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Assessment of the Carbon Storage Potential of Portuguese Precast Concrete Industry

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Abstract: The concrete sector is known for its significant contribution to CO_2 emissions. There are two main contributing factors in this situation: the large amount of concrete consumed per year on the planet and the high levels of CO_2 released from the manufacture of Portland cement, the key binding agent in concrete. To face the consequent sustainability issues, diverse strategies involving the carbon capture and storage potential of cementitious materials have been explored. This paper addresses the potential of storing CO_2 in concrete during the curing stage within the context of the precast Portuguese industry. To this end, it was assumed that CO_2 will become a waste that will require an outlet in the future, considering that carbon capture will become mandatory in many industries. This work concluded that, in terms of carbon retention, the net benefit is positive for the process of storing carbon in concrete during the curing stage. More specifically, it was demonstrated that the additional emissions from the introduction of this new operation are only 10% of the stored amount, returning a storage potential of 76,000 tonnes of CO_2 yearly. Moreover, the overall net reduction in the concrete life cycle averages 9.1% and 8.8% for precast elements and only non-structural elements, respectively. When a low-cement dosage strategy is coupled with carbonation curing technology, the overall carbon net reduction is estimated to be 45%.

Keywords: carbon capture utilization and storage; precast concrete industry; CO_2 uptake; carbonation curing; Monte Carlo simulation

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1. Introduction

The characteristics of concrete, mainly cost-effectiveness and application versatility, considered essential to the progress of contemporary civilization turned this construction material into the second highest consumed material by volume, just falling short to water [1,2]. In fact, despite the various efforts to promote and/or develop alternative materials (e.g., wood construction or glass reinforced polymers for structural applications), the Global Cement and Concrete Association [3] estimates a yearly increase in demand from the current 14 billion m^3 of concrete to approximately 20 billion m^3 in 2050. Moreover, the specific (by volume or by weight) environmental impact of concrete is lower than many alternative construction materials (e.g., about 300 kg CO_2/tonne for a standard concrete mix versus over 1000 kg CO_2/tonne for steel) [2,4–6] because the components that make up most of its volume (aggregates) are naturally abundant and relatively easy to obtain. However, most of the concrete produced incorporates Portland cement as the key binder, which is responsible for the majority of the environmental impacts. In fact, 80% to 95% of the carbon emissions by mass from concrete are associated with the production of Portland cement [7–9]. As a consequence of the large amount of concrete consumed per year, Portland cement alone is responsible for 5% to 10% of the total anthropogenic greenhouse gas emissions per year, depending on the source [10–17].

Because most of the cement is consumed in the form of concrete (e.g., the proportion of Portland cement used in concrete is more than 80% in the US [18]), the environmental issues pertaining to the cement and concrete industries are interlinked. Liu et al. (2017) [19] assessed the environmental benefits, including a reduction in CO_2 emissions, of several technologies available for cement production. However, considering that roughly 530 g out of the 840 g of CO_2 emitted per kg of clinker produced in the most efficient cement plants nowadays are from the calcination of calcium carbonate, the overall carbon reduction from these technologies is limited. To address this negative environmental impact, all versions of the cement neutrality roadmaps put forth by major organizations (e.g., GCCA 2022 [20], Cembureau 2020, IEA and CSI 2018) identify carbon capture utilization and storage (CCUS) as a key strategy to attain carbon neutrality in the cement industry. IEA and CSI 2018 even forecasted that as much as 14 Mt of CO_2 will be captured and stored per year in the cement industry by 2030. This technology aims to capture CO_2 at the sources of emission to enable its use in useful applications, turn it into a commodity, or simply allow its capture and deposition in natural reservoirs or in other materials, impeding its emission into the atmosphere.

Different strategies with common objectives have been defined for the implementation of CCUS technologies in the concrete life cycle. For instance, the carbonation of products from the recycling of concrete waste is a promising prospect recently explored by the academy for the application of CCUS. In addition to carbon capture, the strengthening of the adherence of the cement mortar layer to the recycled aggregates is also seen as a promising outcome from this strategy [21–23]. Similarly, the concrete waste fines, by-products of the concrete recycling process that are very rich in cement, have also been studied as an addition to new concrete batches, revealing a better performance after a carbonation process [24–26].

Previous strategies established a new operation into the concrete life cycle, closing the CO_2 cycle. Other possible strategies for CCUS focus on the implementation of carbonation processes in the existing concrete production operation chain, namely during the mixing and curing stages. Carbonating during the mixing stage is a strategy applicable to the generality of the concrete industry, from ready-mix to precast concrete, where CO_2 is introduced simultaneously with the other components [27]. A strategy already successfully applied by CarbonCure Technology Inc. (Halifax, NS, Canada) at an industrial level is one in which CO_2 is directly injected into the truck that mixes the concrete in an amount lower than 1% of the cement weight. This strategy targets the carbonation of both the anhydrous components of Portland cement that are still present during the early hydration stage and the few hydration products already obtained at this stage [28–30].

Conversely, the carbonation curing strategy intends to implement a carbonation process in a subsequent process of concrete manufacturing: the curing stage. As in the previous case, the curing carbonation process also involves an acceleration of the strength development, caused by the reaction between CO_2 and the cement compounds, thus reducing the duration of this critical stage [31]. This impact on the duration of the curing stage, as well as the promotion of the product turnover in the precast concrete industry, allows this strategy to play a key role in the competitiveness and profitability of the concrete industry [32,33]. Carbonation curing was already tested in the precast industry in the past, but, motivated by productivity goals, its generalized application was unsuccessful. The reasons for this limited implementation may be related to the lack of technical and scientific knowledge, namely, the full impact of the carbonation reactions on the performance of the cementitious compounds, including long-term durability issues, and the optimal parameters of the carbonation curing process in terms of carbonation efficiency [31]. Currently, the curing stage in the precast industry is sometimes performed through a steam curing that creates an environment with a high temperature and relative humidity. The process is effective in accelerating the strength development, but it is very energy-intensive and can promote some undesirable side effects in the long term [31,32]. As such, carbon curing is seen as a critical strategy for the competitiveness of this industry, with prospects for a determinant role in the length of the curing stage and, consequently, on the productivity of the whole production process [32,33]. The growing focus of the scientific community on mitigating greenhouse gase emissions also contributed to the reignition of the interest in carbonation curing.

The forecasted need of several industries, including the cement industry, to capture CO_2 to meet emission targets will make it an available sub-product for the concrete industry. In fact, the commercial technologies that are becoming increasingly available for CO_2 utilization in the concrete industry, as well as for the many investigation projects that incorporate CCUS technologies, further boost the commitment towards the development of CO_2 capture technologies upstream in cement production plants. The CO_2 emitted by cement manufacturing originates from limestone calcination and fuel combustion (about 60% and 40%, respectively) and forms a polluted CO_2 stream, commonly denominated flue gas [2,7,34]. Thus, CO_2 capture technologies that recover the CO_2 from the flue gas encompass different strategies, from physical/chemical adsorption and absorption methods to direct separation methods, aim to obtain an uncontaminated CO_2 stream of higher commercial value. Hence, the development of CO_2 capture technologies in cement manufacturing plants, along with the development of CCUS technologies in the concrete industry, uncover a feasible prospect for the conversion of waste CO_2 into a commodity [35–37]. Moreover, carbon taxes and other similar carbon mitigation policies, by placing a value on CO_2 emissions, further encourage carbon intensive industries, namely cement manufacturing plants, to pursue CO_2 capture technologies [38,39].

Different studies aimed to investigate the CO_2 absorption capability of different CCUS technologies within the concrete value chain and comprehend the effect of the carbonation process on the final carbonated cementitious product [7,11]. Although these studies report important results for the improvement of different strategies in the introduction of these technologies in the concrete industry, it is equally important to assess their honest impact, considering not only the absorbed CO_2 but also the remaining indispensable processes for the application of the carbonation strategy. Hence, this paper intends to comprehend the real impact of the carbonation curing strategy within the concrete value chain, assessing the feasibility of this prospect for the mitigation of CO_2 emissions in the Portuguese precast industry.

The objective of this paper is to analyse the potential incorporation of the carbonation curing strategy in the Portuguese concrete industry. Restricting the study to this strategy means restricting the analysis to the precast industry. Figure 1 presents the distribution of cement commercialized in Portugal, divided into the resale of cement bags (essentially used in mortars), the precast concrete industry and the ready-mix concrete industry [40,41]. Even though precast concrete corresponds to only 17% of the totality of the cement market in Portugal, when only the concrete manufacturing industry is considered, the precast industry occupies more than a quarter of the cement market. This consideration is especially important, since the manufacturing industry, by utilizing cement to produce a diverse set of cementitious products, divulges different opportunities for the introduction of CCUS technologies [40,41].

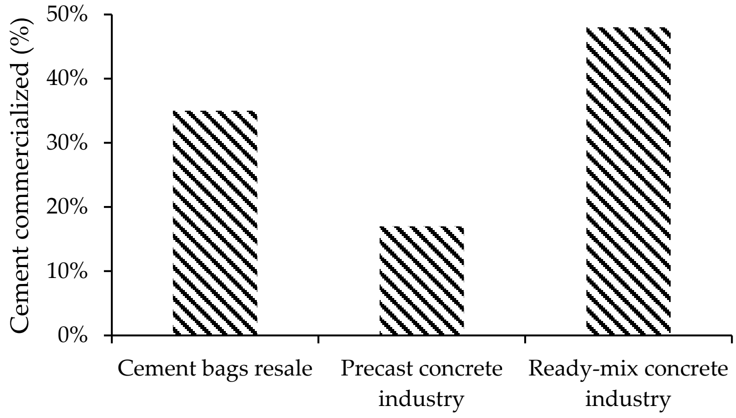

Figure 1. Cement commercialization by sector [40,41].

Several studies have explored the CO_2 balance from the process of mixing or curing concrete with CO_2 and the sequestered CO_2 in the process [42–46]. In one of the most recent efforts, Ravikumar et al. [47] concluded that carbon curing and the mixing of concrete (CCM concrete) may not produce a net climate benefit. These authors account for all emissions associated with the production of concrete components, CO_2 capture and transportation, and CCM concrete production, and consider electricity production from coal as the source of CO_2. In doing so, the authors are implicitly assuming that (i) CCUS technologies will only be implemented in coal power plants; (ii) electricity production from coal will be the main source of carbon emissions; (iii) coal will be the main source of energy for electricity generation; and (iv) it is possible to avoid using concrete in the future.

However, concrete is the most widely used construction material worldwide, and it will probably continue to be in the near future. Even in a scenario in which it becomes possible to completely avoid the emissions from energy consumption related to cement production, the calcination emissions during the clinker production will still be present unless uncarbonated raw material is used. As such, CCUS is regarded as a major strategy for mitigating CO_2 emissions in this industry, as previously mentioned.

On the other hand, the use of coal to produce electricity is being abandoned in several of the most developed countries in their efforts towards carbon neutrality, which is reflected in the decreasing coal demand reported by the IEA in 2021 [48]. In fact, coal is being replaced by natural gas, nuclear energy and/or renewables, depending on the country. In 2020, the share of renewables in global electricity generation reached 29% (IEA 2021), rose to 38% in 2021 [49] and is forecasted to rise to 45% by 2040 (Mathew 2022). There are, naturally, differences between countries. For instance, in the USA, the share of renewables for electricity generation was 21% in 2020, and it is forecasted to reach 42% in 2050 [50,51], whereas countries such as Sweden, Norway or Iceland already have shares of 62% (IEA 2022) [52], 98% (IEA 2022) [53] and 100% [54], respectively.

Therefore, some of the implicit assumptions considered in previous studies are not completely valid, justifying a reflection and adoption of other updated assumptions in this work. Hence, the objective of this research effort is the assessment of the potential for CO_2 incorporation in the precast concrete industry in Portugal based on the CO_2 net balance applied to the curing process. To this end, the following assumptions will be adopted: (i) concrete will be used in the future, regardless of the CCUS strategies eventually in use, and (ii) CO_2 capture will be mandatory for many industries to meet the increasingly stringent emission targets. The carbonation process is considered as described in the literature, and the CO_2 uptake is considered using cement mass. The data from concrete production were collected from surveys filled out by the Portuguese agents of the concrete industry to consider the different amounts of CO_2 absorption achieved by different contents of cement inside the concrete, allowing for a more accurate modelling of the real potential. The variability of the data sources is considered explicitly through Monte Carlo simulation.

2. Methods

2.1. Scope

On the basis of the context defined in the previous section, the present study is carried out assuming that (i) carbon capture will be mandatory in many industries, namely the cement industry, and (ii) the energy required for using carbon in the concrete industry, excluding transportation, will be supplied in the form of electricity. As such, the system analysed is defined in Figure 2, with the functional unit being 1 m^3 of concrete produced.

The assumption that carbon capture will be mandatory allows the exclusion of the associated energy consumption from the analysis. This does not mean that there will not be energy consumption and emissions from it, but rather that the captured carbon will be a waste that needs to be disposed of and not a product that is obtained for a specific application. This assumption is mandatory, as this work intends to assess if the use of concrete as a storage option for the CO_2 captured is viable, rather than if CCUS is viable overall. Additionally, instead of the electricity generation from coal, the cement production will be considered as the source of CO_2 because (i) cement production from natural raw material will always emit substantial amounts of CO_2 due to the calcination stage; (ii) coal power plants are progressively being replaced in many countries, in particular the most developed; and (iii) the number of cement plants, their relative location to concrete production sites and the closed loop created have the potential to create logistical synergies, which could optimize the production, storage and transport of both cement and CO_2 for concrete production.

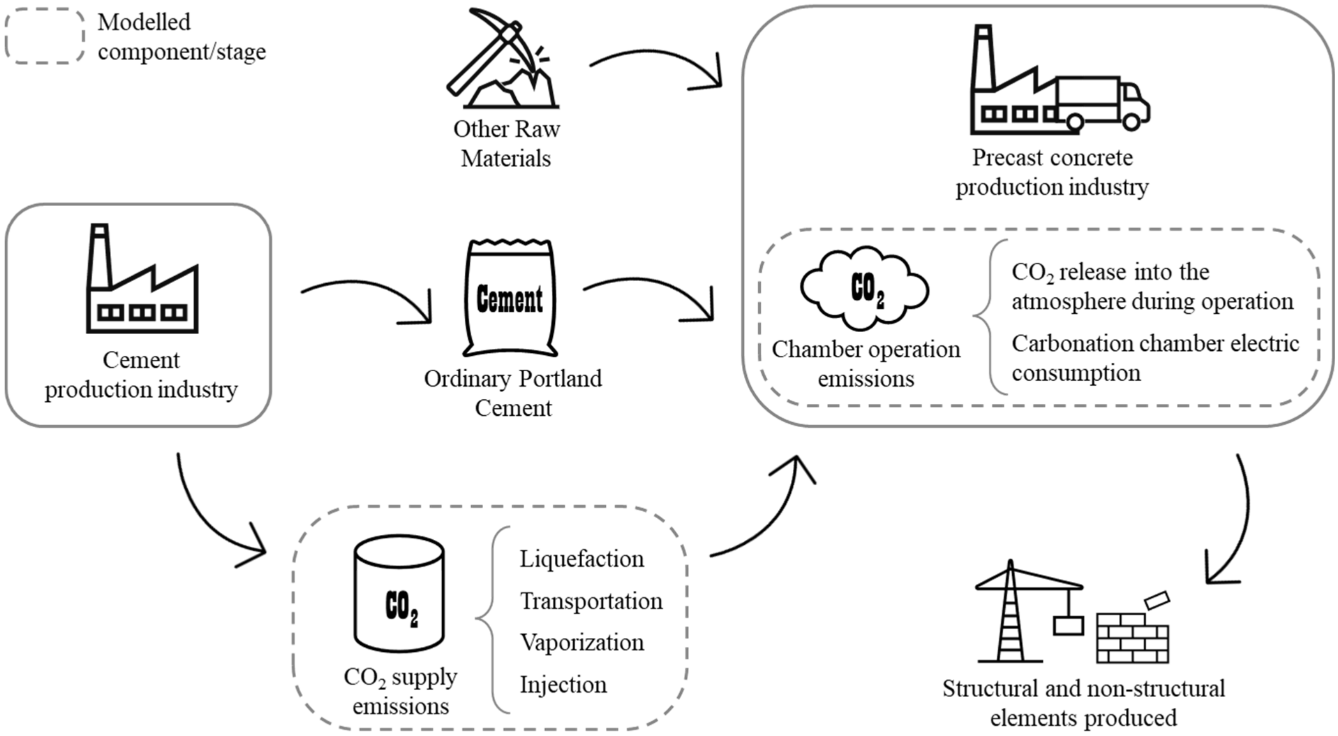

Figure 2. System boundaries.

It is legitimate to assume that the energy used to capture CO_2 at a coal power plant is supplied by the power plant. However, in cement and precast concrete plants, the electricity required is obtained from the grid. As such, the emissions will depend on the specific energy mix of each country, which is variable throughout each year (e.g., the production of renewable energy sources varies) and over the years (e.g., the installed power of each energy source varies).

Finally, since concrete will be produced regardless of using CO_2 for curing, only the additional stages required for carbon curing are modelled. The energy consumption and respective emissions from the remaining stages of the production process can be disregarded for assessing the balance (favourable or not) between the additional CO_2 emissions and the amount of stored CO_2.

In conclusion, the scope of the present research was defined on the basis of the assumption that to meet the carbon emission standards, particularly in the cement industry, which is constrained by the calcination emissions, CO_2 will be a waste flux generated from cement production.

2.2. Methodology and Data

The balance between CO_2 emissions and storage for concrete was assessed by simulating the performance of the stages identified in Figure 2. A mixed approach was adopted to obtain the data required to run the simulation, including (i) official sources (CO_2 emissions from electricity generation and land transportation); (ii) research results from the literature

(CO_2 absorption and energy consumption during carbon curing); and (iii) questionnaire replies (precast concrete consumption and composition).

The CO_2 storage capacity associated with carbon curing depends on the amount of concrete produced in the concrete precast industry and on the CO_2 absorption. The amount of concrete produced by each category of concrete composition was estimated from replies to questionnaires sent to the precast concrete producers. The production data related to the sample of producers that replied were then extrapolated to the total production of the precast concrete industry. The CO_2 absorbed by the concrete during carbon curing depends on factors such as the amount of cement, the type of binders and the curing process. The applicable absorption rates collected by Ravikumar et al. (2021) [47] were used herein, considering only cases without steam curing. The variability of the rates is significant (between 0.05 and 0.2 kg of CO_2/kg of cement), which is explained by the different concrete compositions and ensuing transport properties.

The carbon emissions from carbon curing, shown in Figure 2, can be split into (i) concrete curing chamber operation emissions and (ii) CO_2 supply emissions. The operation of the curing chamber in the precast plant has emissions from (i) CO_2 release into the atmosphere during the loading and unloading of the chamber and (ii) electricity consumption associated with the need to create a vacuum in the chamber before injecting the CO_2. The volume of CO_2 lost will depend on the volume ratio between the concrete element and the curing chamber, which is affected by their shape and the eventual presence of hollows in the concrete element. This ratio was assumed to be, on average, 40% of the volume of the concrete to cure, and a variability between 20% and 80% was considered. This volume also corresponds to the amount of air that the vacuum pumps need to extract, and their specific energy consumption is, on average, 0.025 kWh/m^3 of air [55]. The conversion between the mass and volume of CO_2 was performed using a specific weight of 1.836 kg/m^3 at ambient temperature.

The emissions from the CO_2 supply entail the liquefaction, transport, vaporization and injection, as depicted in Figure 3.

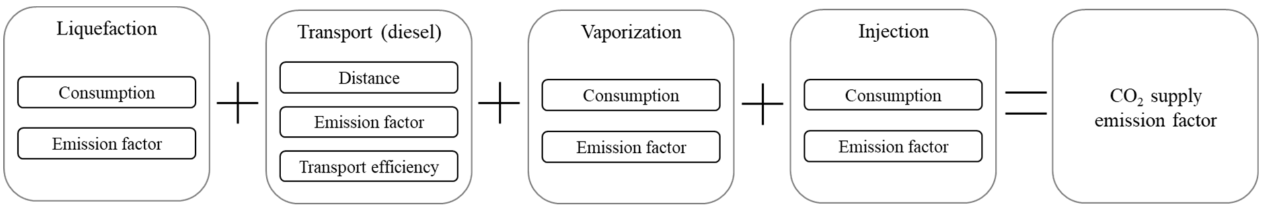

Figure 3. Stages of emission variables in the CO_2 supply chain.

The specific CO_2 emissions were obtained from the European Environment Agency (EEA) up to 2016 and the Portuguese Association of Renewable Energies (APREN—Associação de Energias Renováveis) from 2017 onwards, as shown in Figure 4. The results show a clear decreasing trend that is explained by the continuous installation of generation capability from renewable sources and the transition from coal to natural gas. In Portugal, the generation of electricity from coal ceased in January 2021. Data from 2021 are not available because they are now being reported only in terms of carbon equivalents and not just carbon, but the decreasing trend is maintained (129 g CO_2 eq/kWh in 2021). Conservatively, the median specific carbon emissions from electricity generation in Portugal between 2016 and 2020 (254 g/kWh) were used in the simulations.

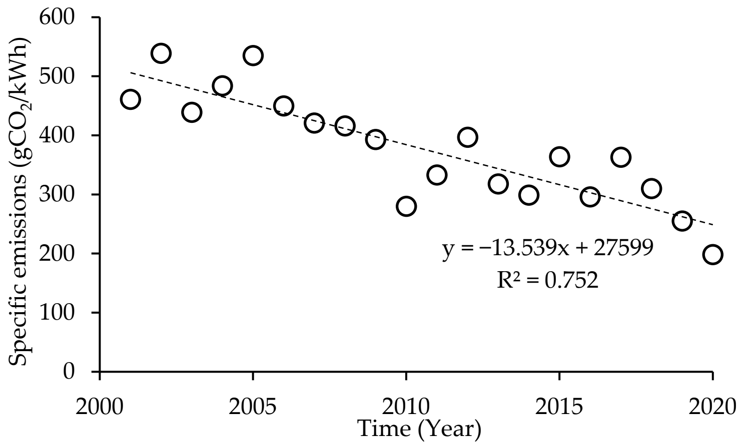

Figure 4. Specific carbon emissions from electricity generation in Portugal [56–60].

Freight transport emissions are usually reported on a distance (per kilometre—km) and weight (per tonne—t) basis (g CO_2/tkm) and are extremely variable depending on the means of transportation and the methodology used in the estimation [61]. As Figure 5 demonstrates, these differences are even found in distinct time series reported by the EEA.

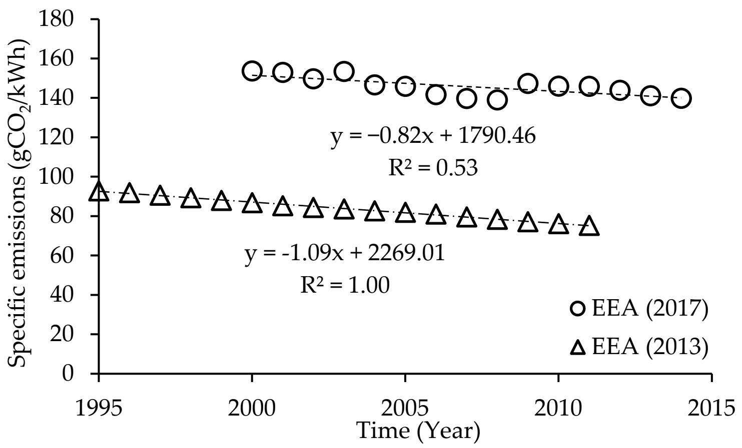

Figure 5. Specific carbon emissions from road freight transportation in Europe [62,63].

Regardless of the offset in the values depicted by the different time series presented in Figure 4, the variation over time is relatively small. For road transportation, the specific emissions factor is found to be more variable with (i) the size of the truck; (ii) the load factor (the ratio between the average load transported and the load capacity); and (iii) the percentage of time running empty. The specific emissions decrease with an increase in truck cargo capacity [64] and load factor and a decrease in the time running empty [65], with values ranging between less than 40 g CO_2/tkm to over 700 g CO_2/tkm, considering the full range of heavy-duty vehicles. Considering only medium and large heavy-duty vehicles, which are most likely to be used for the transportation of the CO_2 captured, the top limit is reduced to 300 g CO_2/tkm [66]. The median of the average specific emissions factor values from various sources reported in McKinnon and Piecyk (2010) [65], Transport & Environment (2021) [64], IEA and UIC (2012) [67] and Ravikumar et al. (2021) [47] is 82 g CO_2/tkm, and this value was used in the simulations. An average distance of 120 km (both ways) was considered adequate, considering the size of Portugal (≈600 × 200 km) and the number of cement plants (6).

The median energy consumption values for CO_2 liquefaction, vaporization and injection are 0.10 kWh/kg CO_2, 0.047 and 0.037, respectively [47,68,69].

To complement the typical deterministic approach, a stochastic analysis, which included Monte Carlo simulation, was also carried out, wherein all input data were assumed to follow a PERT distribution because there are not enough data points for distribution fitting; therefore, a three-point estimating approach was used. The most common distributions used with three-point estimating are the triangular and the PERT, but the latter weights the most probable value more. Therefore, PERT was used to minimize the error due to eventual outliers and the effect it would have on the data sources. When several data points were available, the median was used instead of the average to determine the most probable value since the former is a robust measure of central tendency.

3. Results and Discussion

From the questionnaires sent to the precast concrete producers, six complete replies were obtained, representing a little over 5% of the total cement consumption in the sector. The distributions of cement consumption by type of cement and by dosage and category of concrete precast elements (structural—with steel reinforcement; non-structural—without reinforcement) are detailed in Table 1.

Table 1. Cement consumption distribution from the questionnaires.

Cement			
Dosage	**Type**	**Total Consumption [kg/Year]**	
[kg/m^3]	**[-]**	**Non-Structural**	**Structural**
100 to 200	CEM I 52.5 R	406,458	45,162
	CEM I 42.5 R	191,250	63,750
	CEM II/A-L 42.5 R	5,589,600	891,900
200 to 300	CEM I 52.5 R	714,525	1,538,175
	CEM I 42.5 R	1,243,125	1,519,375
	CEM II/A-L 42.5 R	5,241,750	915,750
300 to 400	CEM I 52.5 R	948,402	8,535,618
	CEM I 42.5 R	1,770,125	312,375
	CEM II/A-L 42.5 R	2,115,575	9,864,925
>400 (average 450)	CEM I 52.5 R	1,151,631	203,229
	CEM I 42.5 R	650,250	114,750
	CEM II/A-L 42.5 R	4,459,275	1,381,725
Total		24,481,966	25,386,734
		49,868,700	

An extrapolation for the entire precast concrete sector was performed simply by scaling up the proportion between the annual cement consumption in the sample (49,868 tonnes) and in the sector (960,000 tonnes). This entails the assumption that the distribution, in terms of type of cement and dosage and category of precast elements, is the same at both scales. Figure 6 presents the data of Table 1 in an alternative way, enhancing the differences between non-structural and structural concrete industries in terms of cement dosage per volume of concrete and cement type.

While the non-structural concrete elements present an evenly distributed consumption of cement throughout the different cement dosages, from 100 to more than 400 kg/m^3, the majority of the structural elements (about 74%) rely on a cement dosage between 300 and 400 kg/m^3. Accordingly, the average dosage of cement is 250 kg/m^3 and 318 kg/m^3 in non-structural and structural elements, respectively. These estimates were obtained by computing the amount of concrete in each dosage range from the corresponding amount of cement (Table 1), assuming the intermediate dosage value. The average dosage of cement involving all the concrete products, regardless of cement type, is 280 kg/m^3. Similarly, regarding the cement type used, the majority of the non-structural concrete elements (about 71%) adopt CEM II/A-L 42.5 R, while the structural elements take higher amounts of CEM II/A-L 42.5 R and CEM I 52.5 R. These values are expected and easily explained by the higher performance required for the structural concrete elements. Conversely, non-the structural elements comprise a wider range of cementitious products, with a diverse set of physical and mechanical properties, namely, masonry blocks, paving blocks, curbs and other small utility products. Moreover, the cement dosage is often conditioned by the early-stage performance in these elements to comply with productivity requirements, unlike the case of structural elements where the cement dosage is mainly conditioned by the lifetime performance. This flexible composition suggests a greater acceptance of the introduction of CCUS technologies within the manufacturing process of non-structural concrete elements, especially if this interference promotes the early strength (which is the case with carbonation) and controls the costs.

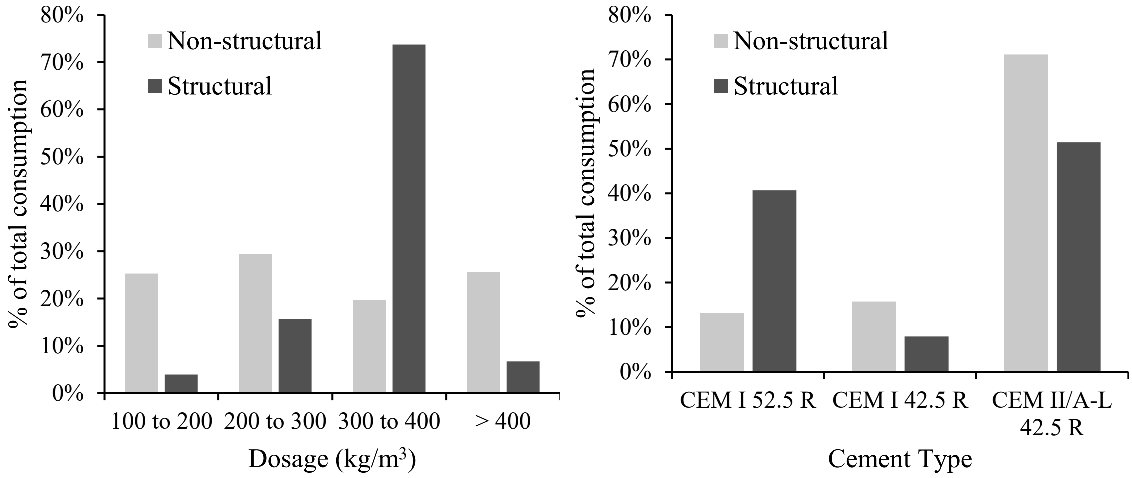

Figure 6. Consumption of cement per dosage (**left**) and per cement type (**right**) in non-structural and structural precast concrete.

Tables 2 and 3 present the various components of the specific emissions of the CO_2 supply and the curing chamber operation, respectively. More information regarding the data sources used can be found in Section 2. Since the sum of the specific emissions of both stages is less than one (median = 0.086 kg CO_2 emitted/kg CO_2 used), it is possible to conclude that the solution provides a net benefit in terms of carbon retention.

Table 2. Emissions estimation from the CO_2 supply.

	Mode	Maximum	Minimum	Units	Sources
Liquefaction	22.60	50.88	12.98	g CO_2/kg CO_2	Calculated
Emission factor (electricity)	253.9	355.3	162.2	g CO_2/kWh	[56–60]
Electricity consumption	0.089	0.143	0.080	kWh/kg CO_2	[47,68,69]
Transportation	15.14	125.87	3.42	g CO_2/kg CO_2	Calculated
Emission factor (fuel)	82.0	300.0	40.0	g CO_2/tkm	[47,64,65,67]
Distance	120.0	300.0	50.0	km	Estimated [1]
Efficiency	0.650	0.715	0.585	kg CO_2/kg transported	[47,64,65,67]
Vaporization	1.79	3.13	0.86	g CO_2/kg CO_2	Calculated
Emission factor (electricity)	253.95	355.31	162.19	g CO_2/ kWh	[56–60]
Electricity consumption	0.007	0.0088	0.0053	kWh/kg CO_2	[47,68,69]
Injection	9.40	14.46	5.40	g CO_2/kg CO_2	Calculated
Emission factor (electricity)	253.9	355.3	162.2	g CO_2/kWh	[56–60]
Electricity consumption	0.037	0.041	0.033	kWh/kg CO_2	[47,68,69]
Specific emission	0.051	0.204	0.023	kg CO_2 emitted/kg CO_2 used	Calculated

Notes: [1] based on the size of the country, number of cement plants and location of major cities.

Table 3. Emissions estimation from curing chamber operation.

	Mode	Maximum	Minimum	Units	Sources
Vacuum	4780	70,937	745	kg CO_2/year	Calculated
Emission factor (electricity)	253.95	355.31	162.19	g CO_2/kWh	[56–60]
Electricity consumption	0.025	0.1	0.015	kWh/m^3 air	[66]
Volume of air	752,864	1,996,462	306,246	m^3 air/year	Estimated [1]
Losses	0.40	0.80	0.20	m^3 CO_2/m^3 concrete	Estimated [2]
Specific emission	0.036	0.048	0.032	kg CO_2 emitted/kg CO_2 used	Calculated

Notes: [1] based on the relation between the size of the curing chamber and the amount of concrete precast elements placed inside in each load; [2] based on the efficiency of the vacuum pumps regarding their ability to recover the CO_2 not absorbed by the concrete during curing.

The volume of air that needs to be extracted each year from the curing chamber corresponds to 40% of the volume of concrete, which is the amount of CO_2 that is assumed to be lost (the difference between the volume of the curing chamber and the volume of the precast elements placed inside). The specific emission is the ratio between the CO_2 used, which accounts for the electricity consumption for vacuum pumping and the losses, and the CO_2 consumed in the curing process. A specific weight of 1.836 kg/m^3 was assumed for the CO_2 at ambient temperature.

The emissions associated with the curing chamber operation presented are for non-structural precast elements. Slight differences exist with the structural elements since the cement consumption in each type of concrete and the corresponding absorption rates are not the same.

Considering the uncertainty of most of the parameters in the simulation, reflected, for instance, by a ratio of almost 10 between the maximum and minimum estimates for the specific emission for the CO_2 supply, a stochastic analysis was carried out. The results of the 10,000 simulations are presented in Figures 7–9 for carbon curing in three scenarios: only the non-structural precast elements, only the structural precast elements and the total precast industry.

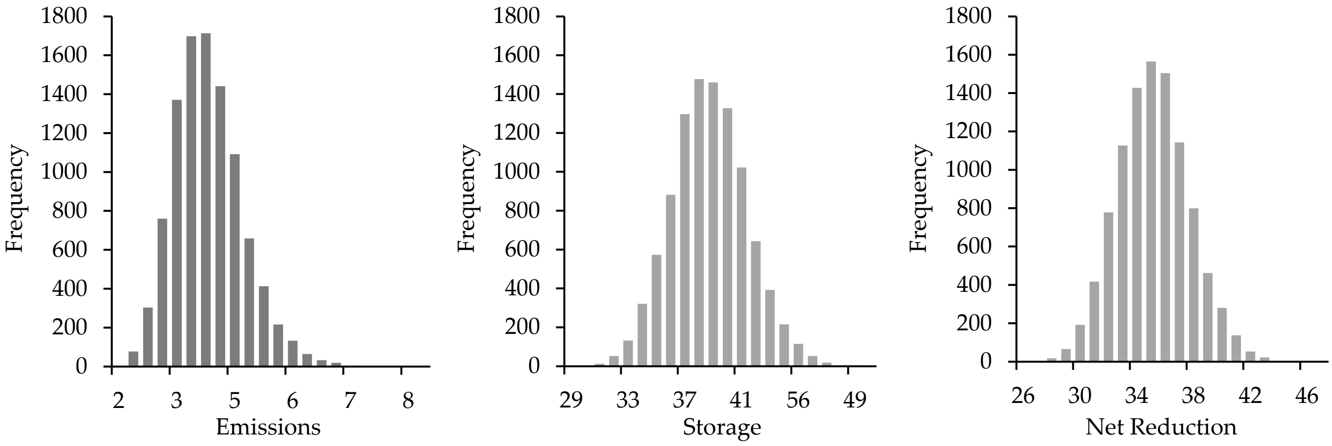

Figure 7. Monte Carlo simulation results for the non-structural precast elements (in 1000 tonnes CO_2/year).

The consideration of these three scenarios is important, since there are plausible doubts regarding the durability of the reinforced concrete after being subjected to carbonation. In the scenario of carbonating both structural and non-structural elements (Figure 9), the emissions from the curing operation are between 4400 tonnes and 15,000 tonnes of CO_2, while the carbon storage potential comprises between 65,000 and 98,700 tonnes of CO_2. As such, the net reduction ranges between 57,500 and 90,400 tonnes of CO_2, with a mode value of roughly 74,000 tonnes of CO_2 that are prevented from being released into the atmosphere yearly. Considering that the most productive forest can sequester up to 11 tonnes of CO_2 per hectare per year [70], this result indicates that the precast concrete industry in Portugal is able to sequester CO_2 equivalent to 6696 hectares of forest per year.

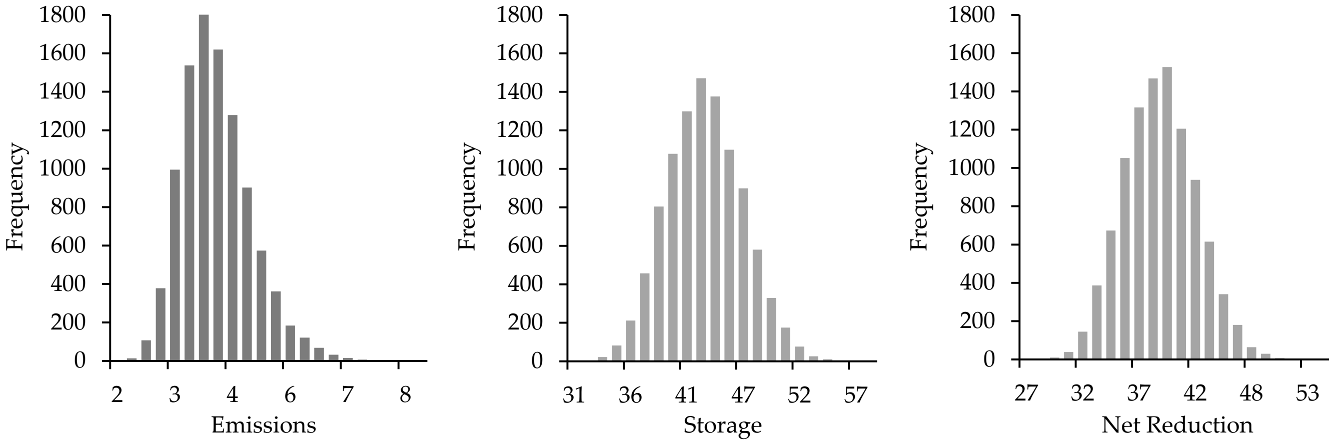

Figure 8. Monte Carlo simulation results for the structural precast elements (in 1000 tonnes CO_2/year).

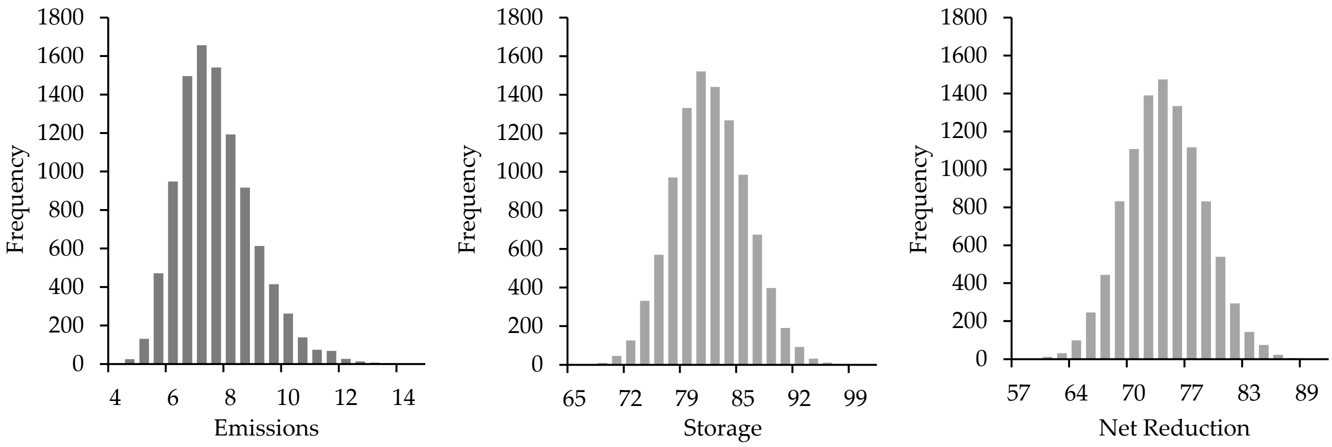

Figure 9. Monte Carlo simulation results for the precast industry (in 1000 tonnes CO_2/year).

If carbonating structural elements is considered unviable, the scenario is restricted to only the non-structural elements. In this case, the emissions from the operation ranges are reduced to between 2100 tonnes and 7400 tonnes of CO_2, and, similarly, the carbon storage potential is also reduced to between 29,000 and 49,000 tonnes of CO_2. Thus, the corresponding net reduction ranges between 25,700 and 45,700 tonnes of CO_2, with a mode value of roughly 34,700 tonnes of CO_2 emissions that are prevented from being released into the atmosphere yearly, which, following a similar method as previously mentioned, yields a CO_2 sequestration value equivalent to 3150 hectare of forest per year.

Regardless of the scenario considered, the carbon storage in the concrete precast industry is largely superior to the emissions in the process, which consist of only around 10% of the stored amount, which translates to a 90% net reduction overall. This conclusion assumes that carbon becomes an industrial waste in the future and the emissions from capturing it are excluded from the calculation.

A sensitivity analysis was performed to assess the parameters that have the greatest influence on the variance of the results (Figure 10). As expected, the absorption rate, the cement dosage and the concrete amount are the most influential parameters, followed by the emissions from the transportation (distance x emission factor) of the CO_2 between the capture point and the precast factories. The electricity consumption in all stages has a minimal impact, which in Portugal may be explained by the significant reduction in the emission factor with the ongoing transition to greener sources of energy.

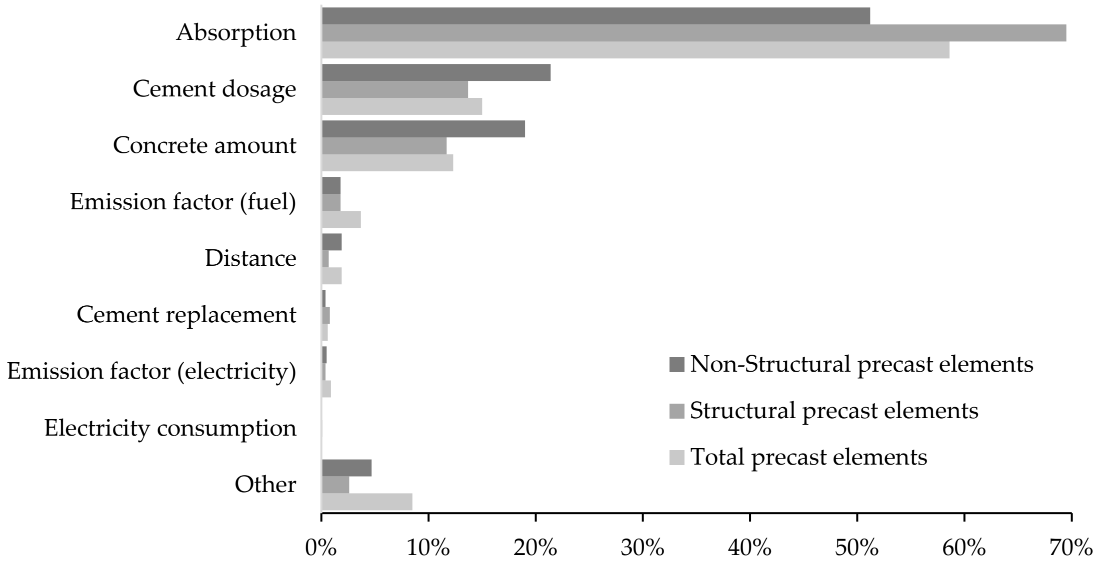

Figure 10. Sensitivity analysis of the net CO_2 reduction potential from implementing carbon curing in the non-structural, structural and total precast industry.

The impact of the positive carbon balance from the carbonation curing on the concrete emissions throughout the concrete life cycle is analysed in Table 4. The results were obtained considering 840 g of CO_2 emitted per gram of cement and the results from Table 1.

Table 4. Net reduction in the CO_2 emissions in the precast concrete industry.

Precast Concrete Products	CO_2 Emissions from Cement Production [kg of CO_2/Year] [1]	Produced Concrete [m^3/Year] [2]	CO_2 Emissions [kg of CO_2/m^3 of Concrete]	Carbonation Curing Technology (Mode Value)			Net Reduction [%]
				CO_2 Emissions [kg/Year] [3]	CO_2 Storage [kg/Year] [3]	CO_2 Emissions [kg of CO_2/m^3 of Concrete]	
Both structural and non-structural elements	806,400,000	3,418,505	236	7,320,000	80,980,000	215	9.1%
Only non-structural elements	395,884,741	1,882,160	210	3,700,000	38,800,000	192	8.9%
Only non-structural concrete with a cement dosage of 150 kg/m^3 (virtual scenario)	237,152,107	1,882,160	126	2,216,460	23,242,881	115	8.9%

Notes: [1] assuming 840 g of CO_2 per kg of cement and data from Table 1; [2] assuming the corresponding cement dosage; [3] using data from Figures 7–9.

Before discussing the impact of the carbonation curing process on the overall CO_2 emissions, it is noteworthy to remark about other results expressed in Table 4. Portugal presents a CO_2 emission estimate of 236 kg/m^3 of concrete when both structural and non-structural precast concrete elements are considered. This value was estimated considering only CO_2 emissions from the cement manufacturing operation which, as previously mentioned, was responsible for an average of 87.5% of the total CO_2 emissions [7–9]. Therefore, an estimate of around 270 kg of CO_2 per m^3 of concrete is obtained if considering the entire chain of the concrete production. This value is smaller than the 300 kg/m^3 of CO_2 per m^3 of concrete usually considered in the literature, which is based on the most common cement dosage of 350 kg of cement per m^3 of concrete [2,4–6]. Conversely, the value of 270 kg of CO_2 per m^3 of concrete considers the distribution of concrete throughout the different cement dosages and is a better estimate of the CO_2 emission of concrete production.

Table 4 also shows that, in the scenario of carbonating both concrete element types, this CCUS technology reduces the amount of CO_2 released per m^3 of concrete from 236 kg to 215 kg, a reduction of about 9.1% of the CO_2 emissions into the atmosphere. When considering only the non-structural concrete elements, the reduction in CO_2 emissions presents a similar value of about 8.9%; however, since the average cement dosage per volume of concrete is smaller, the reduction in CO_2 emissions changes from 210 kg to 192 kg of CO_2 per m^3 of concrete. This result is especially important because it demonstrates the effect of the cement dosage per volume of concrete on the overall CO_2 emissions, in addition to the impact of the carbonation process. In fact, if all the non-structural concrete elements were be produced with a cement dosage of 150 kg/m^3 of concrete, the introduction of the carbonation curing process would lead to a reduction in the overall CO_2 emissions of over 45%, from 210 to 115 kg of CO_2 per m^3 of concrete.

Despite the practical viability of storing carbon during the curing stage of the concrete production process, a large surplus of captured CO_2 will still have to be managed necessitating other solutions. In particular, the production of concrete with a lower cement dosage seems to uncover a non-negligible pathway towards the pursuit of carbon neutrality in concrete production. Naturally, this strategy essentially applies to non-structural concrete products, which represent around half of the entire cement consumption in the case of the Portuguese precast industry (Table 1). The abovementioned lower performance demands of these products facilitate the introduction of new and disruptive carbon mitigation technologies in their manufacturing process.

4. Conclusions

The present research assesses the carbon balance regarding the use of concrete to store captured CO_2. The estimations are calculated on the basis of the assumption that carbon capture will become mandatory in many industries in the future, including the cement industry, which is one of the largest emitters globally. In this context, CO_2 will become a waste that needs to be managed, and the costs (economical and environmental) can be discarded from the analysis. This assessment, applied to the Portuguese precast concrete industry, provided the following conclusions:

- Storing carbon in precast elements is beneficial for reducing CO_2 emissions from the precast concrete industry.
- The carbonation curing of precast concrete is viable, assuming that CO_2 will become a waste product in the future.
- Additional emissions from carbonation curing are only 10% of the stored amount, resulting in an average net reduction of 90%.
- The Portuguese precast concrete industry has the potential to store 76,000 tonnes of CO_2 yearly.
- The overall net reduction in the concrete life cycle averages 9.4% and 8.8% for precast elements and non-structural elements only, respectively.
- A low cement dosage, coupled with carbonation curing technology, produces an estimated net reduction in carbon of 45%.

Hence, this work demonstrates the practical viability of storing carbon in concrete during the curing stage of the process in the near future. Even though the carbonation curing process produces a carbon balance with a positive net reduction in emissions within the precast concrete industry, the overall CO_2 balance is still negative as a result of the manufacture of cement. The estimate of about 200 kg of CO_2 per m^3 of concrete (the average between the situations studied) obtained after the carbonation curing technology is applied will have to be managed by coupling this technology with other carbon mitigation solutions, e.g., reduced cement dosage.

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