominant energy source, but it still represents the main fossil fuel. However, efficiency successes are already notable here (17 % less primary energy than in CCSMAX) as well as a noticeable contribution from renewables. In the NATP scenario effective implementation of major efficiency measures allows the absolute contribution of fossil fuels to be reduced considerably, to represent only 58 % of energy needs by 2050.

Fig. 14-15 compares the changes in primary energy structure in the CCSMAX and NATP scenarios. Put simply, NATP's avoidance of energy demand and greater contribution from renewables is replaced in the CCSMAX scenario by fossil primary energy whose CO_2 emissions are considerably reduced through the use of CCS technology. But in order to meet the 2050

Fig. 14-14:
Primary energy structures in 2000 and 2005 and in the scenarios for 2050, showing the amounts of coal required for production of CCS hydrogen



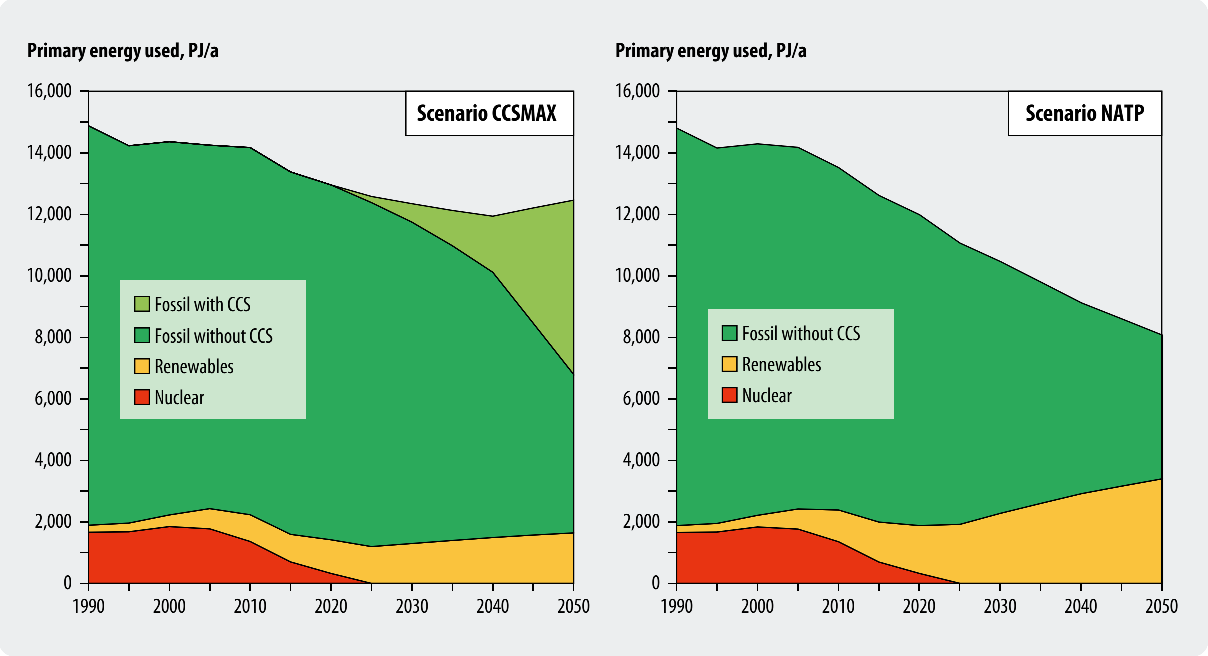


Fig. 14-15: Primary energy sources in the CCSMAX and NATP scenarios

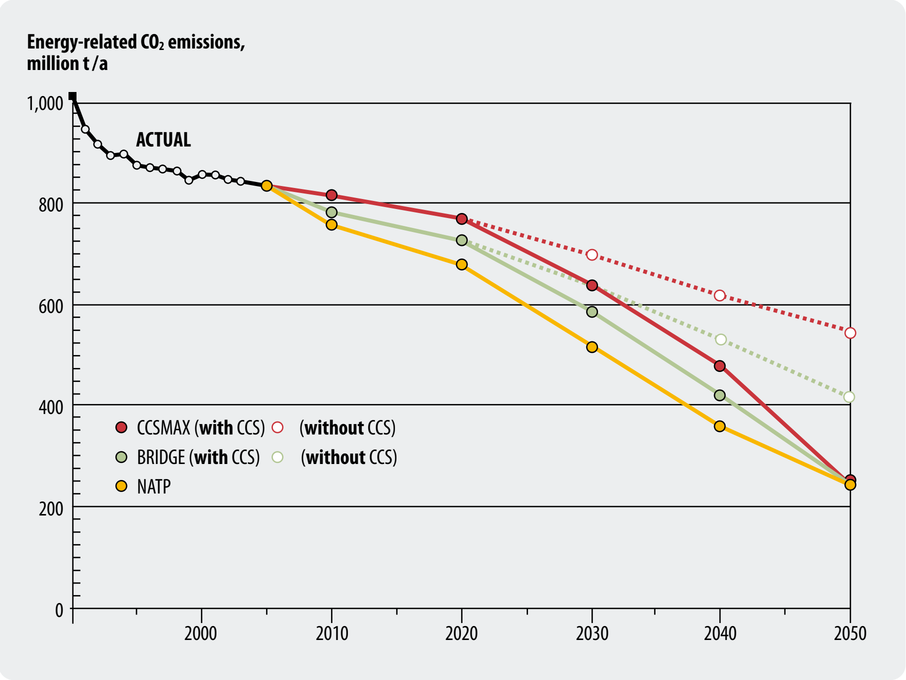


Fig. 14-16: Energy-related CO_2 emissions in the CCSMAX, BRIDGE and NATP scenarios until 2050 (broken line = CCSMAX/ BRIDGE without CCS technologies)

climate protection target extremely fast growth rates in that technology would be required after 2020 – a good deal faster even than the current rates of expansion in renewables.

All the scenarios meet the defined climate protection target in 2050 (Fig. 14-16).[10] In CCSMAX the climate protection measures progress too slowly until 2020 and have to 'catch up' later in order to meet the target by 2050. Altogether CCS can be used to avoid between 175 million t CO_2/a (BRIDGE) and 300 million t CO_2/a (CCSMAX) in 2050, compared to the reference case. In 2030 and 2040 the contribution from the electricity sector still predominates, but by 2050 the contribution from hydrogen production is foremost (Table 14-6). In the CCS scenarios considerable amounts of CO_2 have to be captured and stored. In particular substituting mineral oil with hydrogen from coal (including CCS) requires capturing 2.26 million t CO_2 per *avoided* tonne of CO_2. This puts the amount of CO_2 to be captured and stored in 2050 at between 586 million t/a (CCSMAX) and 328 million t/a (BRIDGE). Under these conditions the available storage volume in Germany would be exhausted within 25 to 80 years in the CCSMAX scenario (44 to 145 years in the BRIDGE scenario).

The **main points** are the following:

- As the main pillar of a climate protection strategy, CCS as modelled in the **CCSMAX scenario** runs into structural limits if the climate protection target of reducing CO_2 emissions by 80 % by 2050 is to be met with efficiency and renewables merely following a 'business as usual' trajectory. The assumption that CCS technologies will not be commercially viable before 2020 necessitates accelerated construction of CCS plant and hydrogen infrastructure during the remainder of the period until 2050. The high demand for coal (in CCSMAX approx. 5,900 PJ/a or 3.1 times today's figure) leads to extensive purchases on the world market which would lead to corresponding price reactions. Cost advantages for the forms of energy produced using CCS (electricity and hydrogen) compared to renewables cannot be identified (electricity) or are small (hydrogen) so from the economic perspective there is no decisive incentive for such a one-sided prioritisation of CCS. Furthermore such a strong expansion of CCS would necessitate starting straight away with great investment in R&D and pilot plants for this technology option on a scale incompatible with the current energy policy of promoting efficiency strategies and expanding renewables. Also a very high degree of clarity would have to be achieved very quickly regarding the ecological compatibility and safety of CO_2 storage. To pursue both strategies 'at full steam' until 2020 (efficiency and expansion of renewables following NATP until 2020; CCS development as in CCSMAX), but then to largely drop one of the options would not be a sensible way to proceed. Also the potential storage capacity for CO_2 is insufficient for the required massive expansion of CCS.

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[10] Here the climate protection target is defined solely in terms of the greenhouse gas CO_2. However, the large amounts of coal required for BRIDGE and especially for CCSMAX are associated with emissions of methane during coal mining, with considerable negative climatic impact (see chapter 10).

Table 14-6:
CO_2 emissions in the scenarios with and without CCS technologies, captured CO_2 quantities and resulting additional primary energy demand

	CO_2 emissions (million t/a)					captured (million t/a)			Additional primary energy demand (PJ/a)		
Year/ scenario	Total without CCS	reduction			Total with CCS	H_2	Electricity	Total	CCS H_2	CCS-electricity	Total
		through electricity	through H_2	Total							
2005	824 *)	–	–	–	–	–	–	–	–	–	–
2020											
CCSMAX	696	41	17	58	638	37	67	94	152	139	291
BRIDGE	638	35	17	52	586	37	48	85	152	110	262
NATP	517	0	0	0	517	0	0	0	0	0	0
2030											
CCSMAX	616	84	55	139	477	125	117	242	502	286	788
BRIDGE	530	72	38	110	420	87	100	187	351	228	579
NATP	357	0	0	0	357	0	0	0	0	0	0
2050											
CCSMAX	544	113	189	302	242	429	157	586	1,725	382	2,107
BRIDGE	417	76	99	175	242	224	104	328	904	241	1,145
NATP	242	0	0	0	242	0	0	0	0	0	0

*) Temperature-adjusted

- A climate protection strategy following the **NATP scenario,** which manages without CCS, would not yet develop of its own accord. As well as maintaining the current dynamic rate of expansion of renewables in the electricity sector and extending their use to the heat sector on a significant scale, considerable additional support measures to encourage much greater efficiency in use and conversion of energy would be required if the 2050 climate protection target is to be met on time by this strategy. Expanding renewables and increasing efficiency are measures that take effect relatively quickly so – as long as the necessary support measures impact quickly – they allow the restructuring process to run more harmoniously than in the CCSMAX case described above. Major transformation of energy infrastructures would be required, but this could be realised in stages. A strategy concentrating especially on energy productivity also makes sense in broader economic terms because many of the efficiency measures to be taken represent the most economic option for climate protection regardless what measures are taken on the supply side. If external costs were included the overall economic situation would be even more favourable. To that extent this scenario represents an **'ideal strategy'** but one which demands that very effective energy policy decisions be taken quickly, especially a clear target oriented and expansion of energy efficiency policy (including combined heat and power). In the longer term this scenario necessitates considerable structural changes, increasing network and system integration on the electricity side, integrating energy import structures (e.g. electricity from solar thermal power plant in North Africa) and greatly expanding district heating systems.

- From today's perspective a development in line with the **BRIDGE scenario** would also definitely require additional stimuli for further increases in efficiency and further expansion of renewables that would have to exceed the current reference development. However, the necessary changes would probably be easier to implement than in the case of the NATP scenario. They are also easier to justify to other countries that have made less progress than Germany in the direction of an 'ideal' NATP strategy or have a greater interest in using coal. The pressure to introduce CCS technologies and a hydrogen infrastructure is less than in CCSMAX because until 2030 the required contributions from these options can remain relatively small. Nor – in the event that CCS technologies turn out to be a sensible energy policy option – does the level that needs to be reached by 2050 come up against any fundamental limits concerning required plant capacity, infrastructure changes or storage capacity.

In view of the real interests involved and the different assessments of technology options in the field of energy (especially in the global context), an energy policy following the BRIDGE strategy can be characterised as a **'pragmatic' strategy.** It demands a general intensification of energy policy efforts on a broad front (CCS, energy efficiency, renewables) if long-term climate protection goals are to be tackled seriously. At the same time this strategy offers the possibility – in the interval until 2020 – of exploring the development and cost potentials of CCS technologies thoroughly and without enormous pressure of time and demonstrating their feasibility in initial pilot plants.

Analyses of the costs of renewables and CCS technologies for producing electricity and hydrogen show no obvious economic advantages for the CCS option. If the learning curves for renewable energy technologies continue and our assumptions about price developments for fossil fuels are correct, electricity generation from most renewable energy technologies around 2020 will tend to be cheaper than electricity generation with CCS. The latter will definitely require CO_2 prices between 30 and 50 €/t CO_2 if it is to be attractive to private investors compared with conventional electricity generation from fossil fuels. After 2020 the costs of renewable energy technologies fall still further, while the real cost of generating electricity from coal with CCS will probably remain roughly constant if technical developments are taken into account. If we include the external costs we find further advantages for energy efficiency and renewables.

There are many uncertainties concerning the relative profitability of CCS and renewables. The assessments presented above for renewables are based on a dynamic global market where very considerable cost-reduction effects can be exploited via mass production and learning curve effects.

One factor that could impede a comprehensive CCS strategy is that the broad introduction of generally expensive low-CO_2 or CO_2-free hydrogen has to come earlier than in a strategy based on the NATP scenario.

The aspects discussed above show that a consistent strategy following the NATP scenario make more economic sense in the medium to long term and should therefore be the goal of energy policy. At the same time it is advisable to subject the CCS option to continued thorough scrutiny and in particular a realistic practical demonstration, in order to have – after about a decade – more precise knowledge of the potential and limits of these technologies. If it then turns out that in the global restructuring of the energy supply the expansion of energy efficiency and renewables is 'only' running at the intensity laid out in the BRIDGE scenario, CCS would offer an additional climate protection option.

14.4 Applicability of Results to Other Countries

The analyses described above were conducted for Germany taking particular account of the situation there. This means they cannot be applied to other countries one-to-one. At the same time certain underlying tendencies do also apply elsewhere and in some cases similar starting conditions are also present (e.g. large demand for short-term power station replacement). The scope of this study precludes us from going into the role of CCS in other countries in detail, but in the following we bring together findings from the scenario analyses for Germany that can be regarded as being more broadly applicable. The concluding chapter of this report (chapter 15) also examines the discussion of the role of CCS from a global perspective.

The following aspects are of a more general nature:

- The future role of CCS is affected by various factors. These include the structure and age of power station capacity and especially the domestic availability of fossil fuels. Countries with large coal reserves of their own (e.g. China, Australia) will be keen to use them as intensively as possible even if conditions (especially climate protection rules) change significantly.

- Large-scale CCS technologies will probably not come on stream until 2020, but the international trend for massive expansion of power station capacity continues apace (especially new coal-fired power stations). Just in China a new power station starts operation every week. This means it is necessary not only to consider new builds but also to direct increasing attention to the retrofitting option. Between 2006 and 2020 China will build about six to eight times more new power station capacity than the current installed total in Germany. Development efforts in this connection are required in particular to reduce the extra fuel required after CCS retrofitting (e.g. through more efficient scrubbing processes). But the question of how power stations can be prepared for later retrofitting (capture-ready status) when they are still at the planning stage (i.e. before they are even built) also needs to be answered.

- A climate protection strategy based largely on CCS appears conceivable neither for Germany nor for most other countries. Structural limits (e.g. storage capacity, infrastructure aspects) mitigate against it as does the necessity, according to climatologists, to take action well *before* 2020 not only to initiate climate protection measures but to implement them too.

- For Germany the analyses show that ambitious climate protection targets can be met without using CCS at all. For other countries with an even stronger focus on coal or faster growth rates for energy demand this might be more difficult or require deeper structural changes. But for these countries too, further expansion of renewables and improvements in energy efficiency will be the climate protection strategy of choice.

- The extent to which renewables and energy efficiency improvement meet with resistance that hinders their implementation and increases demand for supplementary climate protection measures will be a decisive question. This may differ from country to country and increase the necessity for CCS as a bridge technology.

- The decisive factor for introducing CCS need not necessarily be the field of electricity generation. It is also conceivable that the greatest impetus will come from the production of hydrogen from fossil fuels. Rising oil prices in recent years (to more than $90 per barrel) and the almost complete dependence of the transport sector on fossil fuels (especially petroleum products) have increased the incentives to turn to alternative options for supplying fuels. Alongside first- and second-generation biofuels these also include producing liquid fuel from coal. Processes for turning coal into synthetic fuels (coal-to-liquid) are being pursued in various countries, especially China, the United States and South Africa. But they suffer the great disadvantage that (considering the whole process from extraction to combustion) they have 90 % higher CO_2 emissions than conventional petrol or diesel. Even if the CO_2 produced during the conventional coal liquefaction process is captured and stored, the emissions over the process as a whole are higher than for the reference fuels. If coal is to replace conventional fuels while observing climate protection restrictions the only current option is producing hydrogen from coal and capturing the CO_2. This would require infrastructure investment as described above for the CO_2 logistics and for a completely new hydrogen infrastructure.

- Polygeneration projects of the kind currently planned or being implemented by RWE in Germany (and other actors elsewhere in the world) represent door-openers for such developments. These plants, based on gasification technology, possess great flexibility both in terms of the fuel they use and the product they produce. Possible products are electricity, synthesis gas, synthetic liquid fuels (via Fischer-Tropsch synthesis) and hydrogen.

- Finally it must be supposed that countries with potential for EOR or EGR (and consequently with a commercial interest in using CO_2) will be among the leaders. Companies from these countries may also be interested in expanding the capture of CO_2 during natural gas extraction (e.g. in LNG and H_2).

- Decisive impetus is also expected from countries with a strong gas industry (e.g. Norway, United Kingdom). They possess know-how that can be put to profitable use and depleted gas fields with storage potential.

- As well as the aspect of climate protection, implementation of CCS will also be determined by other, sometimes very pragmatic aspects. In particular tangible economic advantages will also make certain countries (or more precisely certain actors from these countries) into pioneers. This applies above all to countries such as Norway and the United Kingdom, which possess considerable storage potential underneath the seabed in hydrocarbon deposits and saline aquifers deep below the North Sea.