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TECHNICAL AND ECONOMIC PARAMETERS OF CO_2 CAPTURE FROM POWER PLANT FLUE GASES

The paper investigates the technical and economic (cost) parameters of the release, capture and disposal of CO_2 from the flue gases of power plants using fossil fuels (coal, natural gas), making comparisons and generalisations on the basis of the analysis of a wide range of data in the literature. First, the paper gives reasons why the topic is a hot issue and proves the role of fossil fuels in future energy supply with forecast data. During the technological improvement of power plants in the last 50 years, block capacity has shown a considerable, 5-8 times increase with thermal efficiency increasing by 50-60%, resulting in a 30-40% decrease in specific carbon dioxide release. The paper briefly refers to the theoretical possibility of the sequestration of CO_2 in geological formations. The effects of the implementation of CO_2 capture on increasing investment costs and decreasing fuel utilisation (thermal) efficiency are analysed. The efficiency of CO_2 capture and the parameters of atmospheric carbon dioxide emission are given for the different fuel types and technological solutions. In relation to the technological solutions of capture, it is indicated what amount of specific costs (USD/t_{CO2}) is expected for CO_2 capture-avoidance and to what extent the costs of electric energy production are increased by capture-avoidance.

1. Introduction: Financing CCS (Carbon Capture and Storage) projects

Like every fundamentally new technological solution, the research and development of energetics systems of large capacity integrating a wide range of technologies and their industrial application require considerable financial resources. The complex technical tasks of large capacity energetics systems (involved in fuel production, processing, combustion, the conversion of heat energy into electrical energy, the treatment and disposal of the combustion products – in this case, those of flue gas CO_2 content), exceedingly high investment costs and long lifecycle raise specific problems. The risks involved in technological solutions and financial (economic) investments also deserve separate consideration.

In relation to the financing of research and particularly investment costs, the different countries apply different solutions. Experts indicate public-private partnership as the precondition for the successful elaboration and actual implementation in industry of CCS or other technologies of similar effect.

The situation in Germany, where RWE Power AG operates two CCS projects bearing the full risks and financial burdens of research and the demonstration plant, is almost unique. [1] One of these projects involves the development of an IGCC (Integrated Gasification Combined Cycle) coal-fired power plant of zero CO_2 emission and 450 MW output while the other is concerned with the implementation of a lignite-fired plant of 1,000 MW output with CO_2 scrubbing.

The condition of development financing is state support, in lack of which economic considerations favour power plants without capture. According to expert opinion, the state should bear the first specific risks of construction and capture. Expectedly, these risks may only be eliminated in the long run. In all probability, it will be unavoidable to compensate first users and initial risk takers.

2. Development of coal-fired power plant technologies towards CO_2 emission reduction (capture and storage)

If one has just a brief overview of the 50 years' past (the period since 1950) and the (currently foreseeable) 15-20 years' future development of coal-fired (coal, brown coal, lignite) power plant technologies, one can say that there is an almost 'paved' way to the minimisation of carbon dioxide emission, and the solution of CO_2 capture from flue gases and its related storage.

In the period between 1950 and 1970, block capacities of 50, 150 and 300 MW operated with thermal efficiency varying between 25-31%. In the period between 1970 and 1990, unit capacity increased to 300-600 MW, which raised thermal efficiency to 31-36% by about 30%. Coal combustion first applied AFBC (Atmospheric Fluidized Bed Combustion) and then PFBC (Pressurized Fluidized Bed Combustion) optimized technology for brown coal fired power plants (German abbreviation: BoA). The current (1990-2010) technology makes 1,000 – 1,100 MW block outputs possible, thus enhancing the parameters of the 31-36% thermal efficiency of the previous period by another 30% and yielding 40-45% efficiency.

In the general course of development, BoA-Plus technology (involving flue gas scrubbing) achieves 38-41%, while CGCC (Coal Gasification Combined Cycle), IGCC (Integrated Gasification Combined Cycle) and gas- and steam-operated (GuD) power plants yield 38-43% efficiency. In addition to enhancing technical parameters (250-270 atm pressure, 500-700° temperature) and flue gas scrubbing, BoA-Plus technologies provide 41-43% efficiency. In this area, the further increase possibilities of technical parameters (p, T) are limited by material quality problems. The technologies of the future (2010-2020) aim at 45-50% efficiency with CO_2 capture although the latter may actually result in an efficiency reduction of 8-12%. Technologies beyond 2020 represent the day after tomorrow with the promise of 55-60% efficiency in the case of certain solutions. (Hybrid-KW 58-63%, SOFC (Solid Oxide Fluid Cell) 50-57%) [9].

The other basic development trend, aiming at the mitigation of adverse environmental impacts, is desulphurisation flue gas scrubbing, widely applied in practice. The development trend of our age and the future is the minimisation of carbon dioxide emission. An essential, reasonable solution to specific carbon dioxide release has been and may remain an increase in thermal efficiency (t_{CO2}/MWh, g_{CO2}/kWh) in the future, as well. Any increase in efficiency reduces specific CO_2 release and emission proportionately. With 150 MW blocks, CO_2 release is 1.3 t_{CO2}/MWh while with 600 MW units, this value is 1.15-1.20 t_{CO2}/MWh. With BoA-Plus technology, specific CO_2 is only 0.8-0.9 t_{CO2}/MWh while with BoA-Plus +700°C, IGCC and CGCC technologies, not even 0.7-0.8 t_{CO2}/MWh is impossible. It is a fundamental objective for the technologies of the near (2010-2020) and more remote (2020 and beyond) future to achieve CO_2 capture (minimisation of emission) and the achievement of zero emission (ZEC, ZECA) with the 'final' sequestration and storage of the CO_2 captured. [10]

These latter technologies of the future (Oxyfuel, Hybrid-KW, SOFC) take into account a decreasing, 600-700 g/kWh specific CO_2 release even without capture.

3. Variation of power plant investment costs for different fuel types, and technologies with or without CO_2 capture

At the turn of the millennium, fossil fuels accounted for more than 85% of the world's energy demand. On the basis of the investigation of coal and hydrocarbon reserves and the prognostication of the changes in energy demands, several experts are of the opinion that until the middle of the 21st century, the rate of fossil fuels will surely be between 50 and 80%. [15, 16, 17, 18, 19]

In the investigation of this topic, it is often crucial to compare the 'use' features of the different fuel types, i. e. coal and hydrocarbons.

With a traditional steam turbine system (PC), specific investment cost is 760 USD/kW with gas combustion and 1,600 USD/kW with coal combustion, the rate being 210%. The surplus specific investment cost of the gas combustion system is 520 USD/kW with a combined steam-gas cycle while that of the coal combustion system with IGCC is 1,700 USD/kW, the latter being 327% of the former. With steam injected gas turbines, the values 410/3,100 give a rate of 317%. The rate of the extra cost of coal use is 258% (400/1,300) with a steam-injected gas turbine with intermediary cooling and 167-188% (600-800/1,000-1,500) with 'state-of-the-art' fuel cell technology. [20]

The technical implementation (and, naturally, the energy demand) of CO_2 capture increases power plant investment costs considerably. Different capture technologies and obviously, different cost enhancing factors present themselves for the different fuel types (gas, coal) and the application of different combustion technologies.

According to 2004 data, the specific investment cost for the gasification combustion of bituminous coal is 1,410 USD/kW without capture and 1,917 USD/kW with capture, the extra cost amounting to 507 USD/kW or 36%. For the gasification combustion of sub-bituminous coal, specific investment cost is 1,502 USD/kW and 2,190 USD/KW, respectively, with an increment of 688 USD/kW or 46%. With the combustion of lignite of lower heating value, for gasification and amine flue gas scrubbing, the increment is 1,184 USD/kW with a rate of 72% for the respective values of 1,644/2,828 USD/kW. For oxyfuel combustion technology, the increment is 2,330 USD/kW equalling a rate of 142% for the respective values of 1,644/3,974 USD/kW. The latter technology requires more than double investment costs to solve capture due to oxygen use and the 'recycling' of carbon dioxide. [21]

In their paper, J. David and H. Herzog [22] developed a complex costing model of CO_2 capture drawing on publications in this topic.

They calculated the 'additional' investment cost for a 1 kg/h CO_2 capture capacity, as well. The specific additional (surplus) cost of CO_2 capture capacity (performance) is lowest for coal powder combustion [~ 300 USD/(kg/h)] while it is ~ 500 USD/(kg/h) for combined cycle coal combustion and 800-900 USD/(kg/h) for gas combustion. The significant, two or three times difference is due to the difference between the CO_2 concentrations and pressure parameters of the flue gas produced and appears in the energy demand of capture, as well.

With gas combustion, flue gas CO_2 concentration is 'only' about 3% and the energy demand of capture is 0.354 kWh/kg_{CO2}, while with coal powder combustion, concentration is about 13% and the specific energy demand of capture is 0.317 kWh/kg_{CO2}. In IGCC power plants, carbon dioxide is in a concentrated flow at a relatively high pressure so the specific energy demand of capture is lowest here with a value of 0.194 kWh/kg_{CO2} (year 2000 data). Forecast values of specific energy demand for the year 2012 are: 0.297 – 0.196 – 0.135 kWh/kg_{CO2}.

4. Efficiency of electricity production and heat use for different fuel types and technologies

From the aspect of the technological-economic assessment of the different technologies and the variations of flue gas production rate, one of the essential parameters is thermal efficiency. In addition to thermal efficiency, the different sources give specific heat use and also often, relative energy output as basic parameters. As the energy demand of CO_2 capture reduces efficiency parameters (gross-net efficiency), it may serve as one of the qualifying parameters of the technological and economic characterisation of capture.

In the investigation of paper [20], the comparative assessment of the different fuel types gave the efficiency values of 36% for gas combustion in a traditional steam turbine system, and 34% for coal combustion in the same period. With coal combustion, thermal efficiency was 94% compared to that of gas combustion. In the case of a combined steam and gas cycle, 47-42% is the efficiency parameter achieved, with the efficiency of coal combustion being 'only' 89% of that of gas combustion. For a steam-injected gas turbine, the respective values of thermal efficiency are 40% and 36%, the thermal efficiency of coal combustion being 10% lower. For the gas-injected gas turbine technology with intermediary cooling, thermal efficiencies are 47% and 42%, giving the rate of 89%. With a modern heating cell solution, estimated efficiency values are 50-55% and 45-52%, with a rate of 90-95%.

The authors of paper [22], relying on a technological and cost model elaborated during the investigation of the issue, characterise the impact parameters of reference (traditional) and capture technologies on the basis of specific heat consumption. In the paper, the dimension of specific heat consumption is Btu/kWh, where the dimension of Btu equals approximately 1,055 Joule.

Table 1 – Data published for the years 2000 and 2012 as per technology

Technology year		Specific heat consumption without capture [Btu/kWh]	Specific heat consumption with CO_2 capture [Btu/kWh]	Reduction of specific energy output due to capture [%]
PC	2000	8,277	11,037	25.0
	2012	8,042	9,461	15.0

IGCC	2000	8,081	9,462	14.6
	2012	7,137	7,843	9.0
NGCC	2000	6,201	7,131	13.0
	2012	5,677	6,308	10.0

Table 1: Specific heat consumption for different technologies (2000 and 2012)

As it can be seen from the data presented, the reducing effect of CO_2 capture on thermal efficiency may generally be **10-15%**, depending on technology. For some projects under planning, it is **6-12%**, and according to the paper published in 2007, it is **8%** with more state-of-the-art coal-lignite fired systems. The combined reducing effect of **capture** + **disposal** (including transportation?) may be **14-28%**, according to paper [12].

5. The amount of carbon dioxide released during combustion, the efficiency of CO_2 capture for different technological solutions

In the use of fossil fuels – especially nowadays, when carbon dioxide release is, in a justified or doubtful way, a hot issue due to technological, economic and environmental considerations – carbon dioxide release/production and atmospheric emission are major considerations and as good as primary assessment parameters. The amount of CO_2 released during fuel combustion basically depends on the type (natural gas or coal) and quality (coal, brown coal, lignite) of fuel and the type, performance, up-to-dateness and thermal efficiency of the combustion system (power plant). Atmospheric emission depends on the flue gas cleaning technology also affected by flue gas CO_2 concentrations and the technological solution and efficiency of CO_2 capture.

With a traditional steam turbine technology, specific CO_2 output is 510/920 g/kWh, with a rate of 180 % (+80 %) while with a combined steam-gas cycle, it is 370/730 g/kWh, with a rate of 197 % (+97 %). With gas injected gas turbines, this value is 440/880 g/kWh, with a rate of 200 % (+100 %) while in the case of steam injected gas turbines with intermediary cooling, the respective values are 370/730 g/kWh, giving a rate of 197 %. For state-of-the-art fuel cell technology, a 330-370/620-700 g/kWh CO_2 release is expected with a forecast rate of 188-189 %.

For the different coal types and the different combustion-capture technologies related to them, data can be found in publications [21] and [23]. Presumably, the authors of both relied on the same input data (Table 2).

Table 2 – Specific CO_2 release for different fuels and technologies

Fuel technology Release emission efficiency		Bituminous coal Gasification	Sub-bituminous coal Gasification	Lignite Gasification	Lignite Amine scrubbing	Lignite Oxyfuel
CO_2 release [g/kWh]	[21]	771	852	883	883	883
	[23]	766	851	892	880	885
Capture [g/kWh]	[21]	641	750	701	823	738
	[23]	650	740	710	820	740
Capture efficiency [%]	[21]	87	92	85,7	95	90
	[23]	85	87	80	93	84
Emission [g/kWh]	[21]	130	102	182	60	145
	[23]	116	111	182	60	145

From the data presented and taken from various publications, it can be concluded that with the currently operating or planned coal (coal, lignite) combustion technologies, CO_2 release/production is generally 800-900 g/kWh (0.8-0.9 t/MWh) amount of CO_2. With natural gas (gas) combustion, specific CO_2 release is 300-500 g/kWh, exactly half of the amount for coal combustion. (Naturally, it is another issue that with gas combustion, flue gas CO_2 concentration is considerably lower (1/3-1/4) than with coal combustion, which increases the technological and cost parameters of capture/concentration).

The efficiency values of CO_2 capture from flue gas are (80) 85-90 (95) %, atmospheric emission is 80-190 g/kWh with coal combustion, 60 g/kWh with flue gas scrubbing, and 40-50 g/kWh with gas combustion. (with 90 % efficiency)

6. Costs of capture and avoidance

In the assessment of fossil fuel use, on the one hand, the technological parameters investigated for the main components give orientation and, on the other hand, it is worth investigating and comparing economic/cost indicators, as well. The effect of CO_2 capture on investment/establishment costs has already been covered. Now, the effect on operational and total production costs is going to be investigated. The costs of production and CO_2 capture generally include investment costs, as well.

Paper [22], which, using a cost model, takes into account detailed input data (e.g. 1.24 USD/MMBtu fuel costs for PC and

IGCC technologies, 2.93 USD/MMBtu for NGCC, which is more than two times higher for gas), as well as capital, operational and maintenance costs in production costs, presents the following parameters. (Table 3).

Table 3 – Specific costs of CO_2 capture for different technological solutions

Technology, period Cost	PC		IGCC		NGCC	
	2000	2012	2000	2012	2000	2012
Electricity cost without capture [USDc/kWh]	4.39	4.10	4.99	4.10	3.30	3.10
Electricity cost with capture [USDc/kWh]	7.71	6.26	6.69	5.14	4.91	4.33
Cost enhancing effect of capture [%]	76	53	34	25	49	40
Cost of CO_2 capture [USD/t_{CO2}]	49	32	26	18	49	41

From the assessment of the mostly actual data on CO_2 capture or avoidance highlighted above, which are confirmed by several other sources, it can be calculated that during the application of current power plant technologies or power plant technologies forecast for decades ahead, the specific cost of CO_2 capture is 30-80 USD/t_{CO2} while the cost of avoidance (capture + disposal) is 50-100(120) USD/t_{CO2}. CO_2 capture from flue gases increases the costs of electricity production by 40-80% (or by 100-120% with oxyfuel technology).

7. Summary, conclusions

According to forecasts concerning the meeting of future energy demands, fossil fuels, i..e. hydrocarbons and coal, will remain dominant in the long run, for another 30-50 years. In view of this fact, it is worth investigating the technological development possibilities of power plants along with expected technological and economic parameters. It is a particularly important current task to specify expectable environmental impacts and particularly, the extent of carbon dioxide production, to forecast technological and economic parameters of capture technologies and define their efficiency, to investigate the chance of minimising CO2 capture and specify the cost limits involved.

It is demanded and expected that R&D on CO2 release, its capture from flue gases and disposal in (underground, undersea) storage places, the establishment of pilot plants, R&D organisations involved in this topic as well as production plants – with the exception of RWE – will mostly be financed from state/central resources.

In the last 50 years, the technological development of power plants using fossil fuels (oil, natural gas, coal, lignite) has been in the direction of modernisation and the enhancing of unit performances. In the last decade, developments have been focussing on the capture of flue gas components (SO2, CO2) causing adverse environmental impacts (SO2, CO2) and the minimisation of their impact. As a result of power plant technological developments, thermal efficiency has increased from 30-32 % to 42-50(55) %-ra, with the direct consequence of a proportionate decrease in specific carbon dioxide release (g/kWh).

The techological implementation of capture from flue gases considerably enhances power plant system investment costs. According to sources, with the currently operating systems, the extra investment costs due to capture amount to 40-90 %, with the new developments, this value is 30-70 %. According to more recent data, for coal, CO2 capture increases specific investment costs from 1.2 · 106 EUR/MW to 1.68 · 106 EUR/MW (~40 %), and for lignite, from 1.35 · 106 EUR/MW to 1.75 · 106 EUR/MW (~30 %).

Depending on the fuel type used and the capture technology applied, the application of CO2 capture generally reduces the thermal efficiency of the system by 10-15%. For some projects currently under planning, a 6-12% reduction in efficiency is taken into account. A more recent paper gives the value of 8% for state-of-the-art coal-lignite combustion.

The joint efficiency reducing effect of capture + disposal (transportation, sequestration) may amount to 14-28 %.

A wide range of the publications considered take into account a CO2 release of 800-900 g/kWh (0,8-0,9 t/MWh) for coal (coal, lignite) combustion and 300-500 g/kWh CO2 release with gas combustion.

The efficiency of CO2 capture from flue gases is (80) 85-90 (95) %, while atmospheric emission is 80-180 g/kWh for coal combustion, 60 g/kWh for flue gas scrubbing and 40-50 g/kWh for gas combustion with 90% efficiency.

With respect to the specific costs of CO2 capture/avoidance and its enhancing effect on electricity costs, it is not an easy task to interpret and assess data found in professional literary sources. Data may come from different periods (effect of inflation) and in many cases, ’cost data content’ is not unambiguous, either. The enhancing effect of capture (avoidance) on specific electricity costs may considerably depend on fuel types and the capture technologies applied, as well.

According to source [21], capture enhances production costs by 40-90% (120% for oxyfuel technology) while source [23] gives the value of 50-90 (110) % for the cost enhancing effect of capture (avoidance?).

Relying on cost model calculations, paper [22] indicates a 50-80 % increase in production costs for traditional coal powder technologies, 25-35 % for IGCC, and 40-50 % for gas combustion (NGCC) due to CO2 capture.

The commonly used parameter for the specific costs of CO2 capture is usually given in USD/tCO2. According to several publications, depending on fuel and technology type, specific capture costs may amount to 30-80 USD/tCO2 with the cost of avoidance (capture + disposal) being 50-100(120) USD/tCO2.

With natural gas combustion, CO2 concentration in flue gases is ’only’ 1/3-1/4 of the 8-12 % value for coal combustion, and the cost of CO2 capture (USD/tCO2) exceeds the costs with coal combustion considerably: capture from flue gases increases the costs of electricity production by 40-80 % (by 100-120 % with an oxyfuel technology).

On the basis of both the specific capture costs (USD/tCO2, USDc/kWh) given in the sources, and Hungarian technological and cost data concerning CO2 sequestration, approximate values are specified for CO2 ’avoidance’ for the different receptive geological formations. In an average case, 9(10)-14(16) HUF/kWh cost may be estimated for coal (lignite) combustion, practically equalling the cost of the current technologies (without CO2 capture), which means that avoidance costs would increase present production costs by a round 80-100 %, in itself a higher value than the full cost of nuclear power plant electricity production.

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