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Enhancing Carbon Capture and Storage Deployment in the EU: A Sectoral Analysis of a Ton-Based Incentive Strategy

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Abstract: The EU considers carbon capture and storage (CCS) technology as an option for achieving climate goals, but its cost remains appreciable. Therefore, the purpose of this research was to investigate the implementation of a ton-based incentive system for CCS in the EU using Croatia as an example based on an analysis of the existing legislative framework in the EU and relevant tax credit provisions in the USA. A novel methodology for the design of the incentive system is presented in the form of partial allocation of the state's auction revenues from the EU emissions trading system (ETS) into the CCS fund for five years. The CCS fund assets then incentivize the capture site for 10 years. The incentives are determined for each emitter in cement, electricity, paper and pulp, glass, oil refining, and petrochemical sectors based on varying European Union allowance (EUA) prices, CCS fund sizes, and CO_2 emission scenarios. In addition to designing the methodology, a novel method for forecasting CO_2 emissions is applied using geometric Brownian motion. The calculated incentives are categorized as underperforming, optimal, or overperforming, with upper and lower limits set to 80 and 10 EUR/t. The results are optimistic, since all sectors can be efficiently incentivized within the defined boundaries, meaning that the incentive system can be applied to all member states. The contracting of the incentives is proposed through carbon contracts for difference to avoid irregularities. Also, regulatory amendments are proposed so that emitters with emissions higher than 100 kt would have to consider CCS. Finally, the contributions are presented by proving the feasibility of the incentive system together with demonstrating its applicability to all member states.

Keywords: CCS; EU ETS; incentives; geometric Brownian motion; CCfD; carbon policy

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1. Introduction

Due to the Paris Agreement [1], greenhouse gas (GHG) emissions are a global issue that must be addressed and handled as a top priority. The climate law [2] envisions a reduction in GHG emissions of at least 55% by 2030, relative to 1990 levels. In addition, the EU intends to achieve climate neutrality by 2050, indicating that its economy will have net-zero GHG emissions.

To attain the aforementioned objectives, it is necessary to implement sustainable water, energy, and environmental systems to address the visible anthropogenic influence on climate change [3,4]. In light of the climate problem [5], the implementation of the aforementioned systems can be viewed within a broader context. In addition, available resources should be utilized more responsibly during the energy transition, specifically by implementing a circular economy [6,7] and more sustainable technologies [8,9]. The use of renewable energy sources in both public and private facilities, the electrification of public transportation, and energy renovations, for instance, have been found to substantially reduce GHG emissions while lowering specific costs as the overall reduction in emissions quantity increases [10,11]. Future energy systems may also rely heavily on alternative fuels such as hydrogen, biodiesel, e-fuels, ammonia, and alcohol-derived fuel [12].

Although there has been rapid growth in the use of renewable energy sources, especially over the past few decades [13], as the cost of variable renewable energy has decreased significantly each year [14], other technologies, namely carbon capture and storage (CCS), should also be considered to accelerate decarbonization. In the EU, the number of planned and operational CCS initiatives is increasing. In 2021, there were 51 planned/operational CCS facilities, with approximately 50 Mt of CO_2/y to be stored by 2030. The number of planned/operational CCS projects increased to 65 in 2022, and it is anticipated that 60 Mt of CO_2/y will be stored by 2030 [15]. More importantly, the number of participating countries in which CCS is planned to be deployed is constantly rising. Even though the number of planned projects in Europe is increasing, the costs of CCS can vary significantly, from between 60 USD/t to more than 120 USD/t [16]. From a cost avoidance perspective, the reported values range from 40 to 70 USD/t of CO_2 avoided [17].

Furthermore, Paltsev and others [18] investigated the role of CCS in the emission mitigation of hard-to-abate sectors (cement, iron and steel, and chemical production) and concluded that global emission mitigation costs are significantly higher without CCS deployment within the industry, which is consistent with other available studies [17]. The production of low-emission cement is highly dependent on CCS, but GHG emissions from the cement industry can be somewhat reduced by utilizing alternative energy sources and raw materials [19].

Regarding carbon capture, it is assumed that the majority of facilities have a 90% capture rate [20]. The authors discuss literature that examines the possibility of moving significantly beyond 90% capture (deep CCS concept) in light of recent developments in process and material design. Moreover, deep decarbonization could be accomplished by combining carbon capture and utilization technology with renewable energy sources [21]. At the site of hydrogen production, carbon capture can also be facilitated (blue hydrogen). George and others [22] conclude that blue hydrogen is likely to emerge as the most cost-effective option, not only as a medium-term low-carbon substitute but also as a long-term low-carbon solution for hydrogen production. Similarly, the deployment of carbon capture can be observed at biomass-fired power plants (bioenergy with CCS, BECSS), resulting in negative emissions. Such a power plant design could achieve negative emissions of -720 kgCO_2/MWhel, for instance [23]. This cutting-edge technology goes even further by introducing carbon-negative hydrogen from BECCS installations [24].

Moving to the CCS business models, Kapetaki and Scowcroft offered an overview of CCS project business models in North America and Europe [25]. The authors concluded that successful CCS project development correlates well with the following: clarity of the regulatory framework, efficiency of permitting processes, and early stakeholder engagement for public acceptance. In addition, regardless of the pathway to industrial CCS deployment, sustained policy support is required [26].

Equally significant is that the legal framework should support the use of technologies that accelerate the energy transition and facilitate decarbonization [27]. Zhang conducted a comparative analysis of regulations for carbon capture, utilization, and storage (CCUS) development in Europe, China, and the Middle East [28]. The following key regulatory issues for Europe were identified: project operators are responsible for all environmental liabilities during the lifetime of the project, and stringent standards for triggering the transfer of liability to a competent state body. Concerning the regions of China and the Middle East, it is concluded that they have yet to establish a specific legislative framework for CCUS, and that clarity is desirable on the project approval process and liability provisions to support CCUS deployment. Overall, political will and support in the form of incentives, tax refunds, and subsidies are required to drive investments in CCS technology and shift away from the alternatives of paying carbon taxes or acquiring emission rights [29].

1.1. Key Provisions of the EU Legislative Framework

The CCS Directive (2009) is the first EU directive affecting the deployment of CCS technology, and it has implications for this work. It establishes a legal framework for environmentally sound geological CO_2 storage to combat climate change [30]. Since it lays the groundwork for CCS technology and its deployment on EU territory, this directive defines every relevant term and procedure, including storage permits and their requirements, conditions, and content. In addition, the directive requires the establishment of storage permits and geologic storage space registers. The operations of exploitation, closure, and post-closure are also regulated, with a focus on measuring CO_2 volume throughout the process and defining penalties for violations. Furthermore, when considering environmental risk, the definition of CCS liability mechanisms is essential [31]. However, because the project operator's temporal and financial liability remains uncertain, current liability mechanisms may be deemed insufficient. As a result, member states should develop a liability policy that encourages investment while holding the operator liable for the majority of contingencies [32]. Finally, the competent authority body of each member state is required to conduct regular inspections and supervision of underground CO_2 storage under this directive.

The EU ETS Directive (2003) establishes a system of trading greenhouse gas emission allowances in the EU [33]. The EU ETS includes emissions from stationary installations as well as the aviation sector and accounts for approximately 40% of the EU's greenhouse gas emissions. The European Union Allowance (EUA) is a tradable commodity within the EU ETS, and it represents the permit to emit one ton of CO_2 equivalent over a given term. It is classified as a "cap and trade" system, which means that a cap is placed on the number of emissions lowered each year, while market participants can trade allowances to comply with the directive. The EU ETS is currently in Phase IV, which will span from 2021 to 2030 and is defined by a fixed cap of 1,571,583,007 EUA with a linear reduction factor (LRF) of 2.2%. This indicates that throughout Phase IV, the cap will be reduced by 43,003,515 EUA each year. However, following the implementation of the "Fit for 55" package, the EU has set a new LRF of 4.3% from 2024, or 4.4% from 2028. As a result, the specified climate targets will be easier to achieve.

In terms of trading on the EU ETS market, each year, emitters must surrender an amount of EUA equal to their verified emissions for that year. If they fail to do so, the emitters face a fine of 100 EUR per missing EUA, as well as the cost of restocking the missing quantity of allowances at the current market price. As a result, the authorities might use the EUA as a tool to compel polluting companies to embrace clean energy to address climate change [34]. Furthermore, the EUA price is rather volatile, with an interdependence with energy (coal, oil, natural gas, and electricity prices), economic (industrial production, economic sentiment, bank lending), and temperature variables [35]. However, the EUA price is vulnerable to unforeseen market shocks, such as the Brexit announcement, which had considerable adverse effects [36] on the market. Furthermore, when shocks occur, the EUA price shows a high responsiveness to its previous price [35]. As a result, the market stability reserve (MSR) is implemented as an additional essential element of the EU ETS to buffer the detrimental consequences of external major shocks. The MSR operates in such a way that EUAs are either withdrawn or added to the system based on the type of market occurrences. Currently, 24% of the cap is fed into the MSR, and that amount is expected to remain constant until Phase IV concludes in 2030. Furthermore, 2% of the cap is distributed to the modernization fund (MF), which is a program aimed at assisting lower-income EU member states to shift to climate neutrality by modernizing their energy systems and improving their energy efficiency. An additional 2.5% of the cap is projected to be allocated to the fund by 2024. Apart from the percentages indicated, member states can voluntarily transfer an additional number of allowances to the MF (Croatia, Czechia, Lithuania, Romania, and Slovakia opted to do so).

Concerning the allocation of EUAs, they are either auctioned or allocated for free. According to the European Commission, 57% of EUAs were auctioned in Phase III of the EU ETS, and this figure is also regarded as accurate for Phase IV. The free allocation methodology is based on benchmarking, with the benchmark for a product being based on the average GHG emissions from the top 10% of EU-based installations that manufacture that product. This means that all EUAs will be provided free of charge to installations that reach the benchmark. Those installations that do not meet the criteria, on the other hand, will receive less EUA than they require, obliging them to cut their emissions, purchase EUAs, or combine the latter two alternatives. Within the scope of the Fit for 55 package, free allocation will be phased out until 2030 for less-exposed sectors, and until 2034 for the sectors that are most susceptible to carbon leakage (cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen sectors). This can be perceived as an essential driver for the widespread deployment of CCS technology, as every facility will be required to purchase EUAs for their emissions in the near future. As a result of the above, the activities relevant to this research that fall within the authority of the EU ETS directive are CO_2 capture, CO_2 transport, and CO_2 geological storage. This means that facilities that capture CO_2 from their flue gas stream, transport it via pipeline, and store it underground do not need to surrender a certain number of EUAs equal to the number of tons of CO_2 that are adequately captured, transported, and stored, because that amount of emissions will be counted as not emitted. The above cost avoidance within the EU ETS market represents one of the key drivers for the deployment of CCS technology.

The last relevant directive is the directive on industrial emissions (2010). It regulates the operation of installations whose activities may have an impact on emissions and pollution of the environment [37]. Of significant importance for this research is Article 36 of this directive, which implies geological storage of CO_2. Operators of combustion plants with a rated electrical output of a minimum of 300 MW and whose operating license is issued after enactment of the CCS directive (2009) should assess possibilities for deploying CCS if suitable storage sites are available and if transport and retrofitted capture facilities are technically and economically feasible. This assessment is inspected by member state authorities. Furthermore, by satisfying the criteria above, member states need to ensure that space for CO_2 capture and compression is set aside at the combustion plant's site.

1.2. CCS Incentives in the USA (45Q)

In contrast to the EU, the USA does not have a federal "cap and trade" ETS. However, most CCS projects in the USA rely on the 45Q section of the internal revenue code from 2008 [38], in which carbon oxide sequestration credits (45Q) were first enacted, representing a form of tax credit per ton of CO_2 captured. Following its introduction, dedicated geological storage incentives were 20 USD/t, and enhanced oil recovery (EOR) incentives were 10 USD/t. The Bipartisan Budget Act [39] boosted the tax credit significantly in 2018, depending on CO_2 disposal methods. The tax credit grows ratably to 50 USD/t for dedicated geological storage and 35 USD/t for EOR and other eligible utilization methods, such as photosynthesis/chemosynthesis or chemical conversion to a carbon-storing material or compound, by 2026. Afterward, the tax credit is inflation-adjusted. Based on the CO_2 source and disposal method, a minimum quantity of emissions must be captured:

- For dedicated geological storage and EOR, the minimum captured quantities for power plants are 500 kt/y, and for other industrial facilities or direct air capture (DAC), they are 100 kt/y.
- For utilization, regardless of the source, the minimum emissions to be captured are equal to 25 kt/y. Additionally, each CO_2 source cannot be greater than 500 kt/y.

These incentives last 12 years and can be revoked for irregularities. Instead of a tax incentive, Bright suggested a direct pay option for 45Q credit to make the incentive more appealing [40]. Considering reported amendment suggestions, the Inflation Reduction Act of 2022 included significant 45Q incentive modifications [41]. The eligible project annual capture criterion was substantially reduced for power plants to 18.75 kt, industrial facilities to 12.5 kt, and DAC to 1 kt. A base credit was introduced, equaling 17 USD/t (36 USD/t for DAC) for dedicated geological storage and 12 USD/t (26 USD/t for DAC) for EOR and usage storage. However, facilities that pay prevailing wages throughout construction and the first 12 years of operation and meet registered apprenticeship criteria will receive higher tax credits:

- For industrial and power sector projects, 85 USD/t for geologically sequestered CO_2 or 60 USD/t for utilization or storage in hydrocarbon fields via EOR.
- For DAC, up to 180 USD/t for geologically sequestered CO_2, or 60 USD/t for utilization or storage in hydrocarbon fields via EOR.

The 12-year incentive period persisted, and a direct payment was introduced so that profit entities could obtain payments for 5 years and tax-exempt entities could receive payments throughout the duration of the tax credit. Summarizing the above, the current opportunities of 45Q incentive are graphically described in Figure 1.

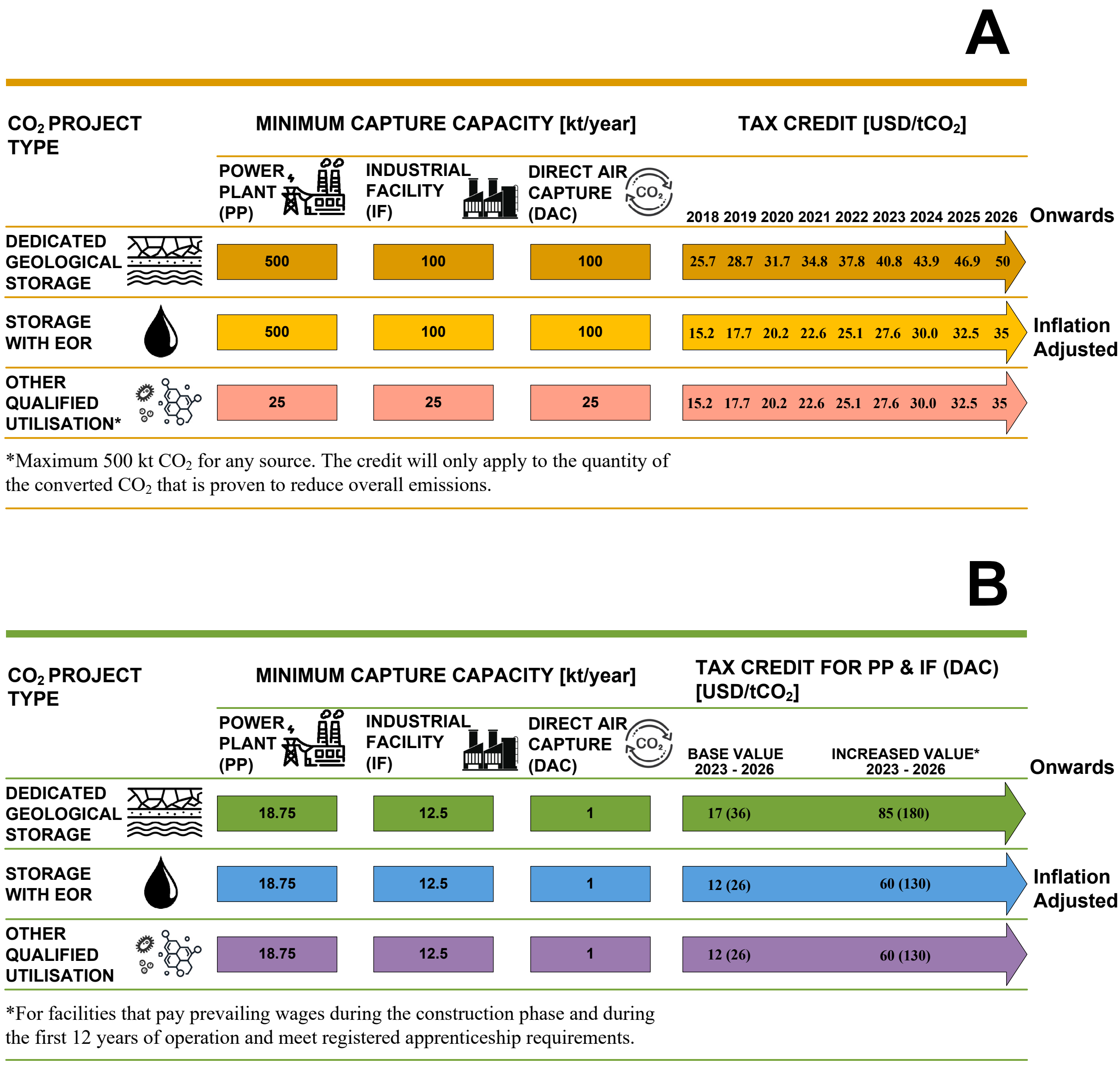

Figure 1. Variations in CO_2 project types, minimum capture capacity, and level of tax credit in the USA for equipment placed in service after 8 February 2018 and before 1 January 2023 (**A**) and for equipment placed in service after 31 December 2022 and construction beginning before 1 January 2033 (**B**). Equipment placed in service before 8 February 2018 is no longer eligible for the 45Q tax credit. Data source: CRS [42].

Based on an analysis of the key provisions of the EU regulatory framework and CCS incentives in the USA, the purpose of this research is to determine whether rapid deployment of CCS technology on the EU level is feasible through the implementation of a ton-based incentive system that would increase investment interest in the aforementioned technology.

2. Methods

This chapter presents the methods for creating a ton-based incentive system. The implementation of the concept is demonstrated through the use of Croatia as an example. This country has comparatively low CO_2 emissions compared to other EU member states; roughly 0.5%. As a result, it is considered a promising choice for a pilot phase. If the proposed incentive system is demonstrated to be viable, it may be implemented in all member states of the EU. This is highly significant, considering that the EU, along with China, the USA, and India, is one of the largest contributors to global CO_2 emissions. Therefore, it is necessary to precisely define the systematic procedure for the methodology steps:

- Firstly, EUA auction volume is forecasted in accordance with the legal regulations of the EU. The quantity of auctioned EUA is determined on the EU level by using an estimate by the European Commission of 57% of the cap being auctioned. Subsequently, Croatia's allocated amount of EUA for auctions is calculated by considering its proportionate emissions within the EU while accounting for the quantity that is transferred to the MSR and MF from Croatia's gross volume of EUA.
- Secondly, EUA price trendlines are determined by assuming three linear and incremental scenarios.
- With known EUA auction volume and EUA price, auctioning revenues can be calculated by multiplying the aforementioned variables.
- Part of the revenue will be allocated for five years (until 2027) to the newly established CCS fund. This part of the revenue is referred to as the CCS fund size, with four different fund sizes being envisaged by this work: 5%, 10%, 20%, and 30%.
- After the financial resources accumulated for 5 years in the CCS fund, these assets are used to incentivize the deployment of CCS technology at the CO_2 capture site for 10 years. To determine the exact level of incentives for each emitter, their CO_2 emissions are forecasted by implementing geometric Brownian motion in Python.
- Based on known forecasted CO_2 emissions and funds in the CCS fund, incentive options are determined for each emitter, with an arbitrary set upper and lower limit of 80 and 10 EUR/t of CO_2 captured, respectively.
- If the emitter and the state find the incentive level option acceptable, the signing of an agreement between the parties can be realized in the form of a carbon contract for difference (CCfD).

As mentioned in Section 1.1, the EU has set a cap for 2021, equaling 1,571,583,007 allowances (permits to emit one ton of CO_2). Also, the LRF is set to 2.2% until 2024; that is, 4.3% from 2024 to 2028. This means that each year, the cap ($CAP_{EU,\,t}$) will be reduced by a fixed number of allowances, equaling 43,003,515 until 2024 and 84,052,325 from 2024 onwards:

$$CAP_{EU,\,t} = CAP_{EU,\,t-1} - LRF \tag{1}$$

In general, not all allowances (EUAs) defined by the cap are auctioned. As stated in the EU ETS directive, the share of allowances to be auctioned (AS) shall be 57%, meaning that the volume of the auctioned cap ($CAP_{Auctioned,\,t}$) can be calculated as follows:

$$CAP_{Auctioned,\,t} = CAP_{EU,\,t} \cdot AS \tag{2}$$

Also, within the scope of the EU ETS directive, emission shares (ES) for each member state are defined, and this equals 0.5199% for Croatia [43]. The gross volume of allowances ($Gross\_EUA_{Croatia,\,t}$) for Croatia can be defined as follows:

$$Gross\_EUA_{Croatia,\,t} = CAP_{Auctioned,\,t} \cdot ES_{Croatia} \tag{3}$$

Since 24% of the cap ($MSRS_{EU}$) is currently transferred into the MSR, the volume of EUA that Croatia transfers to MSR ($MSR_{Croatia,\,t}$) can be estimated by applying its share within the MSR feeds ($MSRS_{Croatia}$) of 0.4684%, which is available in legal texts from the European Commission [44]:

$$MSR_{Croatia,\,t} = CAP_{EU,\,t} \cdot MSRS_{EU} \cdot MSRS_{Croatia} \tag{4}$$

Croatia also opted for additional participation within the MF in which it was obliged to transfer the revenues from auctioning 597.885 EUAs ($MF_{Croatia}$) each year until 2030. Finally, the net volume of EUAs available for auctioning by Croatia ($Net\_EUA_{Croatia,\,t}$) can be calculated by subtracting the feeds to the MSR and MF from the gross volume of EUAs:

$$Net\_EUA_{Croatia,\,t} = Gross\_EUA_{Croatia,\,t} - MF_{Croatia} - MSR_{Croatia,\,t} \tag{5}$$

After the EUA auctioning volume is defined, adjacent EUA prices should be forecasted. To do so, historical data for EUA futures prices must be provided. From the available data [45], it can be observed that the starting price of EUA in 2021 was approximately 30 EUR, increasing to 80 EUR until the end of 2021. In February 2022, the EUA price reached almost 100 EUR. A sharp decline in the price between February and March 2022 was the result of the beginning of the war in Ukraine. However, the market responded quickly, and the price remained stable until mid-2022, varying between 80 and 90 EUR. The EUA price started from 80 EUR in 2023 and promptly reached 100 EUR in February. Since then, the price continued to range from 80 to 100 EUR. Hence, to determine EUA price trendlines in this work, the EUA price for 2023 was set to 90 EUR, and it represents the starting point of the forecasting process.

Since the observed period is set until 2027, three forecasting scenarios can be differentiated:

- LOW scenario: Linear increase in price equal to 3 EUR/EUA each year.
- MID scenario: Linear increase in price equal to 6 EUR/EUA each year.
- HIGH scenario: Linear increase in price equal to 9 EUR/EUA each year.

Since the historical tracks of the EUA prices depict their volatile nature, the purpose of the above scenarios is not to link the explicit EUA price to a certain time, but instead to define representative curves (trendlines) between which the actual EUA price will fluctuate. Another justification for implementing the linear scenarios is that the MID and HIGH scenarios were used for the STRATEGY CCUS project [46] in a tool that was used to evaluate the impact of several variables on CCUS costs and breakeven prices in the regions of interest, including Croatia. Succeeding the auctioned volume of allowances and EUA prices forecast, revenues from auctions ($Revenue_{Croatia,\,t}$) can be calculated for each year and price scenario ($Price_{EUA,\,t}$):

$$Revenue_{Croatia,\,t} = Net\_EUA_{Croatia,\,t} \cdot Price_{EUA,\,t} \tag{6}$$

The EU ETS directive envisages that the member states decide on their use of revenue generated from the auctioning of EUAs. However, the usage of the financial assets needs to fit into one of the 14 different categories that are defined in the above-mentioned directive. These categories can be described as measures that encourage GHG emissions reduction, investments in renewable energy sources, increasing energy efficiency, and green policies in general. It is worth noting that environmentally safe CO_2 capture and geological storage is one of the categories. Based on the "Decision on adoption of the Plan for the use of financial resources obtained from the sale of allowances through auctions in the Republic of Croatia from 2021 to 2025", the distribution of revenues from allowance auctions in Croatia will be distributed throughout the following categories [47]:

- Low-carbon energy transition (LCET)—5%,
- Non-energy sector (NES)—17%,
- Climate change adaptation (CCA)—24%,
- Research and development (R&D)—4%.

While reading the decision, no funds are envisaged for CCS in Croatia. Hence, in this work, the authors propose the establishment of the CCS fund, which is also the next step in the methodology. Consequently, the revenues from auctions would require redistribution, which means less funding for some of the projects from the existing categories within the current plan. Despite the above, since CCS is explicitly categorized as a funding option within the EU ETS directive, the establishment of the CCS fund has its legitimacy.

The concept is that the portion of the revenues from auctioning EUAs is allocated to the CCS fund for 5 years (2023–2027), after which it will be used to incentivize captured CO_2 for 10 years. Since CCS could fall into two categories of the plan, namely LCET and NES, the funding pool could be as large as 72% of the revenues from auctions. The proposed partitioning of the CCS fund in the revenue distribution is modeled reasonably, since the expectation of 72% being channeled for CCS is unrealistic. Therefore, the funds within the CCS fund ($Fund_{CCS,\ t}$) are defined by four different CCS fund sizes ($Fund\_Size$) of 5%, 10%, 20%, and 30% of revenues:

$$Fund_{CCS,\ t} = Revenue_{Croatia,\ t} \cdot Fund\_Size \tag{7}$$

This means that for each of the four CCS fund size scenarios, three EUA price scenarios are taken into consideration, for a total of 12 scenarios of CCS fund sizes that vary with EUA price. Furthermore, the emitters in Croatia whose CO_2 emissions are to be forecasted until 2027 need to be included in the EU ETS, and their CO_2 emissions must exceed 100 kt at least once since Croatia joined the EU (2013). The only exception to the EU ETS inclusion is for sustainable bio-mass power plants that can generate negative emissions if CCS (BECCS) is deployed. This is of high significance, since the European Commission is currently defining a certification framework for carbon removal certificates [48]. Also, the 100 kt criterion is defined by the CCS directive as the minimum eligible quantity to be stored underground. Regarding the observed time, 2022 is the last year for which verified emissions are known from the EU ETS registry, and 2013 was the year when Croatia joined the EU.

Since the emitter's CO_2 emissions can vary to a certain extent every year depending on the market conditions, fuel used, efficiency of the production process, and internal company policy, to perform an emissions forecast, it is decided to conduct random walk simulations in Python which are defined by a geometric Brownian motion stochastic differential equation.

When the random walk is referred to as geometric Brownian motion (GBM), the CO_2 emission changes (dS) are assumed to be normally distributed. In this study, the distribution parameters are estimated using a smaller sample of the complete population (mean and standard deviation of the dS for GBM).

If a time series of data is observed over a certain period, it can be seen as random variations of the observed parameter during that period or as potential temporal realizations of a dependent variable. These realizations can include the Wiener process, $z(t)$, in which the relationship between the change in z (Δz) over time (Δt) and the random variable (ε_t, N (0,1)) is connected:

$$\Delta z = \varepsilon_t \sqrt{\Delta t} \tag{8}$$

For Δt that is infinitesimally small in continuous time, the Wiener process becomes:

$$dz = \varepsilon_t \sqrt{dt} \tag{9}$$

Brownian motion can develop from the generalized Wiener process:

$$dS = \mu \cdot dt + \sigma \cdot dz \tag{10}$$

where μ is the drift, and variance σ is volatility (standard deviation) that can be calculated from historical yearly percentage CO_2 emissions changes (x) and their mean value ($\overline{x}$) within the observed time, T:

$$\mu = \overline{x} \tag{11}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{T}(x_i - \overline{x})^2}{T-1}} \tag{12}$$

A more generalized form of the Wiener process is:

$$dS = a(S,\ t) \cdot dt + b(S,\ t) \cdot dz \tag{13}$$

Geometric Brownian motion is a special case when $\mu \cdot S = a(S, t)$ and $\sigma \cdot S = b(S, t)$, being μ and σ constants:

$$dS = \mu \cdot S \cdot dt + \sigma \cdot S \cdot dz \tag{14}$$

When a random walk is characterized by GBM, it is assumed that the increment of an observed value (CO_2 emissions) is normally distributed in time. As this is a Markov process [49], the analysis of the parameters that affect the observed value is irrelevant, because the random walk is only affected by the starting value of the variable and is unaffected by the history of the process. If a variable is CO_2 emissions (S), the random walk, i.e., GBM, can be expressed as:

$$\ln\left(\frac{S_t}{S_{t-1}}\right) \sim \Phi\left(\mu - \frac{\sigma^2}{2}\right)T,\ \sigma\sqrt{T} \tag{15}$$

The natural log of CO_2 emissions at time step t (S_t) divided by the emissions at the time-step (S_{t-1}) is continuously compounded (rate of) return on a continuously compounded frequency (constant Δt). It is approximately normally distributed (Φ denotes normal distribution) with the mean ($\left(\mu - \frac{\sigma^2}{2}\right)T$) of drift ($\mu$) minus half of the variance (σ^2) over time (T) and volatility (σ) scaled by the square root of time.

Brownian motion can be considered as a log-normal diffusion process. A simple implementation is given in Monte Carlo simulation, which will include a deterministic component and a stochastic component:

$$\ln\left(\frac{S_t}{S_{t-1}}\right) = \alpha + z_t\sigma \tag{16}$$

The deterministic component (α) is proportional to drift as a constant part of the equation since it equals ($\left(\mu - \frac{\sigma^2}{2}\right)T$), and the stochastic component z_t σ represents "random shock"; that is, the volatility multiplied by a random variable (z_t).

Expressed from a moment t = 0 with the CO_2 emissions at that moment (S_0), the equation for the simulation of CO_2 emissions at year t could be also written as:

$$S_t = S_0 e^{\alpha t + z_t \sigma} \tag{17}$$

This leads to the fact that geometric Brownian motion can be characterized by only two parameters: drift and volatility. For this reason, an attempt is made to calculate the volatility and drift for each of the selected emitters based on the relative change in the yearly CO_2 emissions between 2018 and 2022. From the above, it can be observed that volatility is considered a critical parameter since it defines the amplitude of the CO_2 emissions forecast, unlike the drift, which defines the direction of forecasted emissions. In principle, the forecasting is performed on a "five-for-five" principle, meaning that 5 years of historical

CO_2 emissions are used for forecasting 5 years of CO_2 emissions. The approach of using GBM for emissions forecasting is considered valid for two reasons. The first is its robustness, since the forecasted emissions are dependent only on historical emissions. The second reason is that the historical emissions contain data about the variables that affect future CO_2 emissions such as fuel type and consumption, the efficiency of the process, market conditions, and the company's business practices.

With known volatilities and drifts, along with initial CO_2 emissions in 2022 for each emitter, 10,000 simulations of random walk are performed until 2027. Moreover, based on the dataset of 10,000 simulated cases, three percentile curves are defined which are then used as three representative emissions forecast scenarios for each emitter:

- P90–90th percentile
- P50–50th percentile
- P10–10th percentile

The purpose of this approach is not to explicitly define CO_2 emissions at a given timestep, but instead to allow for exploring the efficiency of the incentive system if CO_2 emissions are to be in between the defined emissions forecast scenarios.

The final step is to determine the performance of the incentive system after 5 years of allocation of the funds in the CCS fund; that is, in 2027 for each emitter via the incentive level (Q) in EUR/ton for an incentivization time (T) of ten years:

$$Q = Fund_{CCS,\ 2027}/(T \cdot S_{2027}) \tag{18}$$

The performance of the newly proposed incentive system can be categorized as optimal if the incentive level is within the range of 10–80 EUR/t, as overperforming if it is higher than 80 EUR/t, and as underperforming if it is lower than 10 EUR/t. It is worth noting that overperforming scenarios allow for the formation of CCS clusters, since not all funds will be used for incentivizing one CCS project due to the 80 EUR/t limit.

The goal of the incentive system is to lower the costs of deploying CCS technology for CO_2 emitters in Croatia, making the technology more appealing to investors. By utilizing CCS, positive business practices may result in lower technology costs. Furthermore, if the incentive strategy is found to be practical or of optimal performance for Croatian emitters, it may simply be implemented in other EU member states or participants in the EU ETS, thereby hastening the deployment of CCS technology on the EU grounds. More specifically, this work attempts to investigate the possibility of incentivizing a set quantity of emissions to be captured for ten years by altering EUA prices and the size of the CCS fund that was accumulating assets for five years.

Maximum value is represented by the calculated incentive level options, which are not required to be implemented. This is because the ultimate agreements between the emitters and the state (funder) should be established in the form of CCfD, which consists of two prices: the strike price and the carbon price. More accurately, a strike price of carbon should be established over a 10-year period; that is, for the duration of the incentivizing period, and it should be equal to the total cost of the CCS for a specific emitter that is reduced by any external funding (such as the innovation fund or similar) and expressed in EUR/t. On the other hand, a carbon price is represented by the EU ETS price increased by the amount of incentive, which is likewise denoted in EUR/t. That way, the state would pay incentives in the full amount only if the carbon price is lower or equal to the strike price. Conversely, if the carbon price is higher than the strike price, incentives would be paid out in such the amount that equals the difference between the strike price and the EU ETS price. This means if the EU ETS price itself is higher than the strike price, no incentives would be paid to the emitters. But since they opted for CCS deployment, the emitters are still avoiding the costs, since it is less expensive to store CO_2 underground than to buy EUAs on the EU ETS market.

Finally, after the calculations, an amendment proposal of the regulation on the limit values of emissions of pollutants into the air from stationary sources [50] is presented to make a more stringent regulatory framework for CCS in Croatia and to persuade the stakeholders to consider/reconsider investing in CCS technology.

3. Results and Discussion

The results from Equations (1)–(5), which refer to the calculation of the auctioned volume of EUAs by Croatia, are depicted in Table 1.

Table 1. Calculation of auctioned volume of EUAs by Croatia.

	EU Cap	Auctioned Cap	Croatia Gross	MF	MSR	Croatia Auctioned
	Equation (1)	**Equation (2)**	**Equation (3)**	**-**	**Equation (4)**	**Equation (5)**
Year	**[Thousands EUA]**					
2023	1,528,579	871,290	4530	598	1718	2214
2024	1,444,527	823,380	4281	598	1624	2059
2025	1,360,475	775,471	4032	598	1529	1904
2026	1,276,423	727,561	3783	598	1435	1750
2027	1,192,370	679,651	3534	598	1340	1595

The cap in 2027 was reduced by approximately 22% when compared to the 2022 data, which can also be applied to Croatia's auctioned volume of EUA since it directly depends on the cap level and auction share, and MF feeds and MSR feeds are kept constant throughout the observed time. The auctioned quantities of EUAs for Croatia vary between 2.2 and 1.6 million EUAs from 2023 through 2027. That number is reasonably low when compared to other countries of the EU, but this is justified by the low emissions share of 0.5%.

The EUA price trendlines with adjacent cumulative auction revenues are outlined in Figure 2.

As expected, among the linear scenarios from Figure 2A, the HIGH scenario depicts the highest EUA price that could be achieved throughout the observed timespan. On the other hand, the LOW scenario yields the lowest EUA price possibility. In 2023, all the EUA prices are set to 90 EUR, and from that point, their trendlines increase depending on the scenario. In 2027, the representative EUA trendlines reached the following values: LOW 102 EUR, MID 114 EUR, and HIGH 126 EUR. Consequently, the cumulative auction revenues (Figure 2B) from Equation (6) are proportional to the EUA price trends. In 2027, the cumulative auction revenues are equal to 909 million EUR for the LOW scenario, 962 million EUR for MID, and 1014 million EUR for the HIGH scenario.

After the revenues from auctioning EUAs are made available, the estimation of funds within the CCS fund (Equation (7)) can be approached by varying the fund sizes (Table 2).

Table 2. Funds within CCS fund (mil. EUR) depending on the fund size and EUA price scenario.

CCS Fund Size	EUA Price	2023	2024	2025	2026	2027
5%	LOW	9.96	19.54	28.68	37.34	45.47
	MID	9.96	19.84	29.56	39.01	48.10
	HIGH	9.96	20.15	30.44	40.67	50.72
10%	LOW	19.92	39.07	57.35	74.68	90.95
	MID	19.92	39.69	59.11	78.01	96.20
	HIGH	19.92	40.31	60.87	81.35	101.45
20%	LOW	39.84	78.14	114.71	149.35	181.89
	MID	39.84	79.38	118.23	156.02	192.39
	HIGH	39.84	80.61	121.75	162.69	202.89
30%	LOW	59.77	117.21	172.06	224.03	272.84
	MID	59.77	119.07	177.34	234.03	288.59
	HIGH	59.77	120.92	182.62	244.04	304.34

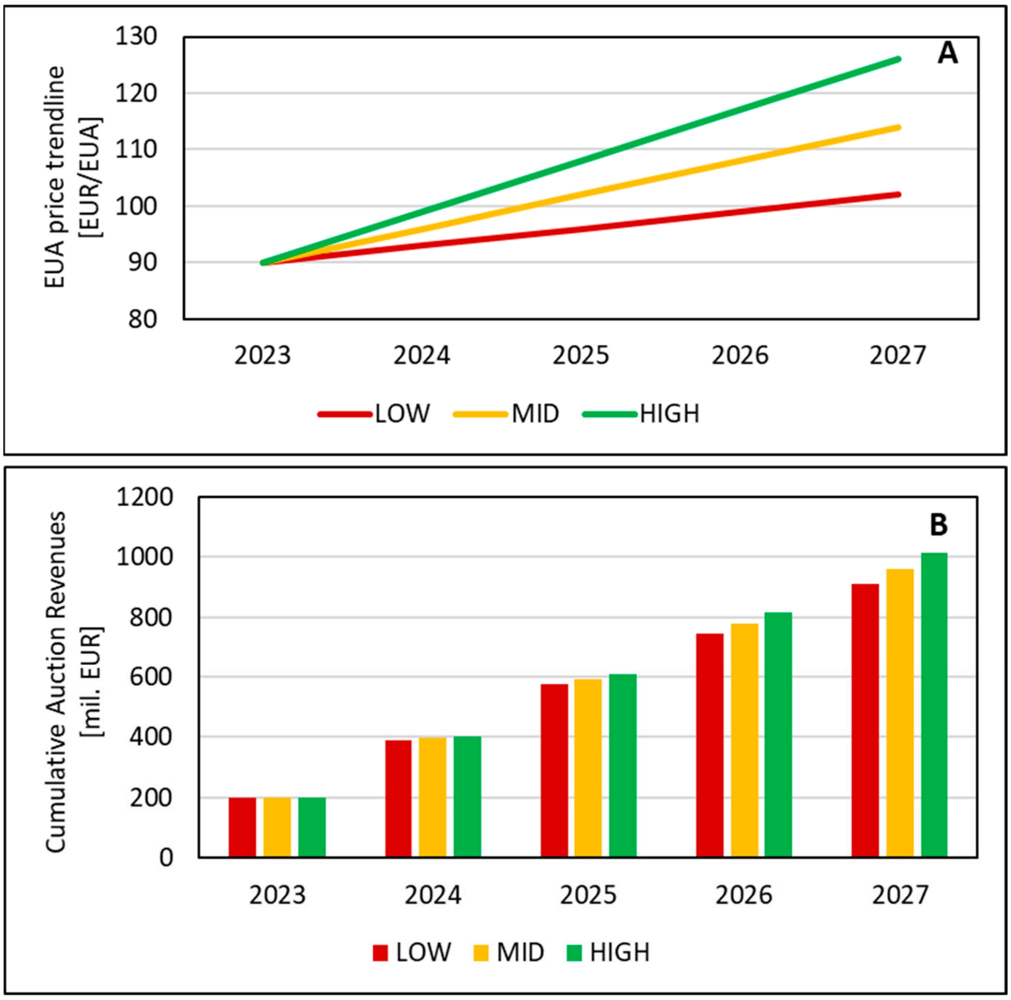

Figure 2. EUA price trendlines (**A**) and adjacent cumulative revenue from auctions (**B**).

Table 2 demonstrates the financial scale of the CCS fund which the Republic of Croatia has at its disposal. The conclusion arises that the larger the size of the CCS fund and the higher the EUA price, the greater the amount of funds within the fund. After 5 years of allocation, the funds vary from 45.47 million EUR for the lowest EUA price scenario and smallest fund size; that is, LOW and 5% to 304.34 million EUR for the highest EUA price scenario and the largest fund size, HIGH and 30%, respectively.

In terms of fast and efficient CCS deployment in Croatia, the optimum CCS fund size that is observed in this work would be 30%. However, the realistic case could be smaller; that is, 5 or 10%, since CCS is competing with other technologies and measures within the LCET and NES categories. Within the LCET category, the following prominent measures will be funded: renewable energy sources, increasing energy efficiency, energy storage systems, combating energy poverty, etc. Even though CCS is not explicitly declared as eligible for funding in the LCET category, the funding is envisaged for other measures that have effects in achieving the goals of the energy transition, meaning that the scope of CCS could fit into the description of the measure. Similarly, within the NES category, funds are envisaged for greenhouse gas emissions reduction in the industrial processes and waste management sector, which could lead to funding CCS.

Following the establishment of the CCS fund, the emitters who could deploy CCS technology on a commercial scale need to be targeted based on the EU ETS membership and the 100 kt of CO_2 emissions criteria described in Section 2. The spatial distribution of the CCS-eligible emitters and their sectoral affiliation are depicted in Figure 3, along with the existing transport infrastructure (pipelines and roads) and potential storage sites in terms of deep saline aquifers (DSA) or nearly depleted hydrocarbon reservoirs (DHR).

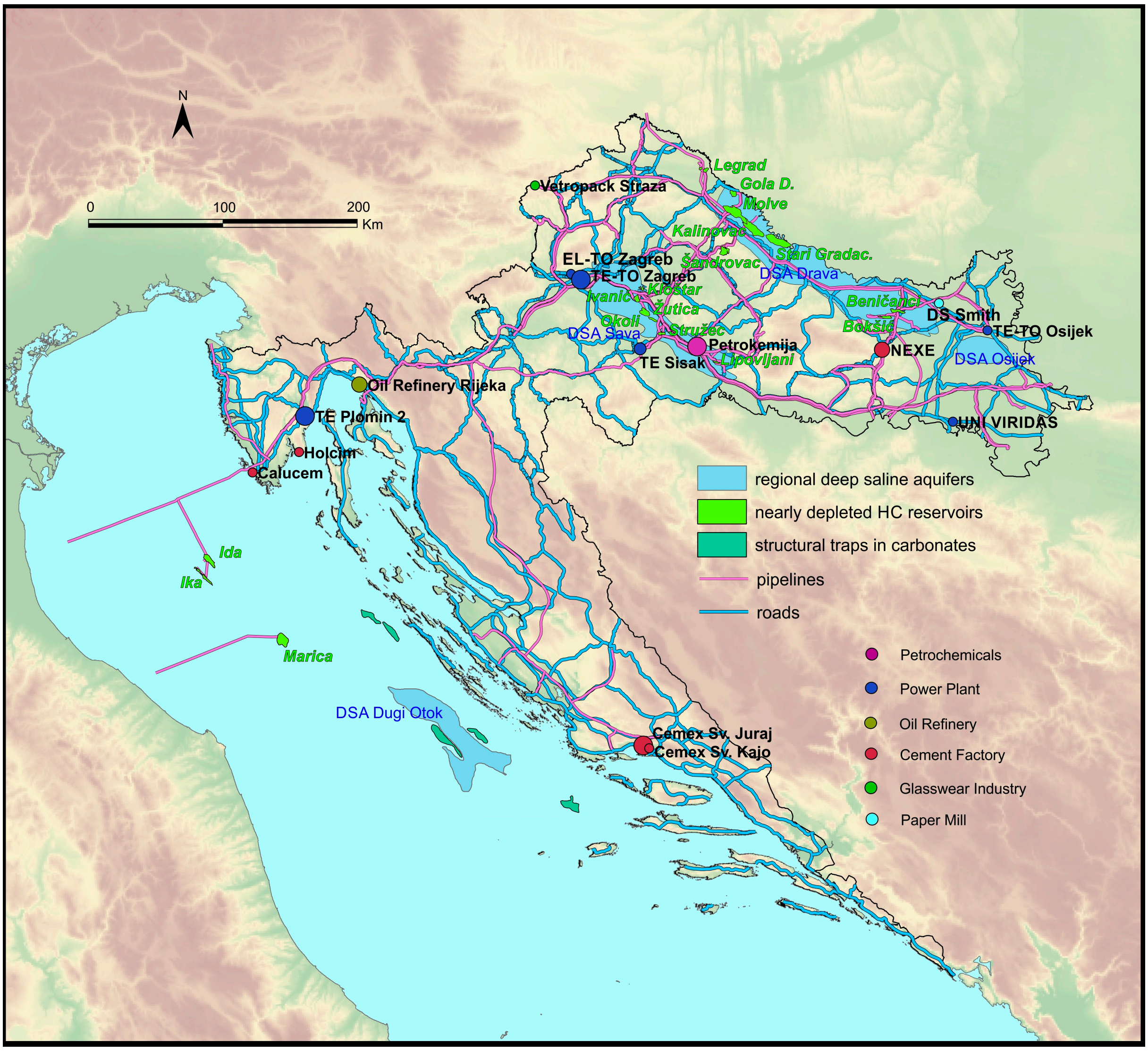

Figure 3. Spatial distribution of qualified emitters, transport, and storage network—emitter's symbol sizes are proportional to their verified emissions within EU ETS in 2021 [51,52].

From Figure 3, it can be observed that the locations of 15 CCS-eligible emitters in Croatia are quite dispersed, with most emitters affiliating to the power sector, including biomass-fired (UNI VIRIDAS), natural gas-fired (EL-TO Zagreb, TE-TO Zagreb, TE Sisak and TE-TO Osijek), and coal-fired (TE Plomin 2) power plants. The power sector is followed by the cement sector, of which five emitters are included: NEXE, Holcim, Calucem, CEMEX Sv. Juraj, and CEMEX Sv. Kajo. The rest of the sectors are represented by one emitter; that is, the petrochemicals sector by Petrokemija, the glass manufacturing sector by Vetropack Straža, Oil Refinery Rijeka for the oil refining sector, and DS Smith for paper and pulp sector.

Regarding the transportation infrastructure shown in Figure 3, all the depicted pipelines are currently used for the transportation of natural gas, but the idea is to repurpose them for the transport of CO_2 or to build a new pipeline that will follow the trajectory of the existing pipeline. This is due to resolved property-legal relations and is meant to minimize the adjacent environmental impacts (e.g., deforestation, a decrease in agricultural land, and impacts on endangered and protected flora and fauna). With the number of planned CCS projects rising rapidly, the challenges of CO_2 transport via pipelines must be observed, including the repurposing of the existing pipelines [53]. When considering repurposing, the examined priority categories include the level of impurities in the CO_2 stream, the quantity of captured CO_2 that is to be transported, the critical pressure of the mixture, the potential for occurrence of the two-phase flow, and the existing maximum allowable operating pressure (MAOP) of the pipeline to identify the requirements for a use change [54]. Additionally, the presence of an existing pipeline can bring direct savings for CCS projects, and if the emitters use the same transportation infrastructure (share costs), the capital costs for transport form a reasonably low share of 10–20% in the total costs [55]. This is of great importance for this research, since the existing pipeline infrastructure is near all emitters, making access to the future transport network more accessible by both technical and financial means.

Concerning the potential storage sites, underground injection of CO_2 is practiced in the form of CO_2-EOR as one of the most profitable industrial large-scale carbon sequestration projects, which along with the sequestration of CO_2 results in the creation of additional value (oil recovery) [56,57]. However, CO_2-EOR is not within the scope of this research; hence, no incentives are envisaged for deploying this technology. Regarding CO_2 storage in DHRs, it is observed as one of the most practical options, since the caprock sealed the hydrocarbons prior to the depletion in the reservoir for a geological timespan. Despite the above, when CO_2 is injected into the reservoir, it replaces the hydrocarbons, which consequently reduces the interfacial tension between the reservoir fluids, causing a reduction in the sealing capacity of the caprock [58]. This means that before the project begins, the caprock sealing pressure should be determined and not be exceeded. Therefore, to ensure long-term storage security and optimize injection regimes, a detailed characterization of the geology and heterogeneity of the reservoir is necessary [59]. In the same research, an approach for evaluating the suitability of different geological formations for CO_2 storage is provided, and DSAs are categorized as very effective in terms of CO_2 storage, with relatively low safety risks and mitigation of CO_2. On the other hand, other research has analyzed horizontal DSAs and concluded that long injection periods and high injection rates can increase the radial migration of CO_2 and make leakage probable when CO_2 finds an upward pathway in the aquifer [60].

Regardless of the available storage options, in Figure 3, it can be observed that each emitter in Central and Eastern Croatia has either onshore DSA or a DHR less than 200 km distant, which is not the case for the emitters in Southern Croatia, where the nearest accessible storage site is offshore, making the transport and storage for those emitters more expensive.

The historical CO_2 emissions of the emitters are presented in Table 3.

Table 3. Historical CO_2 emissions of the selected emitters (kt).

Sector	Emitter	2022	2021	2020	2019	2018
Cement	CEMEX Sv. Kajo	49	87	187	157	204
Cement	Holcim	313	346	345	322	320
Cement	Calucem	132	125	121	117	114
Cement	NEXE	656	635	646	651	637
Cement	CEMEX Sv. Juraj	611	758	647	642	687
Power	UNI VIRIDAS	106	105	103	101	102
Power	EL-TO Zagreb	210	216	201	206	208
Power	TE-TO Sisak	525	409	487	299	284
Power	TE-TO Zagreb	859	756	774	649	551
Power	TE-TO Osijek	45	70	57	66	74
Power	TE Plomin 2	1295	1221	1022	1349	1157
Paper and pulp	DS Smith	96	101	96	94	90
Glass	Vetropack Straža	117	112	95	105	106
Oil refining	Oil Refinery Rijeka	699	717	770	708	1005
Petrochemicals	Petrokemija	163	833	1264	1257	1102

Some emitters from Table 1 did not have CO_2 emissions higher than 100 kt in 2022 but did reach this threshold any year from 2013 onwards (e.g., TE-TO Osijek in 2014), and hence, an assumption is made that the 100 kt criterion could be satisfied again during CO_2 emissions forecasting. The sectoral emissions share can be defined for 2022 as follows: power sector, 52%; cement sector, 30%; petrochemicals sector, 3%; oil refining, 12%; glass sector, 2%; and paper and pulp sector, 2%. Therefore, it is of great importance to explore the feasibility of the incentive system, especially for the power and cement sector due to their high emission shares, with the latter having a high yield of process emissions.

With known historical emissions, the yearly percentage changes of the emissions and their mean values can be calculated to obtain GBM parameters; that is, volatility and drift by applying Equations (11) and (12) for the period from 2022 to 2018 (Table 4).

Table 4. Calculated volatilities (σ) and drifts (μ) for the GBM simulations.

Sector	Emitter	σ [-]	μ [-]
Cement	CEMEX Sv. Kajo	0.3218	−0.2541
Cement	Holcim	0.0114	0.0367
Cement	Calucem	0.0688	−0.0037
Cement	NEXE	0.0244	0.0077
Cement	Cemex Sv. Juraj	0.1521	−0.0201
Power	UNI VIRIDAS	0.0140	0.0087
Power	EL-TO Zagreb	0.0462	0.0031
Power	TE-TO Sisak	0.3378	0.2016
Power	TE-TO Zagreb	0.0990	0.1211
Power	TE-TO Osijek	0.2419	−0.0900
Power	TE Plomin 2	0.2003	0.0447
Paper and pulp	DS Smith	0.0451	0.0155
Glass	Vetropack Straža	0.1115	0.0289
Oil refining	Oil Refinery Rijeka	0.1601	−0.0756
Petrochemicals	Petrokemija	0.4215	−0.2497

The calculated volatilities varied between 0.0114 and 0.4215, while seven emitters were characterized by volatilities lower than 0.1 and eight emitters had volatilities higher than 0.1. Three emitters with the highest volatilities can be separated: Petrokemija, TE-TO Sisak, and CEMEX Sv. Kajo. The reason for the fertilizer production facility Petrokemija having the highest volatility is its significant emissions drop in 2022. The company stopped its production by the end of March 2022 due to the crisis in the natural gas market and re-established it in July 2023. Regarding the cement production facility CEMEX Sv. Kajo, its high volatility is a consequence of the constant and sharp decline in its CO_2 emissions from 2018. On the contrary, the power sector facility TE-TO Sisak increased its emissions significantly from 2020 onwards, hence resulting in a high volatility.

Lower volatilities imply tighter boundaries of GBM simulations, or in other words, a narrower span of forecasted CO_2 emissions. Drift, on the other hand, determines the direction of the forecasted CO_2 emissions. Hence, if emission forecasting is defined only by drift, positive values would imply that CO_2 emissions will increase, and negative values would imply that CO_2 emission will decrease. Based on Table 4, only six emitters have negative drift values.

When volatilities and drifts are determined, 10,000 simulations of random walk defined by GBM can be carried out in Python for each emitter (Equation (17)). The results of these simulations, together with the Python code, are given in Appendices A and B. Not all of the simulated cases can represent a scenario; hence, three percentiles are defined (10th, 50th, and 90th) for each forecasted year that form three representative emission forecast scenarios (P10, P50, and P90). The CO_2 emissions forecast results are depicted in Table 5.

Table 5. CO_2 emissions forecast (tons)—percentile curves from GBM simulations (red text marks scenarios below 100,000 tons of CO_2 emissions in 2027 that are excluded from further analysis).

Sector	Emitter	Scenario	2022	2023	2024	2025	2026	2027
Cement	CEMEX Sv. Kajo	P10	48,547	31,699	26,541	22,997	20,421	18,344
		P50	48,547	47,634	46,933	46,309	45,995	45,519
		P90	48,547	72,288	84,497	95,363	104,785	112,595
Cement	Calucem	P10	131,779	129,867	129,124	128,501	128,018	127,605
		P50	131,779	131,778	131,771	131,778	131,773	131,762
		P90	131,779	133,686	134,612	135,198	135,716	136,168
Cement	Holcim	P10	313,087	286,572	275,995	268,193	262,741	256,331
		P50	313,087	313,088	312,669	312,797	312,645	313,268
		P90	313,087	341,887	354,206	364,418	373,271	381,399
Cement	NEXE	P10	656,243	635,842	628,143	622,269	616,335	611,719
		P50	656,243	655,959	656,211	656,351	656,490	655,567
		P90	656,243	676,952	686,068	692,696	697,961	702,903
Cement	CEMEX Sv. Juraj	P10	610,703	502,133	464,829	436,884	414,880	397,456
		P50	610,703	611,339	610,995	612,988	610,496	611,836
		P90	610,703	744,392	805,478	857,634	901,670	938,969
Power	UNI VIRIDAS	P10	105,582	103,742	102,983	102,357	101,897	101,413
		P50	105,582	105,611	105,559	105,590	105,576	105,594
		P90	105,582	107,506	108,293	108,950	109,417	109,892
Power	EL-TO Zagreb	P10	210,129	197,966	193,208	189,966	186,753	184,380
		P50	210,129	210,101	210,226	210,234	209,870	209,763
		P90	210,129	222,827	228,817	232,468	236,536	239,288
Power	TE-TO Sisak	P10	525,195	345,396	294,286	260,046	232,687	210,568
		P50	525,195	531,339	536,939	542,587	553,452	558,091
		P90	525,195	810,975	989,759	1,138,943	1,291,615	1,459,808
Power	TE-TO Zagreb	P10	859,167	756,480	717,548	687,522	665,147	644,542
		P50	859,167	859,557	860,561	860,817	860,695	861,685
		P90	859,167	974,151	1,029,007	1,073,191	1,110,760	1,144,899
Power	TE-TO Osijek	P10	45,409	33,012	29,066	26,010	23,802	21,960
		P50	45,409	45,239	45,358	44,877	44,736	44,494
		P90	45,409	61,433	70,170	76,961	82,880	88,342
Power	TE Plomin 2	P10	1,295,063	1,003,026	897,236	821,152	774,290	719,873
		P50	1,295,063	1,297,865	1,292,474	1,296,201	1,294,000	1,292,871
		P90	1,295,063	1,672,421	1,877,579	2,022,157	2,167,932	2,295,290
Paper and pulp	DS Smith	P10	95,748	90,263	88,135	86,591	85,290	84,359
		P50	95,748	95,701	95,743	95,795	95,789	95,728
		P90	95,748	101,462	103,972	105,936	107,622	108,988
Glass	Vetropack Straža	P10	117,145	101,514	95,957	91,478	88,113	85,219
		P50	117,145	117,437	117,546	117,467	117,910	118,037
		P90	117,145	135,400	144,159	151,541	157,135	161,627
Oil refining	Oil Refinery Rijeka	P10	698,531	567,388	516,162	483,582	456,753	436,489
		P50	698,531	698,281	694,950	695,172	696,382	694,909
		P90	698,531	859,822	932,207	992,074	1,041,758	1,093,593
Petrochemicals	Petrokemija	P10	163,428	92,500	71,625	58,918	50,726	43,942
		P50	163,428	159,253	154,152	152,056	147,832	144,978
		P90	163,428	272,445	329,948	385,863	441,744	492,993

The P10 scenarios imply a CO_2 emissions decrease, in contrast to the P90 scenarios, which yield a CO_2 emissions increase. The P50 scenarios represent "status quo" scenarios, since the emissions remained almost the same as they were at the beginning after the observed forecasting period. Additionally, the emitters' forecasted emissions described by lower volatilities have smaller discrepancies between the P10 and P90 scenarios.

In Table 5, the red text marks represent the scenarios that did not achieve 100 kt of CO_2 emissions in 2027 and were omitted from further analysis since this quantity is the criterion within the main directive that regulates CCS in the EU; that is, the CCS directive. Among the emitters who had less than 100 kt of CO_2 emissions in 2022, the cement factory CEMEX Sv. Kajo and the paper and pulp facility DS Smith managed to reach 100 kt of CO_2 emissions in the P90 scenario, while the power plant TE-TO Osijek failed to reach the criterion and was thus omitted from further analyses.

There are also cases of emitters that managed to reduce their emissions in the P10 scenarios to below 100 kt by 2027: the glass factory Vetropack Straža and the fertilizer production facility Petrokemija. Even though Vetropack Straža's volatility is reasonably low (0.1115), the reason why its emissions in 2027 for the P10 scenario are lower than 100 kt is its low initial emissions at the beginning of forecasting in 2023 (117 kt). On the other hand, the main reason for Petrokemija's low CO_2 emissions for the P10 scenario in 2027 lies within its very high volatility (0.4215).

All the other emitters that were characterized as CCS eligible remained as such, regardless of the emissions forecast scenario.

The last step is to analyze the performance of the incentive system by determining the incentive level options using Equation (18) for emissions in 2027 under the assumption that all are available for capture. The latter will be categorized as optimal, overperforming, or underperforming, as described in Section 2. The results for the cement sector are depicted in Figure 4.

As depicted in Figure 4, 156 incentive level options within the cement sector are characterized by the emitter's emissions forecast scenarios, EUA price scenarios, and CCS fund sizes. They differ into 33 overperforming (21%) and 15 underperforming options (10%), while the number of optimal options is 108 (69%). This means that in 90% of cases, CCS projects within the cement sector can be incentivized, with 21% allowing for cluster formations, if possible (mainly regarding smaller emitters such as CEMEX Sv. Kajo, Calucem, and in some cases, Holcim).

The cement facilities that can be most easily incentivized are CEMEX Sv. Kajo, Calucem, and Holcim, since incentive level options are all feasible even with the smallest CCS fund size of 5%, regardless of the emissions forecast scenario and EUA price. For CEMEX Sv. Kajo, all incentive level options except the ones with a CCS fund size of 5% are overperforming, which can be explained by relatively low forecasted emissions. When observing Calucem, for CCS fund sizes of 20 and 30%, all incentive level options are overperforming. Among the optimal options for the above two emitters, the incentive levels vary between 33 and 79 EUR/t. Holcim, on the other hand, shows overperforming options only for the largest CCS fund size, and only for the P50 and P10 emissions scenarios, regardless of EUA price. For all other CCS fund sizes, the incentive level options are within the optimal range, varying from 11 to 79 EUR/t.

Regarding the largest cement production facilities, that is, NEXE and CEMEX Sv. Juraj, there are no overperforming options, since they have the highest emissions within the cement sector. CEMEX Sv. Juraj exhibits underperforming options for the lowest CCS fund size of 5% and the P90 and P50 emission scenarios. The rest of the incentive level options are characterized as optimal and vary from 10 to 77 EUR/t. This wide spectrum of incentive values can be best observed for the CCS fund size of 30% and HIGH EUA price scenario. For that specific case, the incentive level options vary between 32 and 77 EUR/t, depending on the emission scenario, and this is due to the emitter's high volatility (0.1521); that is, a significant difference between the forecasted emissions in the scenarios. Concerning NEXE, for the lowest CCS fund size, all of the incentive level options are underperforming. All the other CCS fund sizes imply incentive level options within the optimum range that vary from 13 to 50 EUR/t. This difference is much lower than for CEMEX Sv. Juraj since NEXE's volatility is significantly lower (0.244). Despite the above, the same conclusion can be applied to both of the largest representatives from the cement sector: higher CCS fund sizes are needed to incentivize their deployment of CCS technology (20 and 30%).

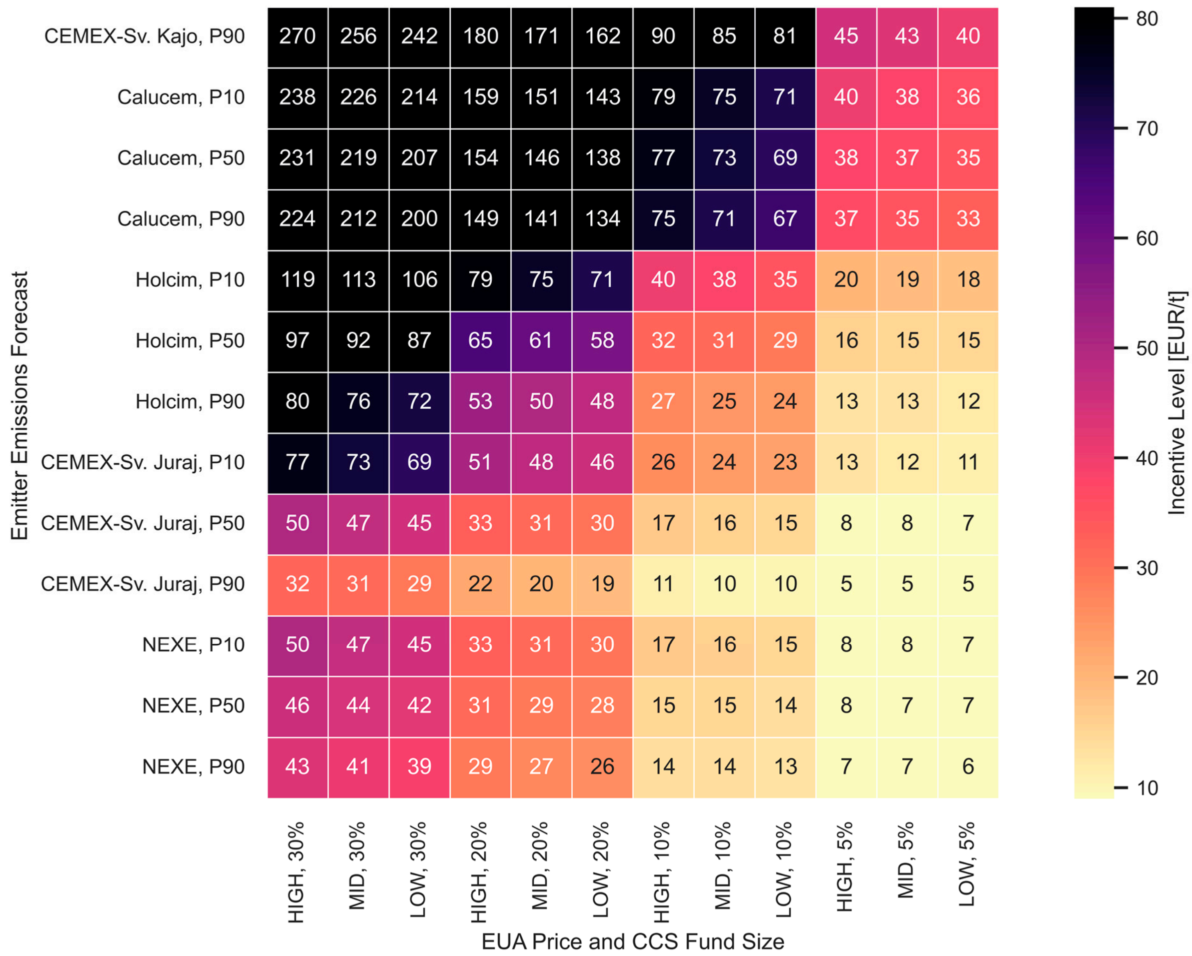

Figure 4. Incentive levels for the cement sector in Croatia (EUR/t).

The incentive levels for the power sector are depicted in Figure 5.

Of the 180 observable incentive level options for the power sector, 49 of them are overperforming (27%), 92 are optimal (51%), and 39 are underperforming (22%). The most feasible incentive system results are for the biomass-fired power plant UNI VIRIDAS, since there are no underperforming options for this emitter. In fact, overperforming incentive level options are exhibited by all emissions and EUA price scenarios, for CCS fund sizes of 10, 20, and 30%. For the case of a CCS fund size of 5%, all of the calculated options are optimal and vary from 41 to 50 EUR/t.

Concerning the gas-fired power plants, EL-TO Zagreb yields overperforming options for all the scenarios within larger CCS fund sizes; that is, 20 and 30%, with two exceptions for the P90 emissions scenario, CCS fund size of 20%, and LOW and MID EUA price scenarios. CCS fund sizes of 5 and 10% exhibit optimal incentive level options of values between 22 and 55 EUR/t. Observing TE-TO Sisak, the incentive level options are overperforming for the P10 emissions scenario with 30 and 20% CCS fund sizes, regardless of EUA price, while for CCS fund sizes of 5 and 10%, the results are optimal and vary from 22 to 48 EUR/t. In the case of the P50 emissions scenario, incentive level options are within the optimal range for CCS fund sizes of 10, 20, and 30%, varying between 16 and 55 EUR/t. When the CCS fund size is set to 5%, the incentive level options are underperforming for the P50 scenario. For the P90 scenario, smaller CCS fund sizes (5 and 10%) imply underperforming results, whereas larger CCS fund sizes exhibit optimal incentive level options between 12 and 21 EUR/t. Again, significant discrepancies between the incentives for different emissions scenarios are explained by TE-TO Sisak's high volatility of 0.3378. Concerning TE-TO Zagreb, the highest incentive level that can be achieved is 47 EUR/t, meaning that there are no overperforming options. Underperforming options are characterized by all the scenarios with a CCS fund size of 5%, while for the case of a CCS fund size of 10%, underperforming options are defined by the P90 emissions scenario, regardless of the EUA price scenario. The calculated optimal options among the rest of the scenarios range from 11 to 47 EUR/t.

Regarding the coal-fired power plant TE Plomin 2, which is also the largest emitter in Croatia, the highest incentive level equals 42 EUR/t. Proportional to high emissions, all the incentive level options for the CCS fund sizes of 5 and 10% are underperforming, except for the P10 emissions scenario and 10% CCS fund size, which reach the optimal values. For the CCS fund size of 20%, optimal incentive level options are obtained for the P10 and P50 scenarios, regardless of the EUA price scenario, while for the P90 scenario, all of the options underperform. If the CCS fund size is set to 30%, all the incentive level options are within the optimal values between 12 and 42 EUR/t.

The incentive levels for the remaining sectors are depicted in Figure 6.

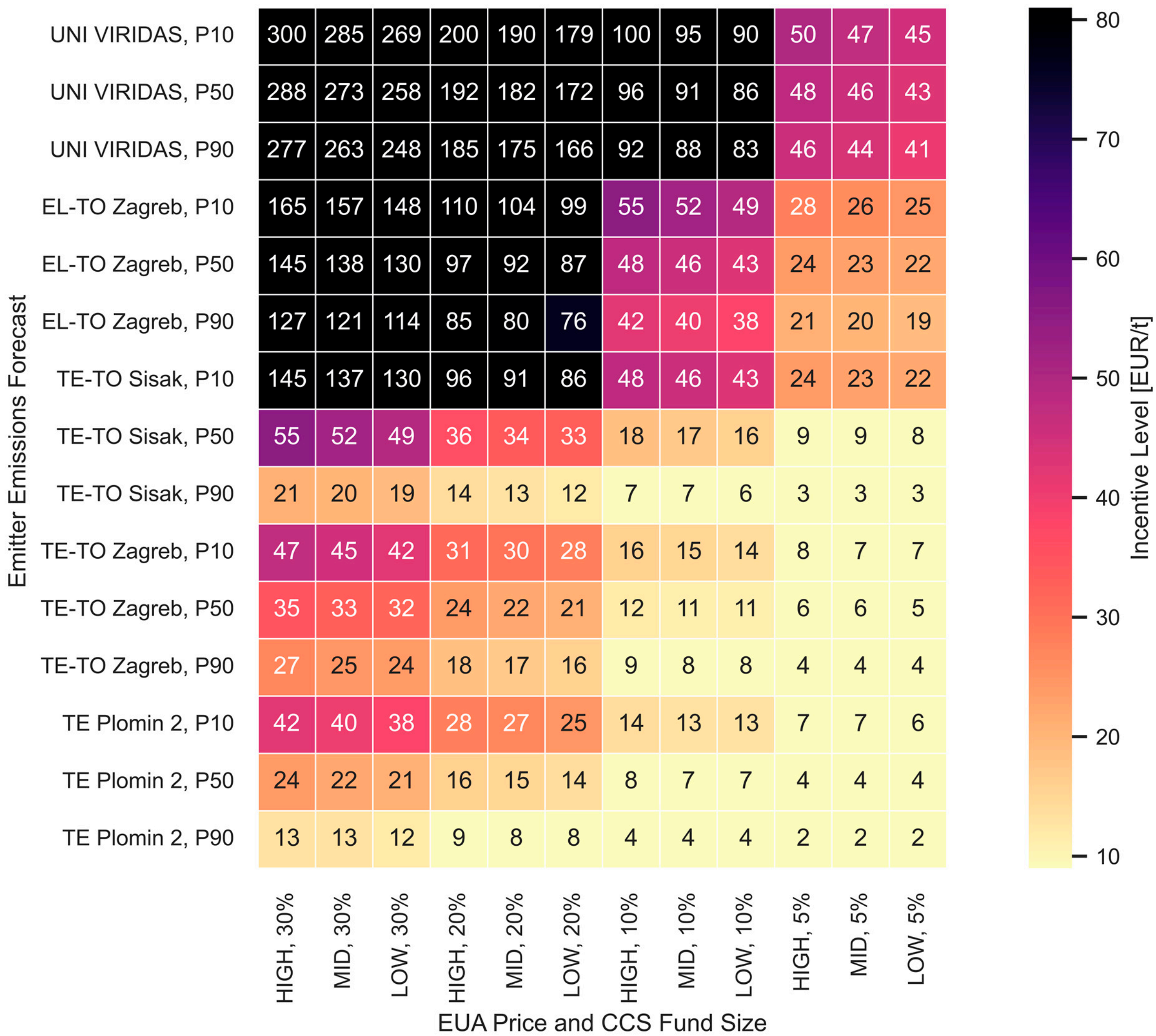

Figure 5. Incentive levels for the power sector in Croatia (EUR/t).

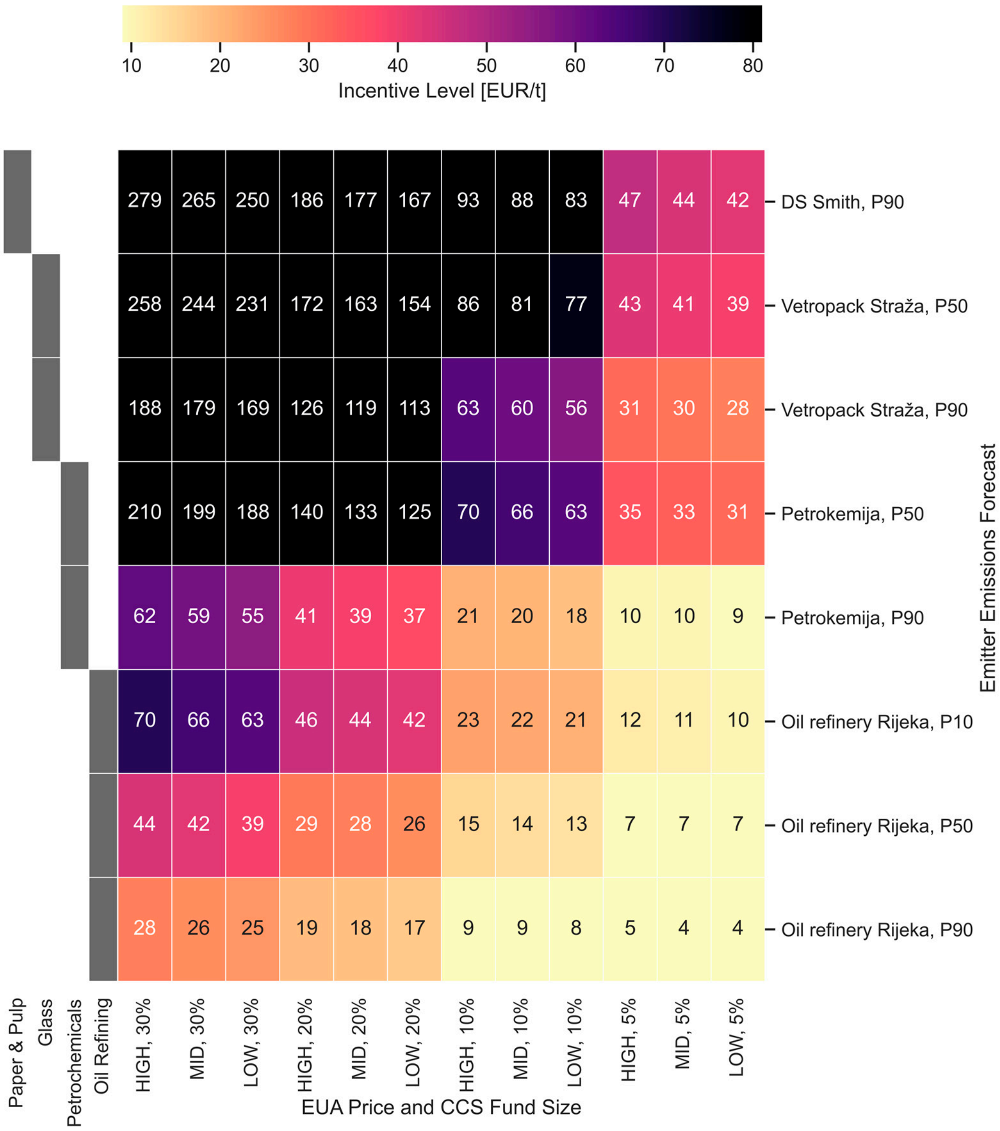

Figure 6. Incentive levels for the paper and pulp, glass, oil refining, and petrochemical sectors in Croatia (EUR/t).

The incentive system is most feasible for the paper and pulp and glass manufacturing sectors, since they have the lowest CO_2 emissions. The paper and pulp facility DS Smith exhibits overperforming results for CCS fund sizes of 10, 20, and 30%, while for the CCS fund size of 5%, the results are optimal, varying from 42 to 47 EUR/t. When observing the glass manufacturing facility Vetropack Straža, larger CCS fund sizes of 20 and 30% show overperforming options. For a CCS Fund size of 10%, the P50 emissions scenario implies an optimal incentive level option for the LOW EUA price scenario (the rest overperform), while the P90 emissions scenario all exhibit optimal results (56-63 EUR/t). For the smallest CCS fund size, all the options are within the optimal range, varying from 28–43 EUR/t. In general, the glass and paper and pulp sectors can be efficiently incentivized, even with the least funding option.

Regarding the petrochemicals sector, overperforming incentive level options are defined by the P50 emissions scenario and CCS fund sizes of 20 and 30%, regardless of the EUA price scenario. Within the same emissions scenario, for the smaller CCS fund sizes, the results are within the optimal range of 31 to 70 EUR/t. For the P90 emissions scenario, the only option that is underperforming is for the CCS fund size of 5% and the LOW EUA price scenario. The rest of the calculated incentive level options vary between 10 and 62 EUR/t.

A significant difference between the incentive levels for different emissions scenarios is explained by Petrokemija's volatility being the highest among all emitters (0.4215).

Concerning the oil refining sector, there are no overperforming options, while the highest achievable incentive level is 70 EUR/t. The feasible options are mainly described by larger CCS fund sizes of 30 and 20%. On the other hand, underperforming options are characterized for a CCS fund size of 5% with the P50 and P90 emissions scenarios, while for a CCS fund size of 10%, only the P90 scenario exhibits underperforming results, regardless of the EUA price scenario.

As noted in Section 2 of this work, the calculated incentive level options represent maximum values that do not need to be realized. The financing of the incentives should be arranged between the emitters and the state through the CCfD for 10 years (duration of incentives) by defining strike and carbon prices, with an example depicted in Figure 7.

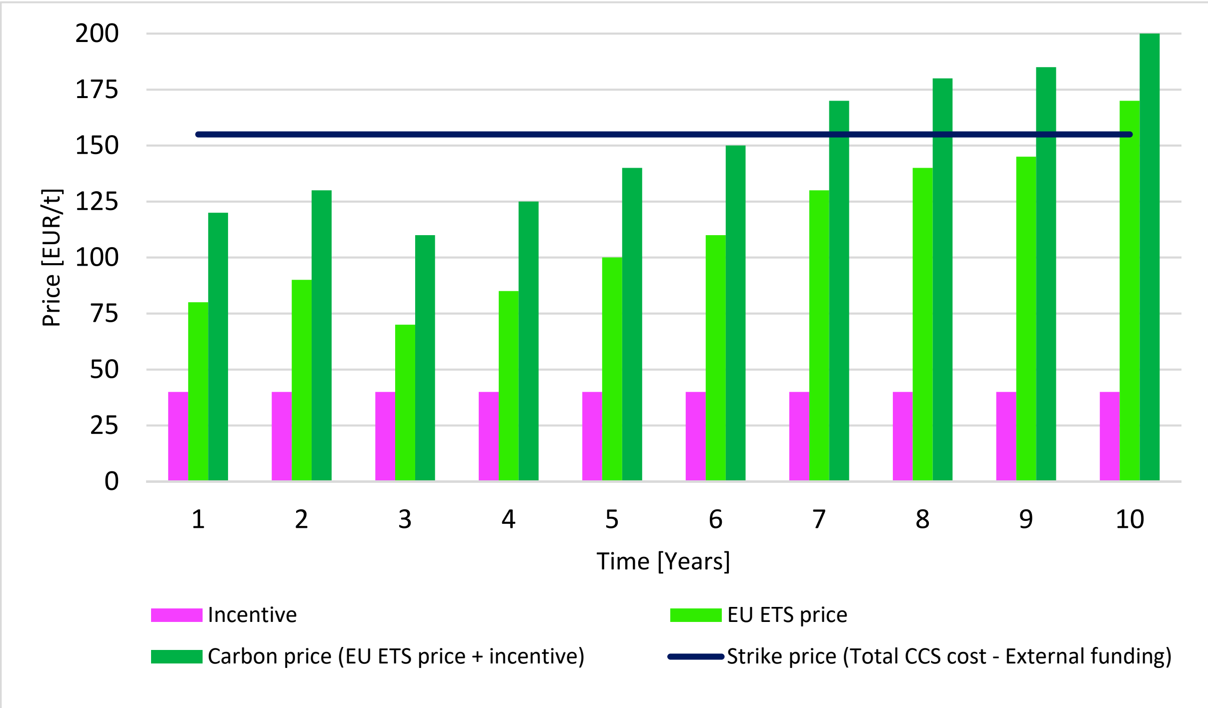

Figure 7. Examples of CCfD parameters: strike price and carbon price.

It is evident from Figure 7 that incentive payments will be made in their entirety for the initial six years, given that the carbon price remains below the strike price. Incentives will be paid in part for the following three years, amounting to the difference between the strike price and the EU ETS price. The emitter has not been granted any incentives for the past year because the EU ETS price exceeds the strike price. Since CCS is predominantly a tool for cost reduction, this mechanism should be implemented to prevent any potential irregularities, such as double counting in the EU ETS, financial overstimulation of emitters, and the creation of additional revenue streams for its deployment. CCfDs promote the formation of CCS clusters, since contracted incentives may be less than those illustrated in Figures 4–6, thereby incentivizing more emitters simultaneously.

Finally, amendments to the regulation on the limit values of emissions of pollutants into the air from stationary sources (OG 42/2021, 2021) are presented. More precisely, Article 36 (Geological storage of carbon dioxide) of the mentioned regulation should be changed in the following manner: The condition for an entity to assess the feasibility of deploying CCS technology should not be defined as a rated electrical output (300 MW or more) and should not only be defined for combustion plants but also for all stationary installations that operate within EU ETS and have verified emissions of CO_2 higher than 100 kt. By enacting this amendment, a more stringent regulatory framework for CCS would be established in Croatia. In other words, a database of feasibility studies would be created across the possible capture, transport, and storage sites. That way, any technical obstacles would be identified, and whether the obstacle can be removed or not would be defined, and if possible, by what means. Additionally, the proposed amendment can be enacted in all member states, since their regulatory frameworks should contain the transposition of the EU directive on industrial emissions.

4. Conclusions

To analyze the incentive system, 432 incentive level options were calculated, categorized as underperforming (<10 EUR/t), optimal (10–80 EUR/t), and overperforming (>80 EUR/t). A total of 25% of the calculated options overperformed, allowing for the incentivization of multiple CO_2 capture facilities and thus the formation of CCS clusters. Since clusters imply joint use of capture hubs, transport, and storage infrastructure, CCS-related costs would decrease. Implementing the ton-based incentive strategy for CCS technology shows that the incentive system depends on three variables: CCS fund size, CO_2 emissions forecast, and EUA price scenarios. If the other two are kept constant, each variable's impact can be seen.

When considering CCS fund size (5, 10, 20, and 30% of EUA auction revenue), larger CCS fund sizes increase the proportion of CO_2 capture that can be incentivized. If the emissions limit between small and large emitters is set to 400 kt of CO_2, then the results show that smaller emitters in Croatia can be effectively incentivized with CCS fund sizes of 5 or 10%, while larger emitters can be more efficiently incentivized with CCS fund sizes of 20 and 30%. Also, the CCS fund size has a deciding impact on the feasibility of the calculated incentive level options and is the only variable that the state as a funder can affect. Low EUA prices lead to lower state revenue from EUA auctions and consequently cause a reduction in financial assets within the CCS fund. As a response, the state could increase the CCS fund size to make the incentive system more engaging, while higher EUA prices would cause an increase in revenue, and the CCS fund size could be reduced. For this analysis, EUA price scenarios have a limited effect on the incentive system due to the narrow boundary conditions. The starting point for all the scenarios was the same, and the EUA price is expected to range from 102 to 126 EUR/EUA by 2027. Thus, for the observed CCS fund size and CO_2 emissions forecast scenario, the EUA price scenario rarely affected the calculated incentive level option's feasibility. Regarding CO_2 emission forecasting, it was performed using a novel approach of applying GBM in Python, with 10,000 simulations for each emitter. More accurately, the 10th, 50th, and 90th percentile datapoints were used as reference scenarios (i.e., P10, P50, and P90) based on the emitter's initial CO_2 emissions, volatility, and drift. Volatilities impacted forecasting the most, since they define the boundaries of GBM simulations, while drift determines the trendline of the forecasted CO_2 emissions. Similar to the CCS fund size, the emissions scenarios also have a decisive impact on the feasibility of the incentive level options. In other words, for the same emitter and defined CCS fund size with the EUA price scenario, both feasible and unfeasible incentive level options exist. Hence, from an incentive perspective, emitters should consider reducing their emissions by applying alternative emission reduction options before deploying CCS.

The sectoral analysis's conclusions involving CCS fund size and emissions can be presented, since the EUA price scenarios had a minor impact on the incentive system:

1. Smaller cement emitters like CEMEX Sv. Kajo, Calucem, and Holcim can be incentivized with CCS funds of 5–10%, while larger emitters like NEXE and CEMEX Sv. Juraj benefit more from CCS funds of 20–30%.
2. In the power sector, biomass-fired UNI VIRIDAS and gas-fired EL-TO Zagreb can be incentivized with a 5% CCS fund size, while gas-fired TE-TO Sisak can be incentivized with all fund sizes. Higher CCS fund sizes (20 and 30%) incentivize the largest emitters, including the gas-fired power plant TE-TO Zagreb and the coal-fired power plant TE Plomin 2, most efficiently. The highest incentive level for the largest CCS

fund size is 13 EUR/t, making it questionable to incentivize TE Plomin 2 as Croatia's largest emitter if P90 is realized.

3. Even with a 5% CCS fund size, the paper and pulp and glass sectors retain high incentives due to their low emissions.
4. CCS funds of all sizes can effectively incentivize the petrochemical sector. The only petrochemical facility, Petrokemija, was shut down for over 15 months from March 2022 due to the natural gas crisis, resulting in low emissions in 2022. If the company's operations continue, P90 is the most realistic emissions scenario, with incentive levels between 10 and 62 EUR/t, and an emphasis on larger CCS funds.
5. The most effective incentivization for the oil refinery Rijeka is achieved with larger CCS fund sizes of 20 and 30%, despite some options being within the optimal range of 10%.

Due to the incentive system's generally viable results, all EU member states should consider applying it to drive decarbonization using the proposed methodology. Since Croatia has a minor CO_2 emissions share in the EU (0.5%), the member states with greater emission shares will generate higher EUA auctioning revenues and might motivate their emitters to deploy CCS more efficiently than Croatia.

The authors suggest contracting incentives through CCfDs between emitters and the state by defining the strike price (total CCS cost reduced by external funding) and carbon price (EU ETS price increased by incentives). This allows the state to fully pay out incentives to emitters for deploying CCS technology only if the carbon price is lower than the strike price, and partially if the carbon price is higher than the strike price. This means that if the EU ETS price itself is higher than the strike price, no incentives would be paid out.

This study also proposes amending the regulation on the limit values of emissions of pollutants into the air from stationary sources by setting an emissions criterion to 100 kt of CO_2 for an entity to assess the feasibility of deploying CCS technology. This would create a database of CCS feasibility studies in Croatia, identifying possible technical and economic obstacles to its deployment. Furthermore, enactment of the proposed amendment can be carried out in all member states, since their regulatory framework should contain a transposition of the EU's directive on industrial emissions.

One of this research's main contributions is developing the methodology of designing a ton-based incentive system for deploying CCS technology in the EU in the Croatian example based on the existing legislative framework of the EU and available tax credit provisions in the USA. Finally, this study also proved the feasibility of the incentive system and presented its applicability to all member states, indicating that the implementation of the ton-based incentive system could accelerate the deployment of CCS technology in the EU, assist in reaching climate goals more decisively, and enable decarbonization more cost-efficiently.

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Appendix A

The results of CO_2 emissions forecasting simulations defined by GBM for each emitter for the timeframe from 2022 (year 0) until 2027 (year 5) are depicted in Figures A1–A15.

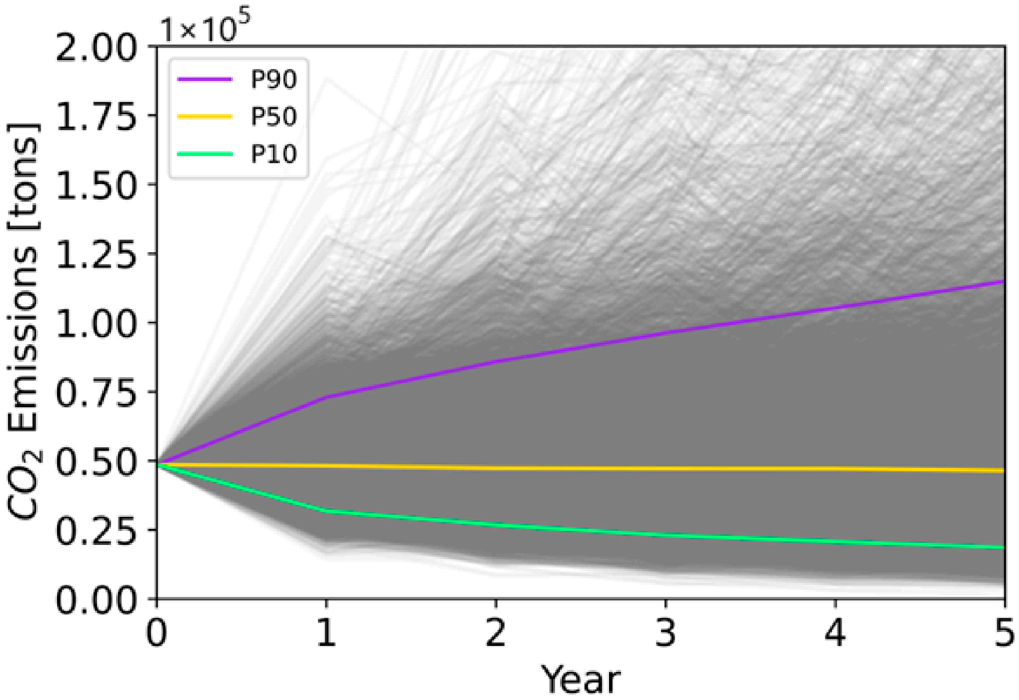

Figure A1. CEMEX Sv. Kajo CO_2 emissions forecast.

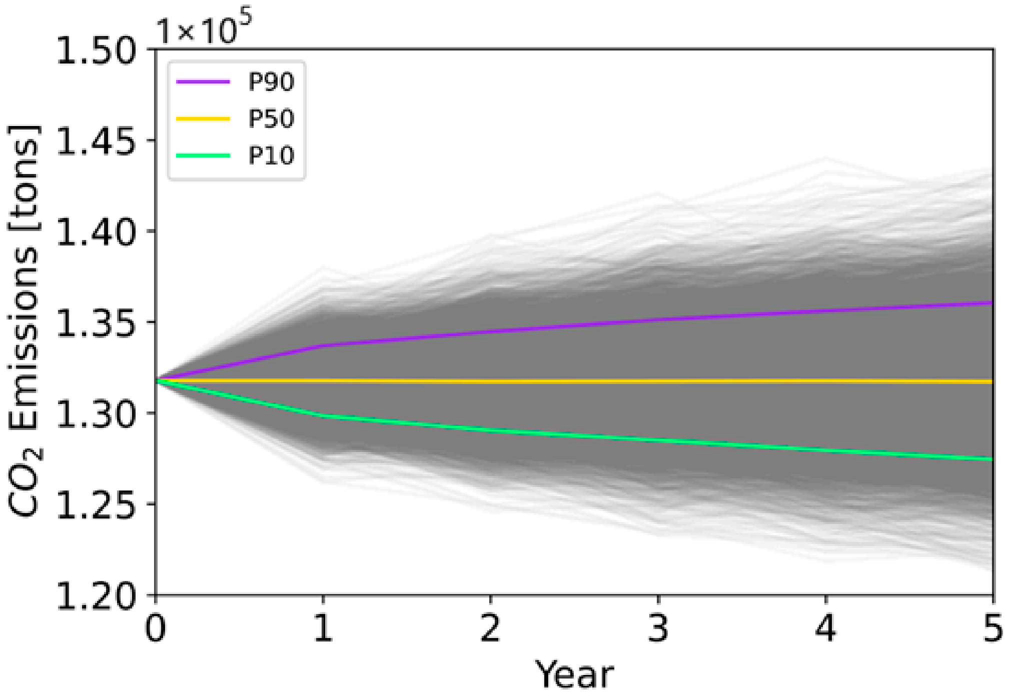

Figure A2. Calucem CO_2 emissions forecast.

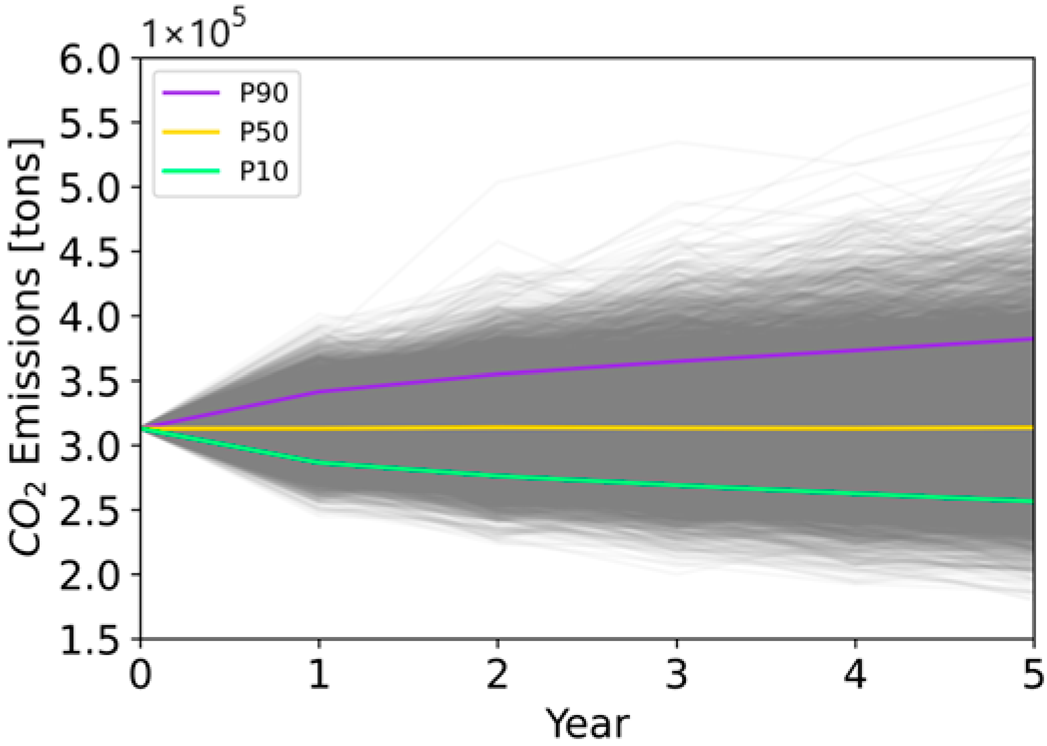

Figure A3. Holcim CO_2 emissions forecast.

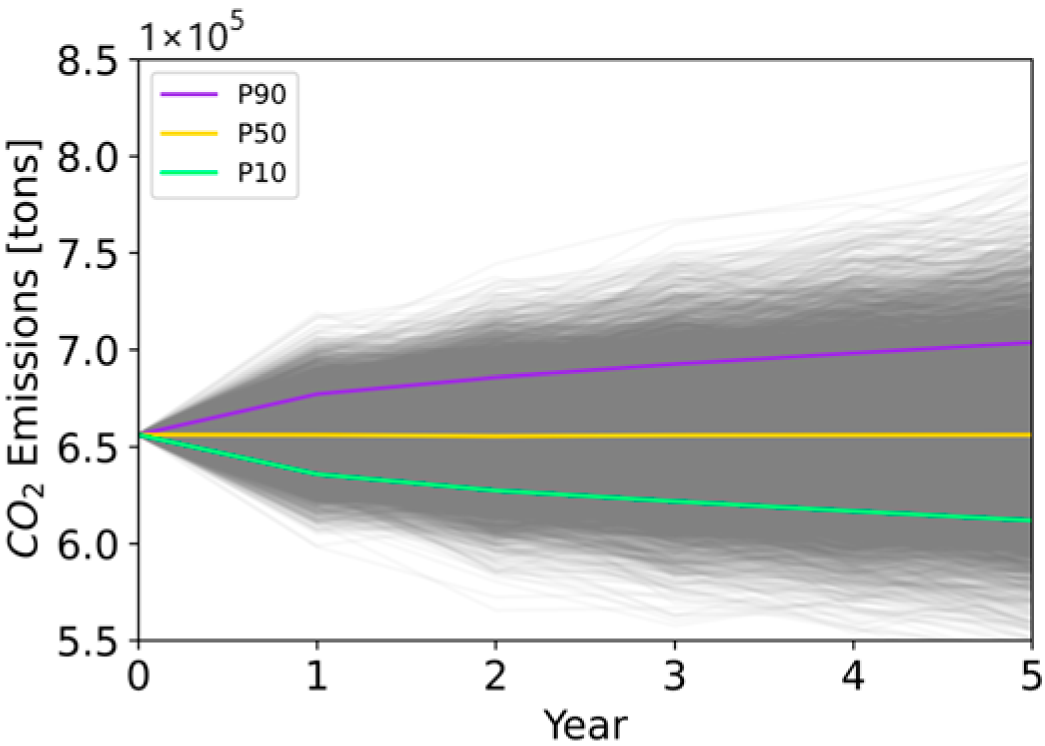

Figure A4. NEXE CO_2 emissions forecast.

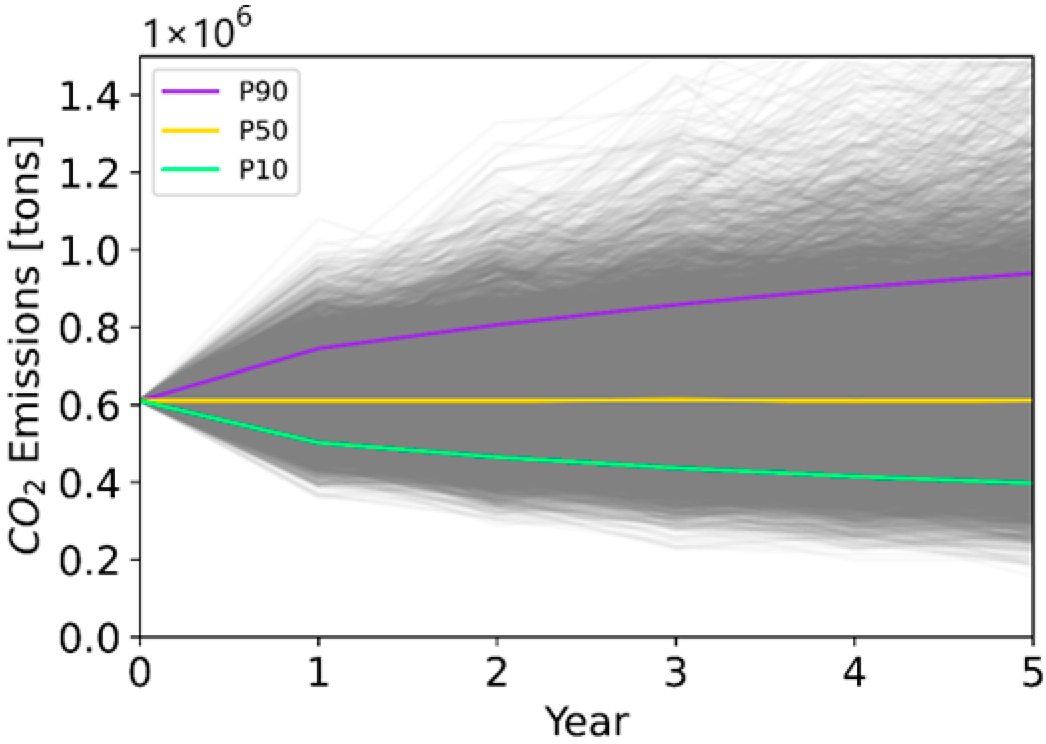

Figure A5. CEMEX Sv. Juraj CO_2 emissions forecast.

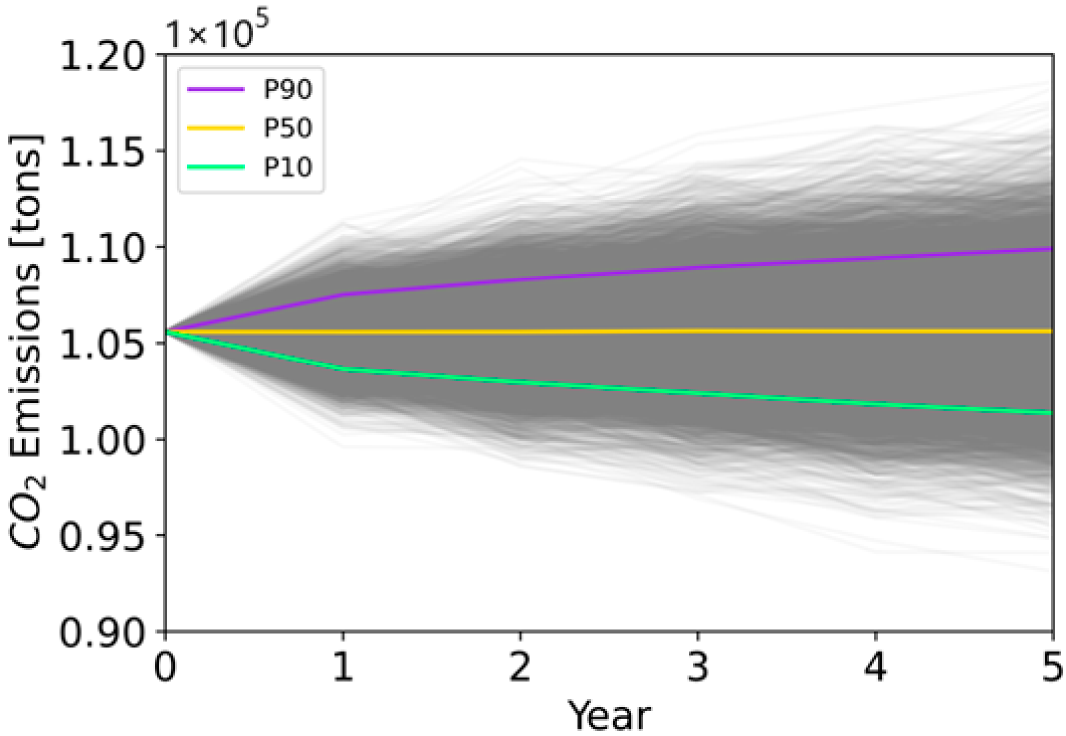

Figure A6. UNI VIRIDAS CO_2 emissions forecast.

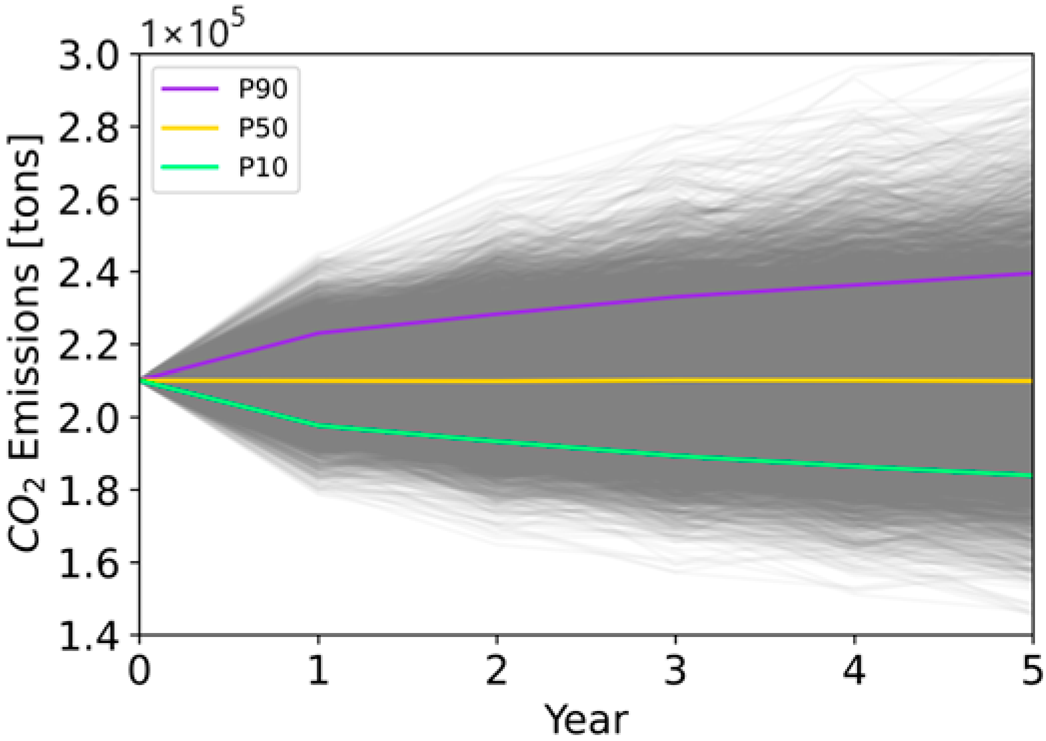

Figure A7. EL-TO Zagreb CO_2 emissions forecast.

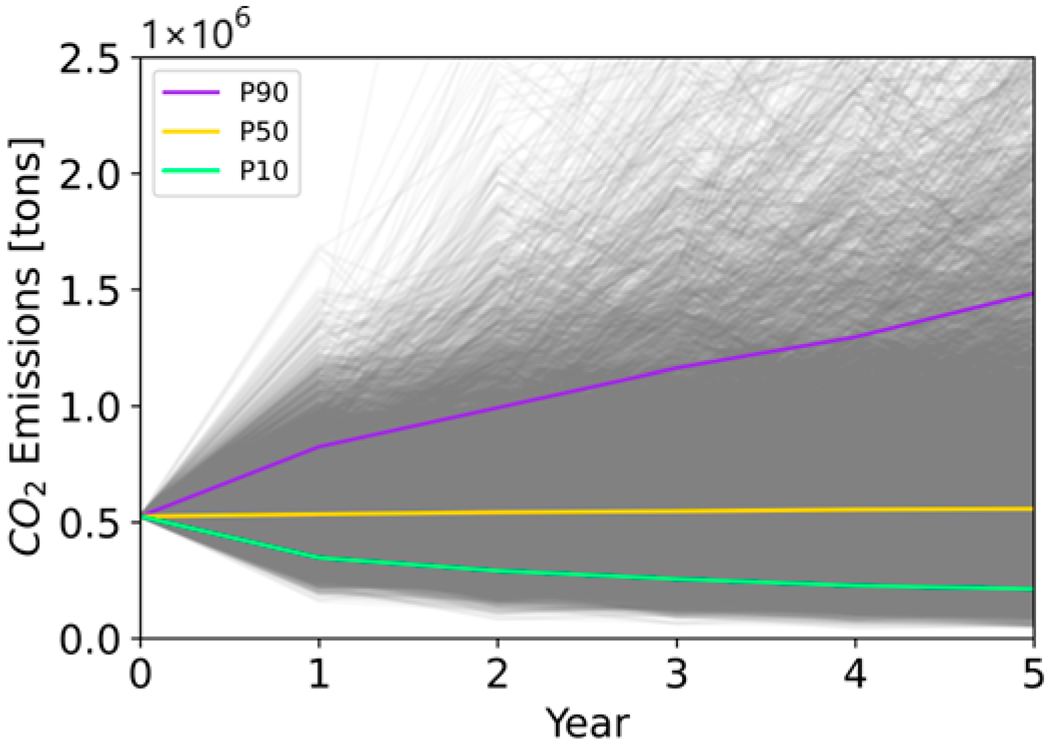

Figure A8. TE-TO Sisak CO_2 emissions forecast.

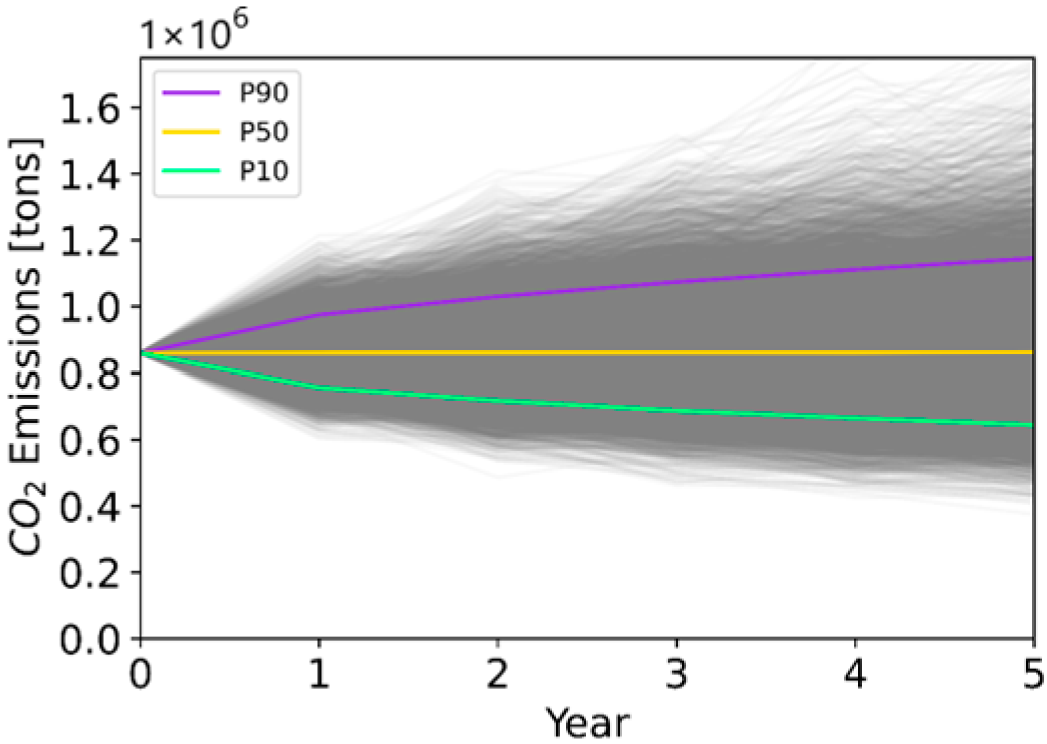

Figure A9. TE-TO Zagreb CO_2 emissions forecast.

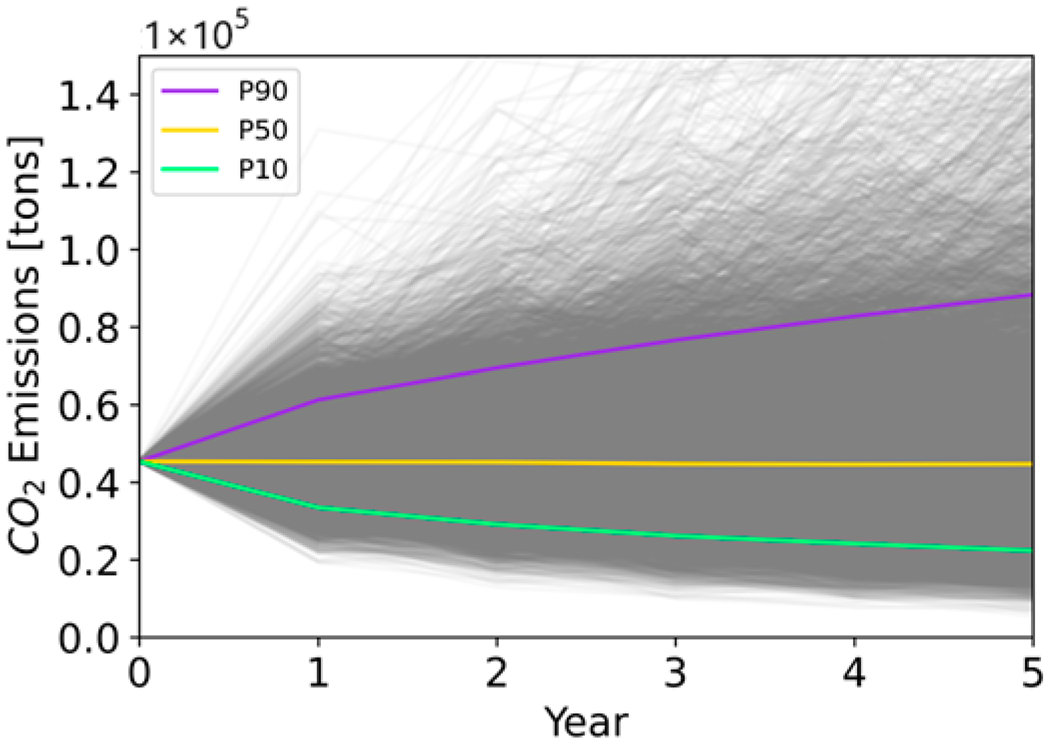

Figure A10. TE-TO Osijek CO_2 emissions forecast.

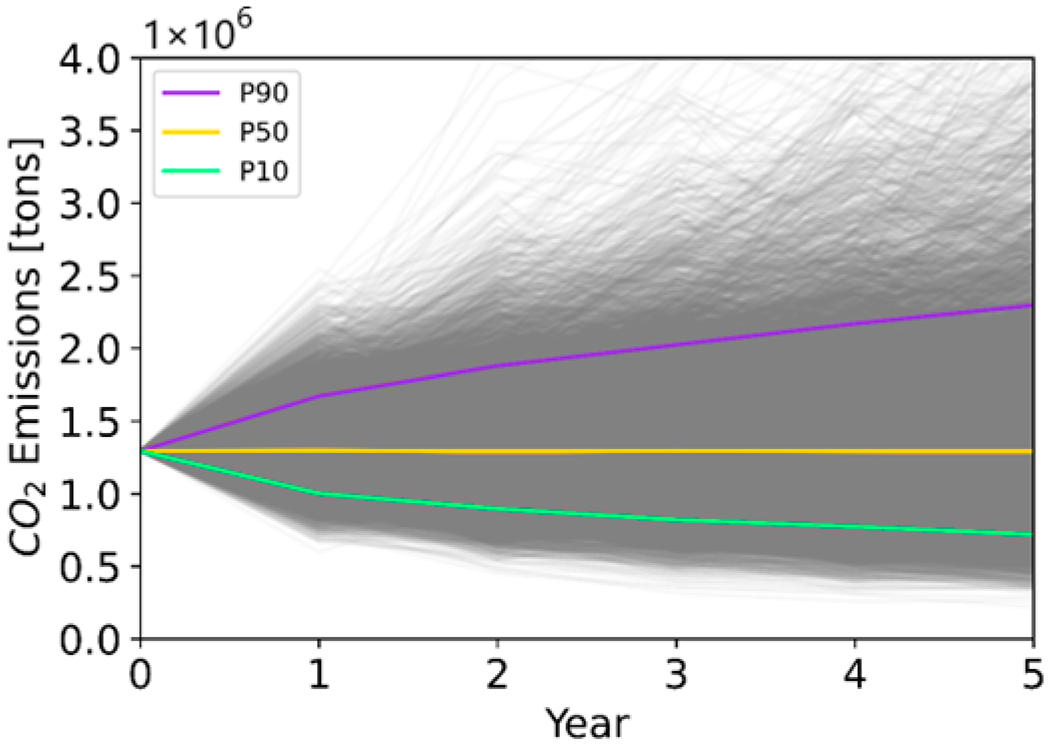

Figure A11. TE Plomin 2 CO_2 emissions forecast.

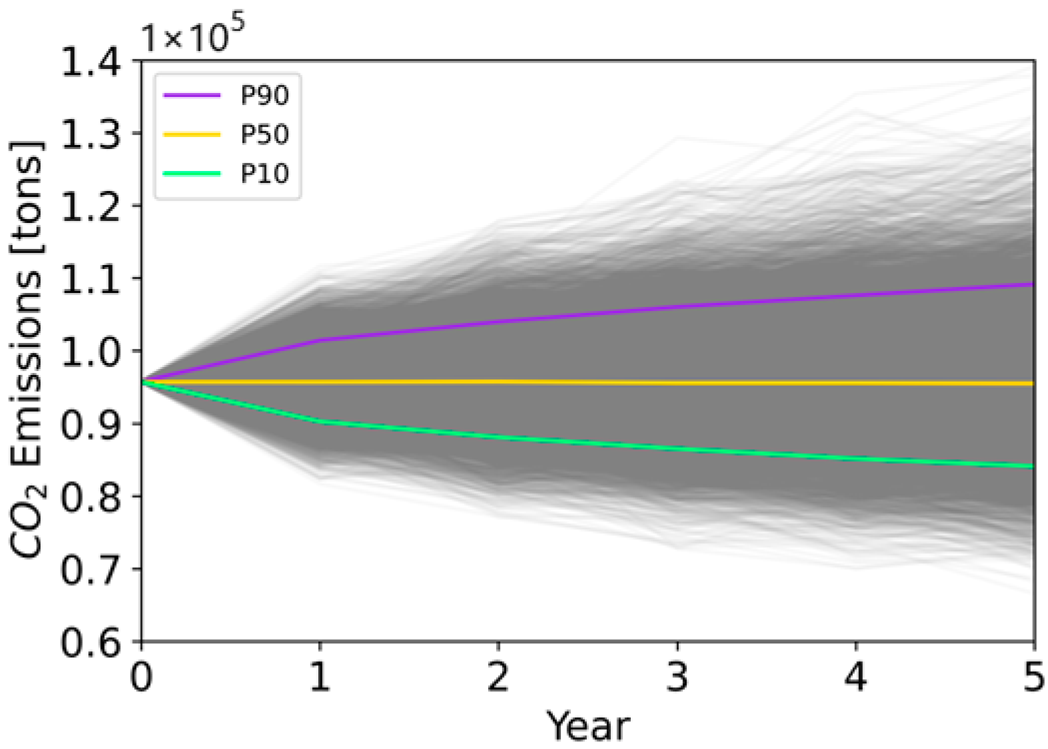

Figure A12. DS Smith CO_2 emissions forecast.

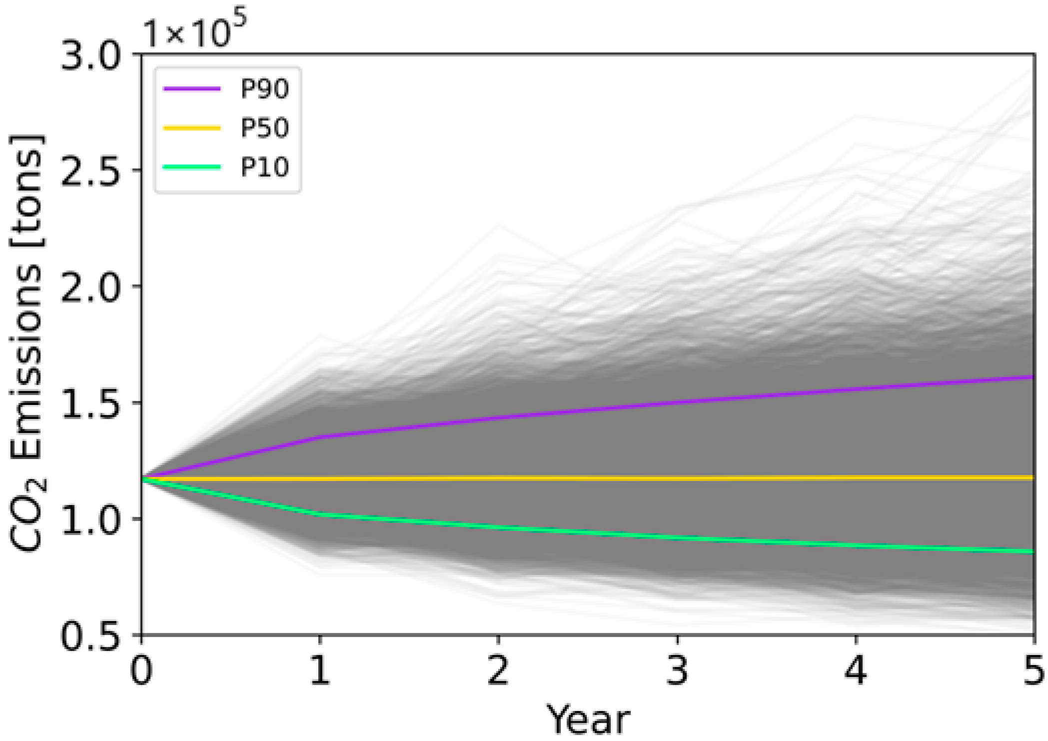

Figure A13. Vetropack Straža CO_2 emissions forecast.

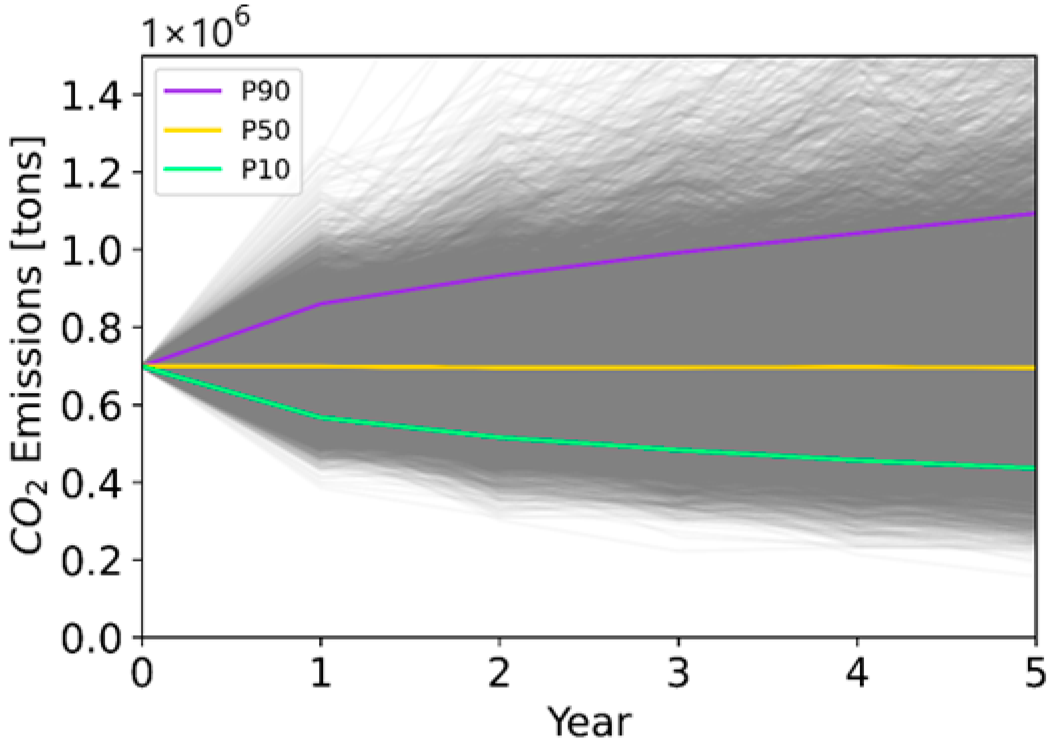

Figure A14. Oil Refinery Rijeka CO_2 emissions forecast.

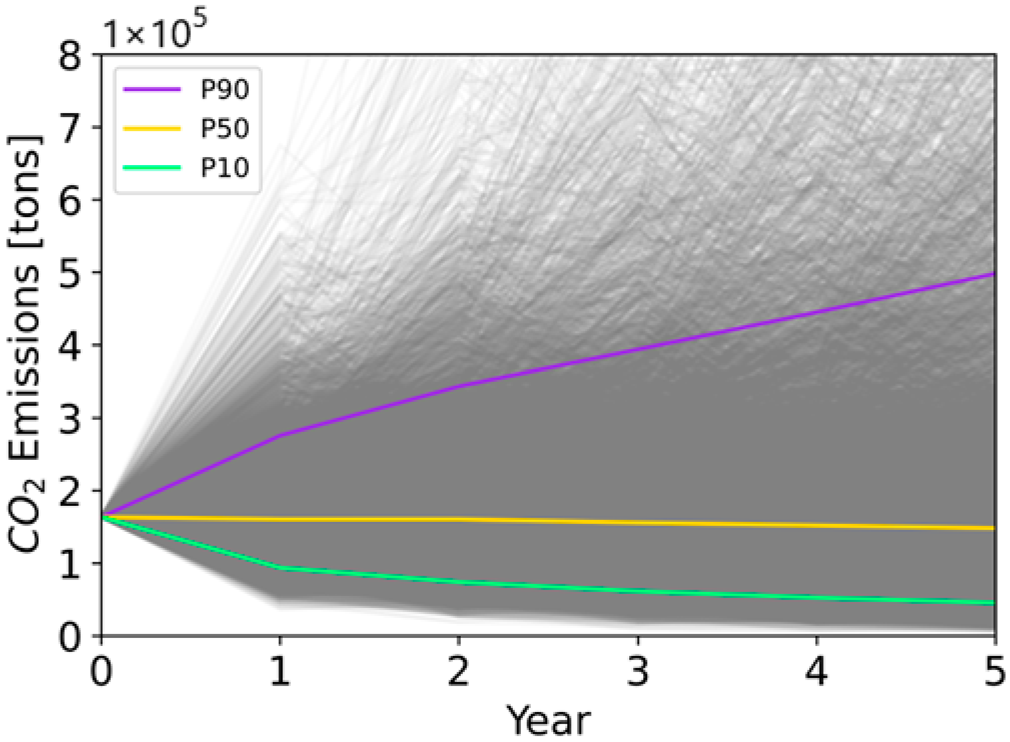

Figure A15. Petrokemija CO_2 emissions forecast.

Appendix B

The code used for the GBM simulations in Python is given as follows:

```
import numpy as np
import matplotlib.pyplot as plt
S_0 = #CO2 emissions in starting year_here
mu = #drift_here
sigma = #volatility_here
T = #forecasting years_here
dt = #time step (1 year)
n = #number of simulations_here

def GBM(S_0, mu, sigma, T, dt, n):

    paths = []

    for i in range(n):
        emissions = [S_0]
        time = 0

        while(time + dt <= T):
                emissions.append(emissions[−1]*np.exp((mu*0.5*(sigma**2))*dt + sigma*np.random.normal(0, np.sqrt(dt))))
            time += dt

        paths.append(emissions)

    return paths

sample_paths = GBM(S_0, mu, sigma, T, dt, n)

sample_paths_array=np.array(sample_paths)

Percentile_10 = np.percentile(sample_paths_array, 10, axis = 0)
Percentile_50 = np.percentile(sample_paths_array, 50, axis = 0)
```

```
Percentile_90 = np.percentile(sample_paths_array, 90, axis = 0)

ax=plt.plot (sample_paths_array.T, color = 'grey', alpha = 0.05)
plt.plot(Percentile_90, label = "P90")
plt.plot(Percentile_50, label = "P50")
plt.plot(Percentile_10, label = "P10")
plt.ylabel("$CO_{2}$ Emissions [tons]", size = 15)
plt.xlabel("Year", size = 15)
plt.legend(loc = "upper left", fontsize = 10)
plt.xticks(fontsize = 15)
plt.yticks(fontsize = 15).
```

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