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Integration of CO_2 storage into deep geothermal energy: Technical potential and industrial policy perspectives through carbon contracts for difference in Germany

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ABSTRACT

Carbon Contracts for Difference (CCfDs) are a key policy instrument in Germany for promoting industrial decarbonisation. By linking a project-specific base price to the development of EU ETS certificate prices, government subsidies are dynamically adjusted to market conditions. This paper defines a use case for CCfDs in which process-related emissions from a cement plant are stored underground using deep geothermal energy systems. The model analysis shows that price developments in the EU ETS have a decisive influence on the level of subsidies and the economic efficiency of CCfDs. Three price paths for the EU ETS are evaluated in detail. In addition, the site-specific CO_2 absorption capacity proves to be an essential technical parameter that significantly influences the feasibility of storing carbon emissions underground. CCfDs currently offer only limited economic advantages for this use case but nonetheless represent an important incentive for industrial transformation. Overall, the study underscores the relevance of CCfDs as a bridging instrument on the path to a climate-neutral industry. However, the effectiveness of CCfDs depends on stable regulatory frameworks and technological advances.

1 INTRODUCTION

The transformation of energy-intensive industry towards greenhouse gas-neutral production is one of the central challenges of European climate policy. Sectors such as the cement industry in particular face structural and technological hurdles due to process-related emissions, which make immediate decarbonisation difficult. Against this backdrop, climate protection contracts have been developed as an innovative funding instrument to incentivise investments in climate-friendly technologies.

In contrast to traditional government support mechanisms, which are based on fixed subsidies, CCfDs link support to the difference between a contractually agreed base price and the current market price for CO_2 certificates in the European Emissions Trading System (EU ETS). This creates a market-based incentive system that shares both the opportunities and risks of price developments between the government and companies.

The aim of this paper is to examine the effectiveness and efficiency of climate protection contracts, in particular CCfDs, using the cement industry as an example. The focus is on the economic evaluation of the subsidy mechanisms, taking into account various EU ETS price paths and geotechnical factors such as the CO_2 absorption capacity in thermal water systems. The analysis aims to assess the practicability and economic efficiency of this funding instrument on an industrial scale.

2 CARBON CONTRACTS FOR DIFFERENCE IN GERMANY

The transition of energy-intensive industries to climate-neutral production processes is one of the central challenges of German climate policy. Numerous technologies that are indispensable for achieving the climate targets by 2045 are not yet feasible. They fail due to high investment and operating costs as well as price fluctuations for important input factors such as hydrogen or CO_2 certificates. Against this background, CCfDs were developed as a new financing instrument.

2.1 CCfDs as a support instrument

Carbon contracts for difference or CCfDs are a key instrument for promoting decarbonisation in emission-intensive industries. Their primary goal is to create investment security and enable the early introduction of climate-friendly production processes. The basic principle is based on a contractual hedging mechanism that protects companies against risks resulting from price fluctuations. While the manufacture of low-emission products incurs a higher cost than conventional processes, the government compensates the additional costs

incurred. Once cost advantages arise in favour of climate-friendly technologies, the flow of payments is reversed with companies making repayments to the government. This model ensures dynamic, flexible and cost-efficient support.

Funding is awarded through a competitive tendering process in which maximum bid prices are set to ensure the long-term economic viability of the projects. Only projects that demonstrate annual CO_2 savings of at least 10,000 tonnes and a relative emission reduction of at least 60% from the third contract year onwards, compared to the reference system, are eligible for funding. From the 14th year of the 15-year contract period, a reduction of at least 90% is required. The contract period begins with the operational start of the project or at the latest 36 months after approval of the grant notice; in justified cases, this period may be extended to up to 48 months. In the case of equivalent bids, a lottery procedure will decide which bid is awarded.

The amount of the annual payments is calculated based on a contractually defined formula (see equation 1) that considers the base contract price (CO_2-price per tonne that allows them to switch to a climate-friendly production), the effective CO_2 price, the actual emission reduction achieved and the production volume. Payment will only be made if a measurable greenhouse gas reduction is achieved.

$$Z_{KSV} = \left(p_{KSV}^{Basis} + \Delta k_{KSV}^{Ref,t} - p_{CO2}^{eff}\right) \times \Delta e^{real} \times Q^{real} - R_{nKSV} - R_{GP} \quad (1)$$

- Z_{KSV} [EUR]: Payment amount under the climate protection contract. Determined annually.
- p_{KSV}^{Basis} [EUR/t CO_2 eq.]: Base contract price. Constant over time
- $\Delta k_{KSV}^{Ref,t}$ [EUR/t CO_2 eq.]: Dynamic component for dynamic energy price adjustment of the reference system. Determined annually.
- p_{CO2}^{eff} [EUR/t CO_2 eq.]: Effective CO_2 price. Determined annually.
- Δe^{real} [t CO_2 eq./ME product]: Realised specific greenhouse gas emission reduction of the project. Determined annually.
- Q^{real} [ME product]: Actual production volume of the project. Determined annually.
- R_{nKSV} [EUR]: Other funding that was approved or increased after the application was submitted and is to be deducted from the payment amount in accordance with section 7.5(c) in the calendar year following the calendar year in which the other funding was paid out or otherwise granted. Determined annually.
- R_{GP} [EUR]: Adjustment term to take account of green additional revenues. Determined annually.

In practice, the subsidy is equivalent to the government purchasing emission reductions, with companies being obliged to meet the agreed reduction targets throughout the entire term of the contract. The combination of cost compensation, repayment obligations in the event of cost advantages and competitive awarding creates an incentive system that ensures both investment security and efficiency in the use of funds (BMWK, 2023).

2.2 Legal basis for contracts for difference

CCfDs are outlined in the German government's Climate Protection and Transformation Fund, which forms the central basis for financing. The Federal Ministry for Economic Affairs and Energy (BMWE) is responsible for implementation. At a European level, the instrument requires approval under state aid law by the European Commission, as it constitutes state aid within the meaning of EU competition law. This approval was granted, meaning that CCfDs are compatible with European state aid rules. This gives the climate protection agreements a legally secure basis within both national and European legal frameworks.

2.3 Financial framework and current funding amounts

The German government is providing considerable financial resources for the implementation of CCfDs. In the first round of tenders, the results of which were published in October 2024, 15 companies from various energy-intensive industries received a subsidy. While a budget of up to €4 billion was originally announced, the actual funding volume committed amounted to around €2.8 billion. According to estimates by Federal Ministry for Economic Affairs and Energy (BMWK), the funded projects could cumulatively save up to 17 million tonnes of CO_2 equivalents (KSV, 2024).

These first CCfDs illustrate the effectiveness of the instrument: they lead to immediate emission reductions and accelerate the introduction of climate-friendly technologies and materials in industrial processes. Following the first auction, the BMWK announced a second round of tenders, for which a low double-digit billion amount is allocated. For the first time, carbon capture and storage (CCS) technologies will also be eligible for funding under this framework. This highlights the growing importance of CCS for reducing unavoidable emissions, particularly in industries such as cement and lime production. The integration of CCS underscores the technological openness and adaptability of CCfDs and their goal of supporting decarbonisation on a broad basis (BMWK, 2023).

3 THE CEMENT INDUSTRY AS A USE CASE FOR CCFDS

The cement industry is responsible for around 7% of global CO_2 emissions and around 3% of CO_2 emissions in Germany (Federal Environment Agency, 2024). This corresponds to an average of around 18 million tonnes of CO_2 emissions in the last three years (VDZ, 2023).

3.1 Cement production and exhaust gases

Cement production is associated with significant greenhouse gas emissions. Each tonne of cement produced generates up to 0.81 t_{CO2eq} /$t_{clinker}$ (Federal Environment Agency, 2025). Most of these emissions occur during the calcination of limestone ($CaCO_3$) to quicklime (CaO) (Herten et al., 2024).

During the calcination of limestone (CaCO3 → CaO + CO_2) in industrial rotary kilns, a significant amount of carbon dioxide is released. The CO_2 content in the flue gas is typically between 20 and 40 vol.% (based on dry exhaust gases) (CEMCAP 201 7). Approximately 60% of total emissions result from the deacidification of limestone, while the remaining 40% are attributable to the combustion of fossil and alternative fuels for heat generation (VDZ, 2020). In terms of mass flow, this corresponds to an average of approximately 0.5–0.6 t CO_2 / $t_{clinker}$ from the decomposition of raw materials and an additional 0.3–0.4 t CO_2 /$t_{clinker}$ from the energy supply. In addition to carbon dioxide, the flue gases consist primarily of nitrogen (approx. 70–80 vol.%) and excess oxygen (2–4 vol.%).

The so-called process-related emissions result from the chemical conversion processes during clinker production and, unlike energy-related emissions, cannot be avoided by conventional process optimisation measures or by electrifying the plants.

The cement industry introduced its first measures to reduce CO_2 emissions in the early 2000s. A key approach was to replace fossil fuels with alternative fuels to reduce emissions caused by energy consumption. The development of the share of alternative fuels is shown in Figure 1.

In the long term, however, the greatest leverage for further emission reductions lies in reducing process-related CO_2 emissions, which can only be achieved by using innovative carbon capture and storage (CCS) technologies.

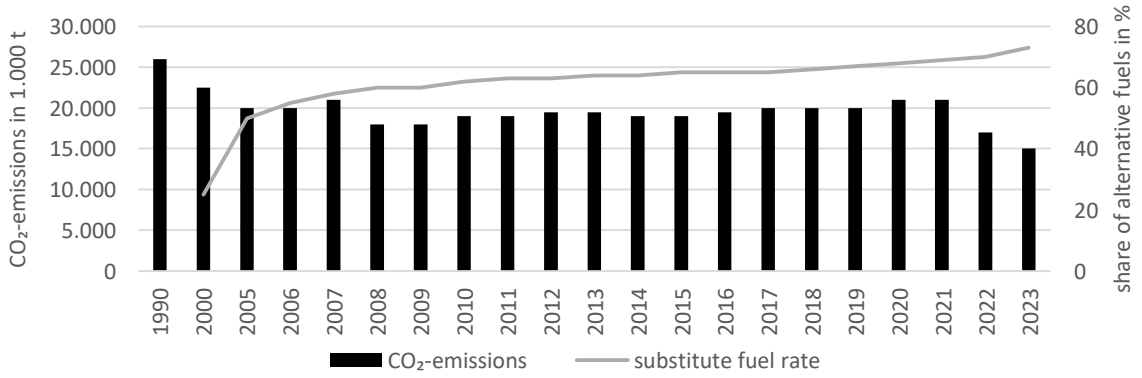


Figure 1. Development of CO_2 emissions and alternative fuels since 1990 (VDZ, 2023)

3.2 CO_2 pricing in the EU ETS

Unlike many of its competitors outside Europe, the cement industry in the European Union is part of the EU Emissions Trading System (EU ETS) and must therefore pay for its CO_2 emissions. As cement production is very CO_2-intensive, these costs have a significant impact on the profitability of production. To avoid competitive disadvantages regarding producers outside the EU, production plants covered by the EU ETS receive a free allocation of part of the required emission allowances (EUA). (AGORA, 2022)

The Carbon Border Adjustment Mechanism (CBAM) is becoming increasingly relevant for the cement industry. When it comes into force on 1 January 2026, the CBAM will be gradually applied to a selective portfolio of emission-intensive products, including cement and clinker. The aim is to subject imports from countries outside the EU, that are not subject to the same CO_2 costs as European producers, to adequate CO_2 pricing. For the European cement industry, this means that the emission allowances previously allocated free of charge under the EU Emissions Trading System will be gradually replaced by real CO_2 costs. Starting 2026 10% of product-specific emissions are subject to CO_2 pricing. An annual increase of 10% follows, meaning the sectors are expected to bear 50% of the corresponding emission costs in 2030 and 100% in 2035. As a result, the financial burden of emissions will increase continuously, while at the same time reducing distortions of competition in the internal market regarding imported products. (AGORA, 2022).

3.3 Technical feasibility of CO_2 storage

Decarbonising the cement industry is particularly challenging because a significant proportion of CO_2 emissions do not come from energy supply but directly from the chemical conversion processes of the raw material. A promising approach to reducing such emissions is the geological storage of the CO_2 using suitable deep geothermal facilities, for example by binding it in carbonate rocks.

3.3.1 Flue gas requirements

A basic prerequisite for feeding CO_2 into the thermal water cycle of a deep geothermal plant is a gas stream with a CO_2 content of more than 80% by volume. This is due to physical solubility requirements: for carbon dioxide to dissolve in thermal water, a sufficiently high partial pressure must be present. According to Henry's law, the solubility of a gas in a liquid is proportional to its partial pressure. In the case of flue gases from cement kilns, which typically contain only about 20–30% CO_2 by volume, the partial pressure is not sufficient to bind large quantities of CO_2 in the water – instead, it would escape predominantly as a free gas in the form of bubbles. Only at very high concentrations of over 80 vol.% does the necessary partial pressure arise for the CO_2 to dissolve stably and then be transported underground with the thermal water. (Kervévan et al., 2017)

The oxyfuel process can be used to achieve the necessary CO_2 content in the flue gas as shown in Figure 2. Oxyfuel combustion is a process in which fuels are burned with pure oxygen and recycled exhaust gas. This removes the nitrogen content from the air and the exhaust gas stream consists almost exclusively of CO_2 and water vapour. After the water vapour condenses, an exhaust gas with a very high CO_2 concentration (> 80 vol.%) is produced. However, the process requires extensive adjustments to the burner technology, material handling and heat balance of the furnace.

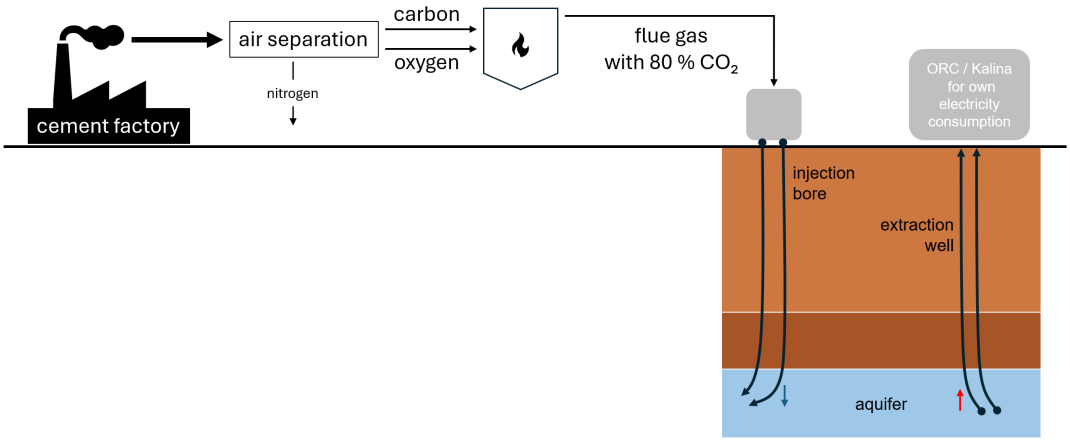


Figure 2. Simplified schematic representation of the oxyfuel process in combination with a deep geothermal plant

3.3.2 CO_2 storage underground (hydrogeological effects)

The targeted reinjection of CO_2 into deep geothermal systems can lead to long-term carbon bonding to the rock. At the surface, the gas mixture is fed into the thermal water cycle of a deep geothermal plant and then dissolved. This injectate is transported to a depth of approx. 3000 m with the circulating thermal water. The aim is to achieve extensive absorption in dissolved form to minimise buoyancy and migration risks caused by free gas-critical phases. During injection, phase behaviour and solubility are subject to strong p-T influences (high pressure promotes solubility, higher temperatures reduce it) and are controlled by flow conditions, dispersion and contact surfaces.

The immediate hydrogeological consequence of an injection is the change in the pressure and flow field in the reservoir. Each injection locally increases the pore pressure and creates hydraulic gradients that determine the direction and velocity of fluid transport; macroscopically, the fluid flow can be described by Darcy's law. Pressure propagation and viscous forces control the lateral and vertical distribution of the injected fluid, whereby preferred flow paths and anisotropic flow patterns can form in heterogeneous carbonate reservoirs (Birkholzer et al., 2011).

Chemically, the dissolution of CO_2 leads to a significant decrease in the pH of the thermal water. The dissolved CO_2 reacts with water to form carbonic acid:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3$$

At a pH value of around 4, uncharged carbonic acid dominates, while dissociation products such as HCO3− or CO32− are hardly present (Stumm & Morgan, 1996). The acid reacts with carbonate minerals in the host rock, especially calcite or dolomite, leading to carbonate dissolution:

$$CaCO_3(s) + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

This process increases the local concentration of calcium and bicarbonate ions and can temporarily increase the porosity and permeability of the rock. In the long term, this changes the hydraulic properties of the reservoir (Gherardi et al., 2007).

Thermal, hydraulic and chemical processes are closely linked in this system. Temperature changes influence both the solubility of CO_2 and the reaction kinetics of carbonate dissolution. Mechanically, changes in pressure and porosity affect the effective stress in the rock, which in individual cases can lead to the reactivation of fault zones or induced seismicity.

Overall, it is evident that CO_2 injection into geothermal carbonate reservoirs creates a complex reactive multiphase system. Effective CO_2 storage therefore requires an integrated approach combining geochemical modelling, pressure and temperature monitoring, mineralogical characterisation, and scaling and corrosion management. If the CO_2 is kept completely in solution and operated under suitable thermodynamic conditions, a significant proportion can be bound as carbonate mineral in the long term and thus stored permanently in a deep geothermal system.

4 ECONOMIC CONSIDERATIONS

A conventional cement plant with a modern rotary kiln and an integrated calciner with a production capacity of 3,000 tonnes clinker per day serves as a reference plant. Assuming year-round production and taking into account the emission factor specified in chapter 3 (0.81 $tonne_{CO2eq}$ / $tonne_{clinker}$), the total annual emissions amount to 886,950 tonnes of CO_2. Approximately 60% (532,170 tonnes of CO_2) are process-related emissions from the deacidification of limestone and 40% (354,780 tonnes of CO_2) are attributable to energy-related emissions from combustion. Energy-related emissions are not considered further, as the industry already largely uses alternative fuels (> 80%, see Figure 1) and this share is expected to increase.

Within the scope of this model analysis only the costs of reducing process-related emissions (532,170 tonnes of CO_2) are considered.

The following requirements must be met to be eligible for placing a bid on CCfDs:

- Every year: minimum reduction of 10,000 tonnes of CO_2 /a
- From the third year: reduction of at least 60% of eligible emissions (≈ 319,302 t CO_2/a)

- From the 14th year: reduction of at least 90% of eligible emissions (≈ 478,953 t CO_2/a)

The design parameter for determining the number of deep geothermal boreholes and the oxyfuel process is 478.953 tonnes of CO_2/a based on the above mentioned requirements.

4.1 Input variables for economic calculation

The relevant input variables for implementing the model analysis are specified below. The cement plant is located in Bavaria, Germany. In the immediate vicinity of the cement plant, there is carbonate rock underground, which is permeable to allow thermal water to circulate.

4.1.1 EU ETS development

The price development of EU ETS certificates is a key influencing factor for the design and weighting of the funding instruments within CCfDs. However, the Federal Ministry for Economic Affairs and Energy does not indicate which initial prices and assumptions about the future price development of the certificates are used as reference values. Therefore, certificate prices based on data from the International Energy Agency's World Energy Outlook (VBW, 2024) are used. Three different price scenarios are considered, which are presented in Table 1.

Table 1: EU ETS price development 2026-2040

Year	Lower price path [€/t_{CO2}]	Medium price path [€/t_{CO2}]	Upper price path [€/t_{CO2}]
2026	65	70	70
2027	64	78	80
2028	64	90	95
2029	64	105	110
2030	64	118	125
2031	67	122	133
2032	70	126	140
2033	73	130	147
2034	76	134	153
2035	80	138	160
2036	85	142	170
2037	90	146	180
2038	96	150	190
2039	102	155	200
2040	108	160	210

4.1.2 Deep geothermal plant

A maximum target depth of 3,000 m is defined for model-based deep geothermal drilling. A volume flow of 100 l/s is assumed for the production well. The temperature of the extracted thermal water is 120 °C, while reinjection takes place at a temperature of 60 °C. These parameters result in a total thermal output of approximately 25.1 MW for the deep geothermal plant. The analysis defines three concentration scenarios – conservative, moderate and ambitious – which differ in terms of the potential amount of CO_2 that can be dissolved per litre of thermal fluid. Table 2 shows the differences between the various scenarios.

Table 2: Scenarios for CO_2 solubility

Scenario	CO_2 solubility [g/l]
Conservative	10
Moderate	15
Ambitious	20

4.1.3 Input parameters for investments

The model analysis uses a combination of the oxyfuel process for CO_2 capture and the integration of deep geothermal energy for permanent storage in geological formations. In addition, the thermal water flow is utilised in an organic Rankine cycle (ORC) to generate electricity to supply the air separation plant of the oxyfuel process itself (not included in the analysis). Table 3 presents key parameters for calculating the total investment costs.

Table 3: Key parameters for investments

Plant	Cost	Source(s)
Deep geothermal plant	€40 million/double drilling	Rödl Auditing GmbH Wirtschaftprüfungsgesellschaft
Oxyfuel process	130 per tonne of clinker	(PROGNOS, 2022)
ORC plant	€4,000/kW_{el}	(BMWK, 2024a)

4.2 Total investments

The scenarios presented in Table 4 show that CO_2 solubility has a significant influence on the technical design and investment structure of the overall system. With solubility increasing from 10 g/l in the conservative scenario to 20 g/l in the ambitious scenario, the CO_2 absorption capacity per doublet increases significantly, enabling a reduction in the number of deep boreholes required from 16 to 8. This reduction in infrastructure costs is directly reflected in the investment costs: the total investment falls from €934 million in the conservative scenario to €538 million in the ambitious scenario. This results in significant economies of scale and improved capital and resource efficiency. At the same time, higher CO_2 solubilities imply potential technical challenges, for example regarding material resistance, process stability and geochemical interactions. Overall, Table 4 illustrates that although an increase in CO_2 solubility has considerable economic optimisation potential, its implementation depends on robust technological and geoscientific validation.

Table 4: Parameters for the economic assessment

Parameter	Unit	Scenario 1 *Conservative*	Scenario 2 *Moderate*	Scenario 3 *Ambitious*
CO_2 solubility	g/l	10	15	20
CO_2 absorption per duplicate	t/a	31,536	47,304	63,072
Target value for CO_2 reduction	t/a	478,953	478,953	478,953
Number of TG boreholes	pcs	16	11	8
Investments:				
Deep geothermal plant incl. piping	million	640	440	32
Oxyfuel	million	143.25	143.25	143.25
ORC	million	152	104	76
Total investment	**million**	**934**	**687**	**538**

4.3 CCfD funding results

The subsidy amounts are calculated based on equation 1, which determines the annual compensation payment under the CCfD. It is based on a linear relationship between the CO_2 emissions avoided and the difference between the contractually agreed base price and the current price in the European Emissions Trading System (EU ETS). The amount of funding is therefore determined exclusively by this price difference.

In the conservative scenario, using the average EU ETS price path (see Table 5), the base price is €130.02/t CO_2. The average price path was chosen because it adequately reflects the development of EU ETS prices to date and thus represents a realistic assumption for the projection of future price developments. The base price was derived from the ratio of the total investment required to the cumulative CO_2 reduction effects over the 15-year period. Table 5 shows that as the EU ETS price rises, the difference to the base price decreases and the annual subsidy amount declines accordingly. From the ninth year onwards, the EU ETS price exceeds the base price, meaning that the subsidy recipient would have to make a repayment.

If, on the other hand, the cement manufacturer in question did not invest in emission-reducing technologies, the gradual introduction of the CBAM from 1 January 2026 would result in an increasing financial burden due to the purchase of certificates for the emissions caused.

Table 5: Calculation methodology for climate protection contracts based on the conservative + medium EU ETS price path scenario

Year	Base price [€/t_{CO2}]	CO_2 reduction [t/a]	EU ETS [€/t_{CO2}]	Subsidy amount [€/a]	CBAM [%]	EU ETS costs [€/a]
1 / 2026	130.02	478,953	70.00	28,748,503	10	-3,725,190
2 / 2027	130.02	478,953	78.00	24,916,879	20	-8,301,852
3 / 2028	130.02	478,953	90.00	19,169,443	30	-14,368,590
4 / 2029	130.02	478,953	105.00	11,985,148	40	-22,351,140
5 / 2030	130.02	478,953	118.00	5,758,758.6	50	-31,398,030
6 / 2031	130.02	478,953	122.00	3,842,946.6	60	-38,954,844
7 / 2032	130.02	478,953	126.00	1,927,134.6	70	-46,937,394
8 / 2033	130.02	478,953	130.00	11,322.587	80	-55,345,680
9 / 2034	130.02	478,953	134.00	-1,904,489	90	-64,179,702
10 / 2035	130.02	478,953	138.00	-3,820,301	100	-73,439,460
11 / 2036	130.02	478,953	142.00	-5,736,113	100	-75,568,140
12 / 2037	130.02	478,953	146.00	-7,651,925	100	-77,696,820
13 / 2038	130.02	478,953	150.00	-9,567,737	100	-79,825,500
14 / 2039	130.02	478,953	160.00	-11,962,502	100	-82,486,350
15 / 2040	130.02	478,953	166.00	-14,357,267	100	-85,147,200
		7,184,2995		**41,359,797**		**-759,725,892**

5 DISCUSSION RESULTS AND CONCLUSIONS FOR ACTION

In summary, climate protection contracts are a new type of funding instrument that differs fundamentally in structure from traditional government subsidy mechanisms. Instead of a fixed subsidy, funding is provided based on the difference between a contractually defined base price and the current price in the European Emissions Trading System (EU ETS). This market-oriented concept links funding directly to the dynamics of CO_2 certificate trading, thus leading to a shared distribution of risk between the government and companies.

The analysis shows that the development of EU ETS prices has a decisive influence on the economic efficiency of climate protection contracts. In the conservative scenario, combined with a lower price path, there is a positive funding effect resulting in around €374 million. In contrast, combining the conservative scenario with an upper EU ETS price path leads to repayments of around €102 million. This clearly shows that the actual effectiveness of CCfDs depends largely on future price developments in emissions trading, and that there is therefore considerable uncertainty when it comes to planning and assessing the subsidy effect.

Another key influencing factor is the CO_2 absorption capacity of the thermal water, which varies from site to site. Due to the geological heterogeneity of the formations, no general statements can be made about the transferability of the results. A detailed long-term analysis of the geochemical and physical interactions would be necessary to be able to thoroughly evaluate the technical and ecological sustainability of such projects.

For the cement industry it appears that climate protection contracts offer only limited economic advantages under the current framework conditions. Nevertheless, the results make it clear that a failure to implement industrial transformation measures is not a viable alternative. The introduction of CCfDs can therefore be seen as an important intermediate step towards the decarbonisation of industrial processes, but it must be accompanied by technological development, improved geotechnical site analyses and long-term stable pricing in the EU ETS.

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