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

Стаття відноситься до технологічних й економічних (вартість) параметрам випуску, захвату й зберігання вуглекислого газу в газах викопного палива (вугілля, природний газ) запущених електростанцій. Містить порівняння й узагальнення обробки широкого діапазону даних зазначених у літературі.

Статья относится к технологическим и экономическим (стоимость) параметрам выпуска, захвата и хранения углекислого газа в газах ископаемого топлива (уголь, природный газ) запущенных электростанций. Содержит сравнения и обобщения обработки широкого диапазона данных указанных в литературе.

The paper deals with the technological and economic (cost) parameters of the release, capture and storage of the carbon dioxide in the flue gases of fossil fuel (coal, natural gas) fired power plants. It makes comparisons and generalisations through processing a wide range of data quoted from the literature.

As the first step, the topicality of the issue is justified by illustrating the role of fossil fuels in the energy supply of the more remote future with forecast data. During the technological development of power plants in the last 50 years, block capacity has increased considerably, 5-8 times, with thermal capacity increasing by 50-60%, as a result of which specific carbon dioxide release has decreased by 30-40%. The paper briefly refers to the theoretical possibility of the sequestration of the carbon dioxide captured from flue gases in geological formations.

The enhancing effects of the implementation of CO_2 capture on investment costs and its reducing effect on net power plant output and utilization (thermal) efficiency are also analysed in the paper. The efficiency of CO_2 capture and the parameters of atmospheric carbon dioxide emission are also given attached to fuel types and technological solutions.

As a parameter of the technological solutions, it is indicated what specific cost (USD/t_{CO2}) is demanded for CO_2 capture or avoidance, and to what extent it raises the costs of electricity production.

Introduction: Financing CCS (Carbon Capture and Storage) Projects

The 2006 reference scenario of World Economy Outlook (WEO) of the International Energy Agency (IEA) forecasts an average annual 1.6% increase in primary energy demands by 2030, and parallel with this, considers coal as the second most important fuel. Taking into account a 70% increase in greenhouse gases between 1970 and 2004 parallel with an increase in energy demand, there is considerable CO_2 emission. In order to decrease the emission of greenhouse gases including CO_2, a widespread implementation of CCS (Carbon Capture and Storage) technology is necessary. In addition to CCS, an important role may also be played by CCT (Clean Coal Technology). Therefore, the research and implementation of these technologies is a current task in our age.

Like every revolutionarily new technological procedure, and in particular, the research and development of high capacity energy systems integrating a wide range of technologies, its actual industrial implementation requires very considerable financial resources. The complex technological problems of a high capacity energy system (production, processing and combustion of fuels, the conversion of heat into electrical energy, the treatment and storage of combustion products – in this case, the CO_2 content of flue gases), the very high investment costs and the long lifecycle raise special problems. The risks of the technological solutions and the financial (economic) resources needed may deserve special consideration.

The budgets of research projects alone may amount to billions (e.g. in Australia, the research budget of the ongoing CCS projects is 5-6 billion A $, in Canada, 86 projects are under elaboration with the participation of 95 organisations, with international involvement in 20 projects and with the participation of state agencies or authorities in 15 projects. The total R&D cost is 92 million C $).

The demands of energy production with CCS technology and its investments costs, which amounts to 1.75 10^6 EUR/MW with lignite combustion according to current estimates, and will be 17.5 10^9 (billion) EUR when the Rhine power plants will be replaced with the same capacity are also a problem [1].

With regard to the financing of research and particularly investment costs, there are different solutions in the different countries. Experts indicate public-private partnership as the precondition of the successful design and actual industrial introduction of CCS technology or other technologies yielding the same result.

So far, two countries, the Netherlands and Norway have an established political (state) framework for the research and implementation of the new technologies (primarily CCS) [2].

The situation in Germany, where RWE Power AG operates two CCS projects, bearing the total risk and financial burden of research and demonstration plant, is almost unique. [1] The two projects involve the development of a coal-fired power plant with zero CO_2 emission and 450 MW output, based on IGCC technology (Integrated Gasification Combined Cycle), and the implementation of a lignite-fired power plant with 1,000 MW output and CO_2 scrubbing.

In the United Kingdom, the introduction of CCS technology is a priority issue on the agenda. [4] In the British treatment of the issue, special significance is given to the CO_2 storage potential in the North Sea. The capacity makes it possible to serve a coal-fired power plant of 100 GW output for its whole lifecycle. There are plans for the build-out of 15 GW electric capacity in the next decade.

The condition of development financing is state subsidy without which reasonable economic considerations prefer power plants without capture. According to expert opinion, the first specific risks of construction and capture should also be borne by the state. It is expected that these risks can only be eliminated in the long run. In all probability, it will be indispensable to compensate both first users and initial stakeholders.

Development of coal-fired power plant technologies in the direction of a decrease in CO_2 emission (capture and storage)

If you have only a brief overview of coal-fired (coal, brown coal, lignite) power plant technologies in the last 50 years (from 1950) and the expected developments in the next 15-20 years (up to 2020), you can say that there is almost a 'paved' way to the minimisation of carbon dioxide emission, and the solution of CO_2 capture from flue gases and, related to the latter, its storage. In the last 50 years, an essential feature of developments has been an increase in the capacity of power plant units (furnaces, turbines) as well as in technological parameters (gas pressure and temperature), and, as a result, an improvement in thermal efficiency.

In the period between 1950 and 1970, block capacities of 50, 130 and 300 MW operated with 25-31% thermal efficiency. In the 1970-1990 period, unit capacity was increased to 300-600 MW with thermal efficiency increasing by about 30% to 31-36%. Coal combustion operated with AFBC (Atmospheric Fluidised Bed Combustion) and with PFBC (Pressurised Fluidised Bed Combustion) technologies while power plants fired with brown coal used BoA (Best Optimised Plant). **Present** (1990-2010) technologies yield 1,000 – 1,100 MW block outputs increasing the 31-36% thermal capacities of the previous period by another 30%, yielding a 40-45% capacity.

As a result of general development, power plants having BoA-Plus (flue gas scrubbing) technologies achieve 38-41% efficiency while those with CGCC (Coal Gasification Combined Cycle), IGCC (Integrated Coal Gasification Combined Cycle) and gas and steam plants (GuD) 38-43%. With an improvement in technological parameters (250-270 atm pressure, 500-700° temperature) and flue gas scrubbing, BoA-Plus provides 41-43% efficiency. In this field, any further increase in technological parameters (p, T) is limited by material quality problems. The technologies of **tomorrow** (2010-2020) intend to achieve a 45-50% efficiency even with CO_2 capture although it may cause an actual 8-12% decrease in efficiency. Technologies prognosticated after 2020 represent **the day after tomorrow,** promising 55-60% efficiency with certain technologies (Hybrid-KW 58-63%, SOFC – Solid Oxide Fluid Cell: 50-57%) [9].

Another fundamental development trend aiming at the reduction of adverse environmental impacts is the already widely introduced desulphurising flue gas scrubbing. The development trend of nowadays and the near future is the minimisation of carbon dioxide emission. A basic, evident solution to the reduction of specific carbon dioxide release (t_{CO2}/MWh, g_{CO2}/kWh) is the increase in thermal efficiency and it may remain so in the future, as well. An increase in efficiency results in a proportionate reduction in specific CO_2 release or emission. With 150 MW blocks, CO_2 release is 1.3 t $_{CO2}$/MWh while with 600 MW units, this parameter 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 or CGCC technologies, even a 0.7-0.8 t_{CO2}/MWh release may be achieved. With the technologies of the near (2010-2020) or more remote (after 2020) future, an essential objective is the implementation of CO_2 capture (minimisation of emission) or zero emission (ZEC – Zero Emission Coal, ZECA – Zero Emission Coal Alliance) with the 'eternal' sealing and storage of CO_2. [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.

Naturally, the 'perfect' nature of the latter technologies as well as the costs and 'eternal' (long-term) reliability of capture, transportation to storage place and disposal (sequestration) remain open questions.

Natural (geographic, sea) formations theoretically suitable for carbon dioxide storage and estimated storage capacities

The different sources consider it theoretically possible to store carbon dioxide in mostly the same natural formations. In this respect, they only deviate from each other in details [11, 12, 13, 14].

As far as land disposal is concerned,

- sequestration into exploited oil and gas fields (driving out of oil and gas, Enhanced Oil Recovery)
- sequestration into non-exploitable coal beds with high methane content (disposal in exploited coal or salt mines)
- deep-lying porous (sandstone) rocks, saltwater storing rocks

Theoretical storage options in seas (deep seas) include

- in solution form at smaller depths (1,500-3,000 m)
- in the form of a carbon dioxide 'pool' at greater depths (>3,000 m)

The geological (underground) environment most suitable for CO_2 storage is indicated to be the formations of depleted oil and gas fields, particularly at a depth of over 1,000 m, where carbon dioxide can be kept in a supercritical condition (31°C, 7.4 MPa), amd above the storage layer, there are impermeable rock beds. Above oil and gas fields, it was this type of cap rock that sealed oil and gas in the storage layer for millions of years. Oil and gas fields which are currently being exploited or are already exploited are most suitable for the start and first implementation of CO_2 storage.

Porous (sandstone) layers holding saltwater are similarly considered as natural storage places. Such formations (aquifers) seem to have a high CO_2 storage capacity although less is known about their structure or parameters than about hydrocarbon fields. Similar formations are the ones storing natural carbonated waters. Sandstone is typically a kind of rock which may be suitable for geological CO_2 storage if it has proper porosity (>0.15-0.20) and permeability (>50 mD).

CO_2 sequestration into coal beds with high methane content, unexploitable for technological and economic reasons, also depends on special conditions. Methane (CH_4) 'driving out' is only possible with proper permeability while the sealing capacity of the cap rock beds may be questioned for tectonic reasons.

Key issues in underground disposal are the choice and assessment of storage place, the verification of the homogeneity of the sealing layers limiting CO_2 seepage, the long-term forecast of fluid flow (CO_2) conditions, and the tracking of sequestration and flow routes with appropriate methods.

In the estimation of **storage capacities**, sources publish relatively divergent data. In the estimation of oceanic (sea) capacities, there are even order differences. Sources underlie that these are only potentials and in general, consideration is restricted to 20 USD/t_{CO2} storage costs. In the assessment of realistic options, the geographical locations of both the release and disposal points should likewise be taken into account as transportation distance determines both the method and costs of transportation.

The cited sources give the potential forecast values in Table 1 for CO_2 storage capacities.

Table 1 – Prognosticated values of potential CO_2 storage capacities

	Reference	IEA	Parson-Keith	IPCC
Depleted oil and gas storage places	Capacity [10^9t CO_2]	920	740-1,850	810
	% of expected emission before 2050	<45		<40
Non-exploitable coal bed rich in CH_4	Capacity [10^9t CO_2]	40	370-1,100	40
	% of expected emission before 2050	<2		<2
Porous sandstone, saltwater aquifer	Capacity [10^9t CO_2]	400-10,000	370-3,700	400-10,000
	% of expected emission before 2050	20-500		20-500

Variation in 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 over 84% of the world's energy demands. These fuels contributed considerably to the high living standards enjoyed by the industrialised world through electricity production. On the basis of the analysis of coal and hydrocarbon supplies and the forecast 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 certainly **vary between 50% and 80%**. [15, 16, 17, 18, 19] The use and (planned) role in energy supply of fossil fuels may be motivated (adversely affected) by the subjective and often overrated issues of the greenhouse effect and global climate change (global warming) in public opinion. If one wants to consider these issues realistically, it is indispensable to analyse the technological potentials of the different combustion (utilisation) technologies and the factors of their economic suitability including the analysis of the investment costs, the efficiency, CO_2 release, capture efficiency and cost demands of the production plants – as regards this paper, those of electric power plants.

In the investigation of this field, the comparison of the parameters of the 'use' of the different fuel types, i.e. coal and hydrocarbons, is often of primary importance, as well. First, the investment costs of some basic technologies (without CO_2 capture) will be quoted. Considering the fact that the different sources refer to different periods, in addition to the absolute values of specific costs, the assessment of the rates will probably be more meaningful.

The technological solution (and naturally, the energy demand) of CO_2 capture will significantly increase power plant investment costs. With the application of different fuels (gas, coal) and different combustion technologies, different capture technologies and naturally, different cost enhancing factors have to be taken into consideration.

According to 2004 data, in the case of the gasification combustion of bituminous coal, there are specific investment costs of 1,410 USD/kW without capture and 1,917 USD/kW with capture. The extra cost is 507 USD/kW, 36%. With the gasification combustion of sub-bituminous coal, specific investment costs are 1,502 USD/kW and 2,190 USD/kW respectively, with an increment of 688 USD/kW, 46%. With the combustion of lower heat content lignite, the values are 1,644/2,828 USD/kW with gasification or amine flue gas scrubbing with an increment of 1,184 USD/kW, 72%. With oxyfuel combustion technology, the values are 1,644/3,974 USD/kW with an increment of 2,330 USD/kW, 142%. The latter technology requires more than twice as much for the solution of capture due to the use of oxygen and carbon dioxide 'recycling' [21].

In the analysis of power plant investment costs, parameters were determined for the years 2000 and 2012 (in the latter case, taking into account expected general technological advancement for both technologies) for both the reference plant without capture and technologies involving capture (Table 2).

Compared to coal, the obvious favourable parameters of natural gas are an advantage for specific investment costs, too, although the effect of CO_2 capture enhancing investment costs exceeds the parameters of traditional coal powder combustion. As a result of the 'generally' more modern facility technologies prognosticated for 2012, specific investment costs are likely to be lower for every option, to a lower extent (~10%) in the case of natural gas and to a higher extent (10-15%) for coal.

In the case of gas combustion, flue gas CO_2 concentration is only about 3% with a 0.354 kWh/kg$_{CO2}$ while with pulverised coal combustion, concentration is approximately 13% and the specific energy demand of capture is 0.317 kWh/kg$_{CO2}$. In IGCC plants, carbon dioxide has a relatively high pressure and is in concentrated flow therefore these plants have the lowest specific energy demand for capture with 0.194 kWh/kg $_{CO2}$ (2000). The values of specific energy demand for 2010 are 0.297 – 0.136 – 0.135 kWh/kg $_{CO2}$, respectively.

With the data in the abovementioned paper [22], where according to 2000 figures, capture represented 37-87% extra investment costs and the forecast estimate for 2012 was 27-70%.

Table 2 – Investment costs related to CO_2 capture

Type of plant		PC		IGCC		NGCC	
Date (year)		2000	2012	2000	2012	2000	2012
Investment costs [USD/kW]	Without capture (reference plant)	1,150	1,095	1,401	1,145	542	525
	With CO_2 capture	2,090	1,718	1,909	1,459	1,013	894
Cost enhancing effect of CO_2 capture		+81	+57	+36	+27	+87	+70
Additional investment cost per unit of capture capacity [USD/(kg/h)]		529	476	305	275	921	829

Variation of the efficiency of electricity production and heat use for different fuels and technologies

One of the basic parameters in the technological and economic assessment of the individual technologies and in the rate of flue gas release is thermal efficiency. With an approximate assessment, it can be said that any increase in the thermal efficiency of fuel transformation (use) practically proportionately reduces the extent of specific CO_2 release. The energy demand of CO_2 capture reduces efficiency parameters (gross and net efficiency) so it may be used as one of the assessment parameters of the technological and economic description of capture.

Also dependent on fuel type as well as on combustion and capture solution, the technological solution of CO_2 capture and the energy demand of capture cause a considerable decrease in nominal (gross) power plant capacity/output. According to the figures in paper [21], the parameters attainable with CO_2 capture are the following [21, 23] (Table 3).

Table 3 – Parameters of capacity use and thermal efficiency with CO_2 capture

Fuel and technology	Efficiency of capacity use, net/gross [%]	Thermal (net) efficiency [%]	Reduction in thermal efficiency [%]
Bituminous coal gasification	75	31.6	9.97
Sub-bituminous coal gasification	69	38.4	14.66
Lignite gasification	65	36.8	13.43
Lignite flue gas scrubbing (amine)	69	34.8	11.63
Lignite oxyfuel procedure	59	41.3	16.74

Paper [21] provides data for the use of natural gas and coal as fuels in different technologies, also taking into account the effect (cost) of capture and storage (Table 4).

Table 4 – Thermal efficiency values with CO_2 avoidance

Fuel and technology	Gross thermal efficiency [%] without CO_2 capture	Net thermal efficiency [%] with CO_2 capture	Reduction in efficiency due to CO_2 capture and storage [%]
Natural gas, NGCC	53.6	43.3	19.2
Coal, ultracritical steam technology (UGS)	42.7	31.0	27.4
Coal, CGCC	43.1	37.0	14.2

Paper [24] provides institutional project data for the use of natural gas and coal as fuels in different technologies with regard to the variation of thermal efficiency values (Table 5).

Table 5 – Thermal efficiency values according to different project data

Fuel and technology	Project, institute	Thermal efficiency [%] without CO_2 capture (gross)	Thermal efficiency [%] with CO_2 capture (net)	Reduction in efficiency due to capture [%]
Natural gas with amine scrubbing	IEA GHG	54	46	8.4
	EPRI turbine	54	42	12.0
	EPRI H turbine	58	47	11.1
	MHI	53	49	4.3
Natural gas combustion	IEA GHG	54	46	7.7
Coal with amine scrubbing	IEA GHG	45	33	12.5
	EPRI	42	30	12.0
	Alstrom	38	25	15.0
	MHI MEA	42	32	9.7
	MHI KS1	42	34	7.5
Coal with oxygen injection	Alstrom	38	25	13.0
	Chalmers	42	34	8.1
Coal, IGCC	IEA GHG	46	38	8.0
	EPRI	45	39	6.2
	RWE (Essen)	46	40	6.0

From the data presented, it can be concluded that depending on fuel type and the chosen technology, the reducing effect on thermal efficiency of CO_2 capture is generally **10-15%**, in the case of some planned projects, it is **6-12%** while according to the 2007 paper, it is **8%** with more up-to-date lignite combustion. According to paper [12], the combined reducing effect on thermal efficiency of **capture + storage** (transportation included?) may amount to **14-28%.**

Amount of CO_2 released during combustion and the efficiency of CO_2 capture with different technological solutions

The amount of CO_2 released during the combustion of fuels substantially depends on the type (natural gas or coal) and quality (coal, brown coal or lignite) of the fuel and the type, output and state-of-the-art quality and thermal efficiency of the combustion system (power plant). Emission into the atmosphere depends on the flue gas scrubbing technology implemented, itself depending on the CO_2 concentration of the flue gases, and the technological solution and efficiency of CO_2 capture.

In the special literature, actual plant data referring to running power plants can be found in several publications while they give estimated, prognosticated data for the capture technologies in the experimental or design phase.

The data in paper [20] give an opportunity to compare the parameters of different fuels and combustion technologies. Due to 'material quality', there is considerably much lower specific CO_2 release with natural gas combustion than with coal combustion. The first figure presented refers to natural gas, the second one to coal.

With traditional steam turbine technology, specific CO_2 release 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 a gas injection gas turbine, the same value is 440/880 g/kWh with a rate of 200% (+100%) while with a steam injection gas turbine with intermediary cooling, it is 370/730 g/kWh with a rate of 197%. With a state-of-the art fuel cell solution, the expected value is 330-370/620-700 g/kWh for CO_2 release with a prognosticated rate of 188-189%.

Data for the different coal types, and attached to them, for the different combustion-capture technologies can be found in papers [21] and [23]. Probably, the authors of both publications relied on the same base data. (Table 6)

Table 6 – Specific CO_2 release for different fuel types and technologies

Fuel and technology Release, emission, efficiency		Bituminous coal, gasification	Sub-bituminous coal, gasification	Lignite, gasification	Lignite, amine scrubbing	Lignite, oxyfuel
CO_2 release	[21]	771	852	883	883	883
[g/kWh]	[23]	766	851	892	880	885
Capture	[21]	641	750	701	823	738
[g/kWh]	[23]	650	740	710	820	740
Efficiency	[21]	87	92	85.7	95	90
of capture [%]	[23]	85	87	80	93	84
Emission	[21]	130	102	182	60	145
[g/kWh]	[23]	116	111	182	60	145

With the different varieties, there is no significant difference in CO_2 release and capture values. With the values of capture efficiency and emission, flue gas scrubbing seems to be the better solution.

Paper [22] compares the CO_2 release and emission values after capture of PC, IGCC and NGCC technologies. As regards the comparison of the efficiency of capture, the same 90% efficiency can be found in relation to both years in all the three cases. (Table 7)

Table 7 – Carbon dioxide release and emission data for different technologies

Technology, year	PC		IGCC		NGCC	
Release, emission	2000	2012	2000	2012	2000	2012
CO_2 release [g/kWh]	789	766	752	664	368	337
Emission after capture [g/kWh]	105	90	88	73	42	37

On the basis of the data presented and quoted from different publications, it can be concluded that with the running coal (coal, lignite) combustion technologies or those under design in the present period, CO_2 release 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 values for coal combustion. (Naturally, it is another question that with gas combustion, flue gas CO_2 concentration is significantly lower (one third or one fourth) than with coal combustion, which increases the technological and cost parameters of capture/concentration).

The efficiency of CO_2 capture from flue gases is (80) **85-90** (95)% while emission into the atmosphere 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).

Costs of capture and avoidance

With regard to the technological parameters of energy production and the related capture, the published data are approximately identical irrespective of the source although there are significant differences in cost elements and the costs of capture. The factors taken into consideration in cost calculation, the effects of inflation on the costs in the different periods as well as the conversion rates for the different currencies may be different. A significant difference in the comparison of costs may also be caused by whether in addition to the costs of capture, the costs of transportation and storage are taken into account in the costs of 'avoidance' or not.

The differences in the data from the different sources are characterised by the presentation of the cost factors in papers [21] and [23] for the same fuel and technology in Table 8.

From the comparison of the cost data of the 'same' type from the two sources, it can be concluded that while paper [21] 'only' takes capture costs into account, in paper [23], specific electricity costs (USD c/kWh) also include the costs of avoidance (capture + storage). The cost in USD/t_{CO2} can be regarded in a similar way. In the first case, the cost of capture gives the cost of avoidance while in the second case, the cost of avoidance is the sum of capture (transportation?) + storage costs.

Table 8 – Specific costs of CO_2 capture and avoidance

	Fuel Technology Cost factor	Bituminous coal, gasification	Sub-bituminous coal, gasification	Lignite, gasification	Lignite, amine scrubbing	Lignite, oxyfuel
[21]	Electricity costs without capture [USD c/kWh]	4.87	3.73	4.45	4.45	4.45
	Cost of CO_2 capture [USD c/kWh]	1.97	2.48	3.94	2.98	5.29
	Electricity costs with CO_2 capture [USD c/kWh]	6.84	6.21	8.39	7.43	9.74
	Cost enhancing effect of capture [%]	40	66	91	67	119
	Cost of CO_2 capture [USD c/kWh]	31	33	56	36	72
[23]	Cost of CO_2 capture (avoidance) in electricity costs [USD c/kWh]	3.1	3.8	6.2	4.7	8.3
	Total production cost of electricity [USD c/kWh]	10.7	9.7	13.1	11.6	15.2
	Rate of CO_2 capture costs within total production cost [%]	29	39	47	41	55
	Cost of CO_2 capture (avoidance) [USD/ t_{CO2}]	47	52	88	57	112

From the data presented above, conclusions can be drawn concerning the effects of fuels, technologies and technological development.

With the use of gas as fuel, lower electricity production costs can be achieved than with coal with both traditional technologies (without capture) and with technologies involving capture in spite of the 2.3 times higher specific fuel costs. The 2.3 rate of 'material costs' decreases to a rate of 1.3 in the case of 'electricity costs'. As has been mentioned, the decreasing rate of the 'favourable character' of gas is due to the fact that with gas combustion, the CO_2 concentration of flue gas amounts to one third or one fourth of the 8-13 % CO_2 concentration with coal combustion, as a result of which with the former, the specific cost of CO_2 capture is 40-50 USD/t_{CO2} in contrast to the capture cost of 20-30 USD/t_{CO2} with coal combustion (ICCC) of the CO_2 present at high pressure in a concentrated flow.

On the basis of the assessment of the data highlighted above, related to CO_2 capture or avoidance (capture, transportation to storage place, storage), which are mostly factual data identical with those quoted from other sources, it can be concluded that with the application of the present power plant technologies or those that can be foreseen for decades, the specific cost of CO_2 **capture** is between 30-80 USD/t_{CO2} while the costs of **avoidance** (capture + storage) amount to 50-100 (120) USD/t_{CO2}. The capture of CO_2 from flue gases increases the production cost of electricity by **40-80** (100-120% in the case of oxyfuel procedure).

In his paper [7] concerned with the general investigation of the subject, Preston Chiaro states in agreement with the opinion of several other authors that for economic reasons, the application of CCS technologies may only be a suitable solution above a 25-30 USD/t_{CO2} 'price'.

Several authors investigate the issue of the costs of CCS technology implementation. According to Mark Trexler's data [8], for example, the specific costs of CO_2 **capture** (avoidance?) are the following:

With PC (pulverised coal combustion)	30-70 USD/tCO2
With IGCC	15-55 USD/tCO2
With NGCC	40-90 USD/tCO2

With respect to transportation + storage costs, paper [1] gives 14 USD/t_{CO2}, which considerably exceeds the (1-8) + (0.5-8) = 1.5-16 USD/t_{CO2} specific costs in paper [7], referred to above.

During our research, we have made calculations for the Hungarian conditions, which show that the cost of CO_2 avoidance **in itself exceeds** the production cost of electricity generated in nuclear power plants.

Summary and conclusions

According to the forecasts about the fulfilment of energy demands in the future, fossil fuels, i.e. hydrocarbons and coal, will continue to play a decisive role in the long run, even within 30-50 years. In view of this fact, it is useful to analyse the technological development options of power stations and to consider the expectable variation of technological and economic parameters. The assessment of expected environmental impacts, and particularly, the determination of the extent of carbon dioxide release together with the prognostication of the technological and economic parameters of capture technologies, the description of their efficiency as well as the assessment of the chance of CO_2 release minimisation and its cost effects are current tasks.

1. With the exception of RWE, the R&D organisations and production enterprises involved substantially intend and expect to finance the research, development and the establishment of pilot plants in relation to the release, capture from flue gases and especially the storage (underground or under the sea) of CO_2 **from central, state sources**.

2. The technological development in the last 50 years of power plants using fossil fuels (oil, natural gas, coal or lignite) has been moving in the direction of modernisation and the increasing of unit output. In the last decade, the capture of flue gas components having adverse environmental impacts (CO_2, SO_2) as well as the minimisation of their impacts have been in the forefront of developments. As a result of power plant technological development, thermal efficiency has increased from 30-32% to 42-50(55)%, which has ‘directly and proportionately’ resulted in a decrease in specific carbon dioxide release (g/kWh).

3. The potential underground (geological) storage possibilities of CO_2 captured from flue gases primarily include exploited oil and gas fields and deep-lying porous sandstone (saltwater aquifer) formations – (given suitable permeability) while debated options are the utilisation for this purpose of non-exploitable coal beds with high methane content and the practical implementation of sea (under sea) storage.

4. The technological implementation of capture from flue gases **considerablyenhances power plant system investment costs**. According to sources, with the currently running systems, the extra investment cost of capture is 40-90 % while with the new developments, this amounts to 30-70 %.

5. Depending on the fuel type used and the capture technology implemented, the implementation of CO_2 capture generally **reduces system thermal efficiency by 10-15 %.** With some project designs, a 6-12 % efficiency reduction is taken into account, or 8 % with state-of-the-art coal-lignite combustion according to a more recent publication.

6. The combined efficiency reducing effect of **capture and storage** (transportation, sequestration) **may be between 14-28 %.**

7. A wide range of the publications consulted take into account **800-900 g/kWh** (0.8-0.9 t/MWh) CO_2 release with coal (coal, lignite) combustion) and **300-500 g/kWh** CO_2 release with gas combustion.

The efficiency of CO_2 capture from flue gases is (80) 85-90 (95) % while emission into the atmosphere is **80-180 g/kWh** with coal combustion, **60 g/kWh**

with flue gas scrubbing and 40-50 g/kWh with 90% efficiency in the case of gas combustion.

8. The enhancing effect of capture (avoidance) on specific electricity costs may also considerably depend on the fuel types and the capture technologies implemented.

According to paper [21], the cost enhancing effect of capture on production costs is 40-90 % (120 in the case of oxyfuel) while according to source [23], the cost enhancing effect of capture (avoidance?) is 50-90 (110) %.

On the basis of cost model calculations, paper [22] indicates a 50-80 % increase in production costs with coal powder combustion, 25-35 % with IGCC technology and 40-50 % with NGCC as a consequence of CO_2 capture.

As in flue gases, CO_2 concentration with gas combustion is 'only' one third or one fourth of the 8-12% found with coal combustion, the costs of CO_2 capture (USD/t_{CO2}) considerably exceed the costs with coal combustion while capture from flue gases increases electricity production costs by 40-80 % (100-120 % with oxyfuel procedure).

9. On the basis of the specific capture costs (USD/t_{CO2}, USDc/kWh) quoted from special literature and the technological cost data of CO_2 sequestration in Hungary, approximate values have been determined for CO_2 'avoidance', attached to the different receiving geological formations. In an average case, 9(10) – 14(16) HUF/kWh cost may be estimated for coal (lignite) combustion, which is practically identical with the production cost of the current technology (without CO_2 capture), which means that the costs of avoidance would enhance present production costs by around 80-100 %, higher in itself than the total production cost of electricity generated in nuclear power plants.

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List of abbreviations used in the paper

Abbreviation	*English*
BoA or BOA	Best Optimised Plant
GuD	Gas and Dampf Process
MEA	Mono-ethanol amine
CCS	Carbon (dioxide) Capture and Storage
CLC	Chemical Looping Combustion
NGCC	Natural Gas Fired Combustion/Combined Cycle
PC	Pulverised Coal Fired Simple Cycles
CGCC	Coal Gasification Combined Cycle
AFBC	Atmospheric Fluidised Bed Combustion
PFBC	Pressurised Fluidised Bed Combustion
SOFC	Solid Oxide Fuel Cell
ZEC	Zero Omission Coal
ZECA	Zero Omission Coal Alliance