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ARTICLE

A study on the contribution of structural concrete to reduce carbon dioxide emissions of the demand side

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Abstract

The CO_2 emitted by concrete, the main material used in structural concrete, is emitted in various processes in its supply chain. Therefore, reducing CO_2 emissions is not just a matter for the supply side, namely cement and concrete manufacturers, but also concerns the demand side including designers, contractors, and the structure owners. However, how much of the reduction in CO_2 emissions should be shared between the supply and demand sides? In this article, the net zero roadmap for concrete by 2050 published by the GCCA, a Global Cement and Concrete Association, and the National Institute for Environmental Studies in Japan, is analyzed to clarify the contribution of supply and demand sides to the reduction of CO_2 emissions. Furthermore, estimates have been made of the reduction in CO_2 emissions for concrete, which is the main material used in structural concrete, and for reinforcing steel, although data is insufficient. And a proposal is made for the indicators that each member of *fib* should aim for. This will make it possible to visualize the CO_2 emissions reduction effects that each member organization can show to stakeholders and motivate the development and implementation of new technologies that contribute to low-carbon and decarbonization.

KEYWORDS
benchmark, decarbonization, demand side, roadmap, supply side

1 | INTRODUCTION

We have now entered the fifth year since the rush to declare global carbon neutrality in 2020. However, we are seeing frequent news reports of natural disasters occurring all over the world. It is said that this is the result of climate change caused by global warming due to greenhouse gases emitted by humans.[1] In addition, Global greenhouse gas emissions decreased during the pandemic in 2020, but subsequently returned to previous levels, reaching a record high of 57.1 Gt of carbon dioxide equivalent in 2023.[2] And now, the 1.5°C scenario of the Paris Agreement to curb global warming is an impossible level of achievement, given that the average global temperature is actually rising by 1.55°C.[3]

In this situation, the world's financial institutions are actively creating rules. For example, the Glasgow Financial Alliance for Net Zero (GFANZ),[4] established in 2021, brings together more than 500 of the world's leading financial institutions and requires the disclosure of

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non-financial information up to Scope 3. Companies involved in construction must also be aware that the same kind of pressure from stakeholders is just around the corner. The author has previously advocated the need to consider the decarbonization and low carbonization of structural concrete throughout its entire lifecycle.[5] And recently, it has become important to consider reducing CO_2 emissions not only in terms of embodied carbon, but also in terms of whole-life carbon.

In the context of the recent trend toward reducing CO_2 emissions, countries and regions such as the EU,[6] Germany,[7] Australia,[8] and India[9] have released their own roadmaps towards carbon neutrality for concrete by 2050. The *fib*, an organization of researchers and practitioners of structural concrete, published the *fib* Roadmap to Carbon Neutrality by 2050 in 2024.[10] It aims to achieve 50% by 2035 and net zero by 2050, starting from 2020. The *fib*'s members consist of material manufacturers, designers, builders and owners. They will work to reduce CO_2 emissions in their respective positions, using this roadmap as a guide.

Net zero for concrete will be achieved through a combination of various technologies. And so far, various decarbonization and low-carbon elemental technologies have been introduced. However, the big question is what level of reduction the concrete demand side should contribute to. Note that in this study, the "demand side" refers to the stakeholders involved in the design, specification, construction, and use of concrete structures—such as designers, contractors, and structure owners—who influence material choices and quantities. Structural concrete, which accounts for around 57% of all cement,[11] emits CO_2 equivalent to 3% of humanity's annual emissions. And how much of that is emitted in each of the lifecycle modules A to D? And what is the ratio between the supply side, which manufactures the concrete, and the demand side, which uses it? At present, this information is not organized.

In this article, based on data from the Global Cement and Concrete Association (GCCA) and the National Institute for Environmental Studies (NIES) in Japan, the specific amount of CO_2 emissions that should be reduced by the demand side is examined. In addition, reinforcing bars and prestressing steel are also used. However, information on roadmaps for reducing CO_2 emissions from steel is extremely limited. This study therefore estimates the potential contribution of the demand side to reducing CO_2 emissions from structure concrete, based on available references. Furthermore, considering cases where the demand side discloses information to stakeholders in various countries and organizations, the concept of benchmark indicators is examined using the *fib* roadmap as an example.

2 | ANALYSIS OF THE CARBON NEUTRALITY OF CONCRETE ESTIMATED BY THE NATIONAL INSTITUTE FOR ENVIRONMENTAL STUDIES IN JAPAN

NIES investigated the amount of CO_2 emissions from concrete in Japan in 2019 and presented a scenario for achieving net zero by 2050.[12] To do this, they used the dynamic material flow analysis model and an associated CO_2 emissions model to estimate the amount of CO_2 emissions. Figure 1 shows the pathway to achieving carbon neutrality in the cement and concrete sector in Japan as presented in Reference [12]. The numerical values and demand side highlighting within the figure were added by the author. This estimate is based on a detailed breakdown of 13 items, including conventional and emergency strategies on the supply side and material efficiency strategies on the demand side. The contribution of each decarbonization strategy was created based on the supplementary information in Reference [12]. Table 1 details the breakdown of the reduction contribution from the demand-side strategies.

In the case of Japan, CO_2 emissions from concrete in 2020 are 31.3 $MtCO_2$ (23.3 $MtCO_2$ + 8.0 $MtCO_2$), and by 2050 they are 27.6 $MtCO_2$ (19.8 $MtCO_2$ + 7.8 $MtCO_2$). The carbon sink of concrete is calculated using physical and chemical models such as those in Reference [13]. And the calculation estimates the carbon sink capacity for 2050 at 7.8 $MtCO_2$.

In addition, demand-side strategies have a larger contribution from material-efficient design and more intensive use, at 9% and 11%, respectively. Lifetime extension accounts for 4%, and construction waste reduction and end-of-life options account for 1% combined. In other words, the strategy for achieving net zero for concrete in Japan by 2050 requires a 25% contribution from the demand side.

Japan's estimated CO_2 emissions by 2050 is 19.8 $MtCO_2$. And since the contribution of the demand side is 25%, this becomes 5 $MtCO_2$. Assuming that 57% of this is CO_2 emitted from structural concrete, this is 2.9 $MtCO_2$. If this is divided by the ratio of decarbonization strategies, the figures are calculated as follows: material-efficient design 1.0 $MtCO_2$, construction waste reduction 0.1 $MtCO_2$, more intensive use 1.2 $MtCO_2$, lifetime extension 0.5 $MtCO_2$, end-of-life options 0.1 $MtCO_2$.

NIES is also conducting research on the limits of quantity and quality in the zero emissions of steel in Japan.[14] It also concludes that the current supply volume cannot be met at all unless the transition from blast furnaces to electric furnaces is implemented boldly. The steel used in structural concrete is reinforcing bars and

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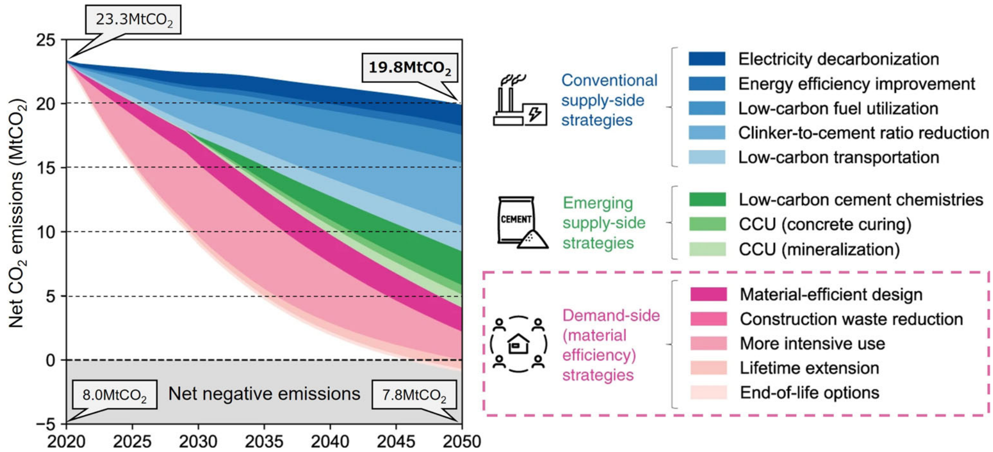

FIGURE 1 Role of supply and demand-side strategies of CO_2 emissions.[12]

TABLE 1 Breakdown of demand side strategies.[12]

Demand side (material efficiency) strategies	%	Demand side concrete ($MtCO_2$)	Structural concrete × 57% ($MtCO_2$)
Material-efficient design	9%	1.8	1.0
Construction waste reduction	0.5%	0.1	0.1
More intensive use	11%	2.2	1.2
Lifetime extension	4%	0.8	0.5
End-of-life options	0.5%	0.1	0.1
Total reduction of demand side	25%	5.0	2.9

prestressing steel, and most of it is electric furnace products. It states that infrastructure can achieve zero emissions through efficient design measures such as reducing the amount used as the case of concrete, even though the supply volume will decrease. And if the electricity for electric furnace products can be covered by renewable energy, CO_2 emissions will be greatly reduced. Unlike the case of concrete, the NIES study on steel does not provide detailed measures to be taken by the supply and demand sides. However, efficient concrete design can similarly reduce the need for reinforcing steel. Therefore, the analysis in Section 5 proceeds under the assumption that the reduction contribution from CO_2 emissions using reinforcing steel in structure concrete is the same as that from concrete itself.

3 | ANALYSIS OF THE GCCA'S ROADMAP TO 2050

The GCCA, an organization made up of cement and concrete manufacturers, published the roadmap to 2050 Net Zero and seven decarbonization levers in 2021[15] (Figure 2). The figures in the diagram are added by the author. According to this, the total amount of concrete used by 2050 is estimated to be 20 billion m^3, with CO_2 emissions of 3.8 $GtCO_2$, or about 1.4 times the amount in 2020.

The largest contribution in the GCCA roadmap is made by carbon capture utilization/storage (CCUS), which contributes to module A, at 36%. This differs significantly from the NIES study. It is estimated that the contribution will increase significantly from 2030, reaching 1370 $MtCO_2$ by 2050. The next largest contribution is expected to come from the efficiency of design and construction, which is related to all modules, and is expected to be 7% by 2030 and 22% by 2050. This is followed by efficiency in concrete production, which contributes to module A, at 11%, savings in cement and binders at 9%, savings in clinker production at 11%, and de-carbonation of electricity at 5%. Furthermore, the amount of carbon sink contributed by modules B, C, and D is estimated to be 318 $MtCO_2$ by 2030 and 242 $MtCO_2$ by 2050, which is 6%. This decrease is due to the impact of the reduction in clinker worldwide. The carbon sink is estimated based on the IVL methodology,[16] and the lower limit is adopted as a conservative value. What is notable about the GCCA roadmap is that the CCUS, we have been expecting, even if it is a conservative value, is not a magic wand.

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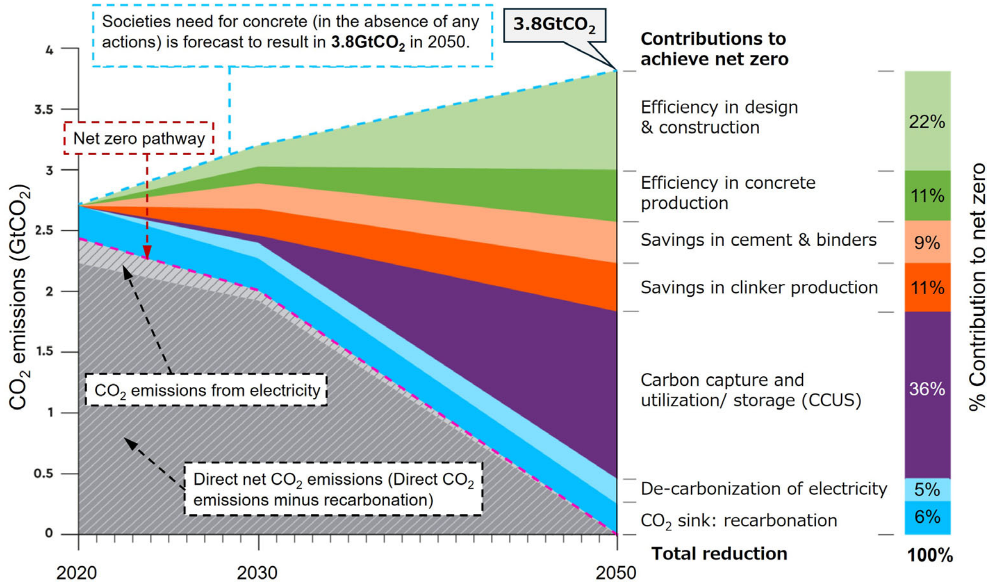

FIGURE 2 Net zero pathway of CO_2 emissions by Global Cement and Concrete Association.[15]

TABLE 2 contribution of each of the seven decarbonization levers.[15]

Decarbonization levers	Module A	B	C	D	%	Demand side concrete ($MtCO_2$)	Structural concrete × 57% ($MtCO_2$)
Efficiency of design and construction	✓	✓	✓	✓	22%	840	480
Efficiency in concrete production	✓				11%	—	—
Savings in cement and binders	✓				9%	—	—
Savings in clinker production	✓				11%	—	—
Carbon capture utilization/storage (CCUS)	✓				36%	—	—
Decarbonization of electricity	✓				5%	—	—
CO_2 sink (recarbonation)		✓	✓	✓	6%	—	—

Table 2 shows the contribution of each of the seven decarbonization levers considered by the GCCA, along with the relevance of each module within the supply chain.[15] Among these decarbonization levers, those on the demand side, using the same definition as the NIES study in the previous section, are efficiency of design and construction. In the future, the specific percentages for each module and the contribution of the supply and demand sides in module A will become clear, but for now, this is considered to be decarbonization levers that the demand side will contribute to. The total is 22%. In 2050, 22% of the 3.8 $GtCO_2$ emissions, is 840 $MtCO_2$. Therefore, the remaining 2960 $MtCO_2$ represents the contribution from the supply side. Since 57% of cement is used for structural concrete, this proportion is considered the CO_2 emitted. Thus, the demand side accounts for 480 $MtCO_2$ and the supply side for 1690 $MtCO_2$.

4 | THE AMOUNT OF CO_2 EMISSIONS THAT MUST BE REDUCED BY THE DEMAND SIDE

The above is an analysis of the NIES estimates for Japan and the GCCA roadmap. The NIES study shows demand-side strategies accounting for 25%, whereas the GCCA's demand-side decarbonization lever is 22%, which is almost the same. Now that the 1.5°C scenario has become impossible to achieve, this demand-side strategy, which can be implemented immediately, should be pursued first. It is crucial that those on the demand side—designers, builders, and structure owners—recognize this and proactively collaborate, starting with actions feasible now.

Strategies for reducing CO_2 emissions on the supply side will be briefly discussed. In Japan, the development of low-carbon concrete technology is progressing in

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construction companies and cement manufacturers. Concrete that reduces the amount of clinker by substituting by-products and non-clinker concrete[17] used in structural concrete are already available. However, the situation for this lever differs depending on the industrial structure of each country. In the case of Japan in particular, blast furnace slag, a by-product of the steel industry, and fly ash from thermal power plants can be used. Although the low-carbon and decarbonization of both of these sectors is still a work in progress, it is significant that the construction sector is actively using these by-products to reduce Japan's overall CO_2 emissions. Low-carbon concrete requires the understanding and cooperation of the demand side.

In terms of carbon sink, the GCCA and NIES are contributing 242 and 7.8 $MtCO_2$ by 2050, or 6% and 28%, respectively. GCCA has adopted a lower limit of 105 $kgCO_2/t$ by applying 20% recarbonation to the theoretical maximum amount of carbonation per ton of clinker (525 $kgCO_2/t$).[15] Based on this, GCCA has derived the estimated value for 2050 by taking into account the decrease in the total amount of clinker by 2050. However, if evaluation technology for recarbonation is established in the future, this contribution amount will increase even further. On the other hand, NEIS has a CO_2 sink of 8.2 $MtCO_2$ and a clinker production volume of 33.1 Mt in 2019,[12] which is 250 $kgCO_2/t$ clinker, 2.4 times that of GCCA. The CO_2 sink of 7.8 $MtCO_2$ in 2050 is calculated by taking into account domestic consumption and in-use stock of concrete.[12]

How to consider the carbon sink in the roadmap will be a matter for individual countries and organizations to decide. However, at a time like Japan's, when the future of CCUS on the supply side is unclear, it is urgent to establish a quantitative evaluation method for carbon sink. This will make it possible to calculate the amount of carbon sink that will change depending on the difference in concrete treatment after demolition as well as during the use stage, at the design stage.

Carbon neutrality is a goal that should be achieved through the efforts of each sector and each organization in a globalized world, and ultimately the liability of each country. The author has been advocating that carbon neutrality should be addressed throughout the supply chain of structural concrete. To this end, it is important for organizations such as the GCCA and NIES to clearly estimate the reduction measures that take into account social changes by 2050. In particular, as shown above, the amount of reduction contribution by each sector on the demand and supply sides can be clarified by using these indicators. This makes it possible to visualize each measure of reduction and its contribution toward achieving net zero by 2050. And for private companies that are required to disclose non-financial information on Scope 3, visualization is a great help in terms of governance.

5 | PROPOSAL FOR THE TARGET VALUE FOR REDUCING CO_2 EMISSIONS THAT THE DEMAND SIDE AIMS TO ACHIEVE

From the analysis of the two roadmaps above, it was found that the demand side of concrete will be required to contribute to a reduction in CO_2 emissions of 22% to 25%. Here, using *fib* as an example—whose membership consists almost entirely of demand-side stakeholders—we consider what level of CO_2 emission reduction should be targeted. Figure 3 is the roadmap published by *fib* in 2024, which covers the period up to 2050.[10] The *fib* does not aggregate the CO_2 emissions of all its members. Therefore, the frame is set so that the CO_2 emissions in 2020 from the entire supply chain are 100%, with the aim of reducing this to 50% by 2035 and achieving net zero by 2050. In addition, although the timeframe is set for each module, the ratio differs depending on the country and structure, so this is a concept. This is thought to be in order to correspond to the scope of the GHG (Green House Gas) Protocol[18] so that the scope of the liability of each player in the supply chain to reduce CO_2 emissions is clear.

The *fib* brings together members who cover almost the entire range of the supply chain for structural concrete, including material suppliers, designers, constructors, and owners of structures. However, *fib*, which is a federation of structural concrete formed by 41 national member groups, differs in scale from the GCCA, which is an association for cement and concrete from around the world. Therefore, the amount of CO_2 emissions reduction is also different, but as the *fib* covers the major CO_2 emitting countries using concrete, the values of the GCCA are used as a basis to take hold of the order of magnitude. As mentioned earlier, to calculate the amount of CO_2 emissions from structural concrete using the GCCA figures,

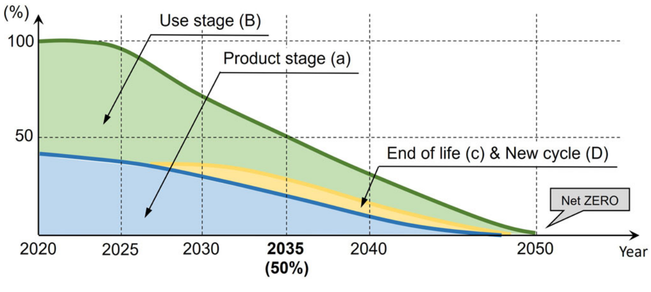

FIGURE 3 *Fib* timeframe for carbon neutrality by 2050.[10]

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the diagram of Reference [19] will be used, as shown in Figure 4. This diagram shows the CO_2 emitted by the concrete, reinforcing steel, and prestressing steel in a typical prestressed concrete girder. These are 0.36, 0.21, and 0.13 tCO_2/m^3 of concrete, respectively, totaling 0.70 tCO_2/m^3. As discussed in Section 2, the contribution of reinforcing steel to reducing CO_2 emissions on the demand side is considered equivalent to that of concrete. Therefore, the coefficient to use for estimating the contribution of reinforcing steel to reducing CO_2 emissions from the concrete value is 0.34/0.36 = 0.9. Table 3 shows the calculation results. The CO_2 emission reduction contribution required from the demand side for structure concrete is 480 $MtCO_2$ for concrete and 430 $MtCO_2$ for reinforcing steel, totaling 910 $MtCO_2$. These represent 53% and 47%, respectively.

Figure 5 shows breakdown of the total estimated CO_2 emissions from concrete by 2050 (3.8 $GtCO_2$, per GCCA roadmap), indicating the proportional contributions expected from *fib* members on the demand side (designers, builders, and owners) versus the supply side (cement and concrete producers) (refer Appendix A) Of these, the demand side will contribute 840 tCO_2 (22%) and the supply side will contribute 2960 $MtCO_2$ (78%) toward the CO_2 emission reductions using concrete. Since 57% of this is to be used in structure concrete, the CO_2 emission reduction contribution attributable to structural concrete amounts to 480 $MtCO_2$ from the demand side and 1690 $MtCO_2$ from the supply side.

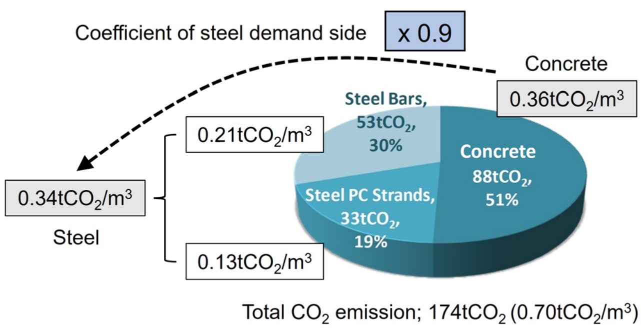

FIGURE 4 CO_2 emission share by different material components of a conventional prestressed concrete bridge.

Furthermore, adding the 430 $MtCO_2$ reduction contribution using reinforcing steel, the total demand-side figure is 910 $MtCO_2$. Thus, the total CO_2 reduction contribution structural concrete should achieve is 2600 $MtCO_2$, comprising this 910 $MtCO_2$ plus the 1690 $MtCO_2$. The ratio between the demand side and supply side is 35% and 65%, respectively.

Having established the CO_2 emission reduction contribution of structure concrete on both the demand and supply sides, the next step is to set the baseline benchmark for 2020. The 2020 benchmark of 400 tCO_2/million € shown in Figure 5 is an indicator of CO_2 emissions per million € of construction costs, based on the UK bridge database presented by the author in Reference [5]. This indicator represents the relationship between cost and CO_2 emissions, derived by the author based on data from Reference [20], as shown in Figure 6. The regression line and corresponding cost figures were added by the author. Although the data in this reference is in tCO_2e, for concrete this is almost equivalent to tCO_2, so it will henceforth be treated as tCO_2. This includes CO_2 emissions from the construction stage (modules A4 and A5), but as these are small compared to the material production stage (modules A1–A3), they are ignored here. The numerator of this indicator corresponds to the sum of the demand side (910 $MtCO_2$) and supply side (1690 $MtCO_2$) shown in the figure. Breaking down the indicator by this ratio gives a demand side of 110 tCO_2/mn€ and a supply side of 290 tCO_2/mn€. Therefore, the demand side should contribute 35% of the CO_2 emission reduction target relative to the 2020 baseline benchmark. Under the demand-side definition outlined thus far, the remaining 65% falls within the uncontrollable supply-side domain. However, collaboration between demand and supply sides enables the development of low-carbon concrete and quantitative assessment methods for carbon sink. Carbon sink, currently underestimated by the GCCA, will allow for more precise evaluation as research advances, making information exchange between both sides crucial.

Next, using *fib*'s roadmap, how the benchmark evolves can be examined. Figure 7 shows estimated CO_2 emissions reduction targets for *fib* members (demand side) and the corresponding supply side in the structural

TABLE 3 CO_2 emissions from structural concrete that should be reduced by demand side.

Decarbonization levers	Demand side concrete for SC ($MtCO_2$)	Coefficient of steel demand side	Total of structural concrete ($MtCO_2$)	Ratio to total
Efficiency of design and construction	480	—	480	53%
		× 0.9	430	47%
			910	

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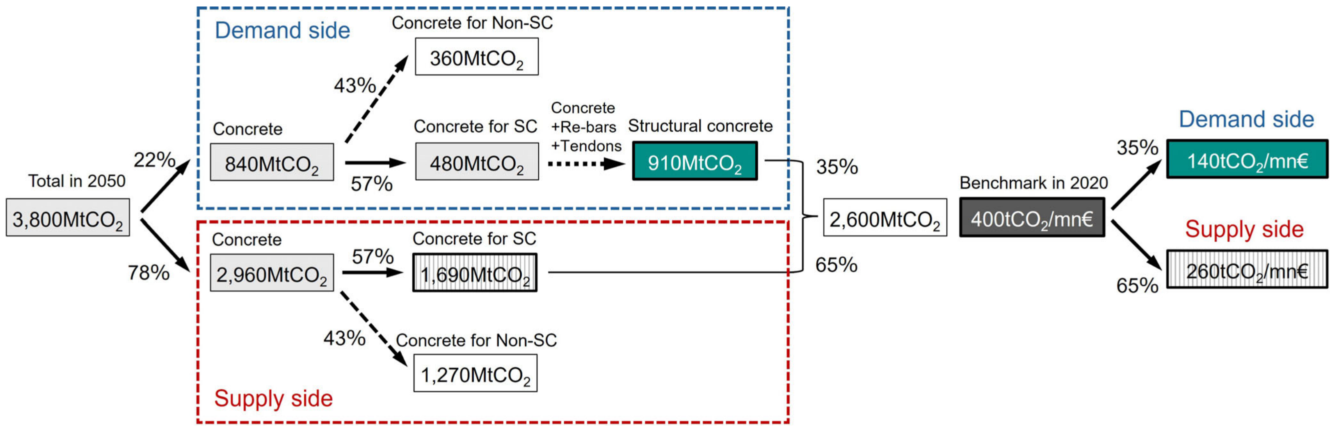

FIGURE 5 Breakdown of the total estimated CO_2 emissions from concrete by 2050.

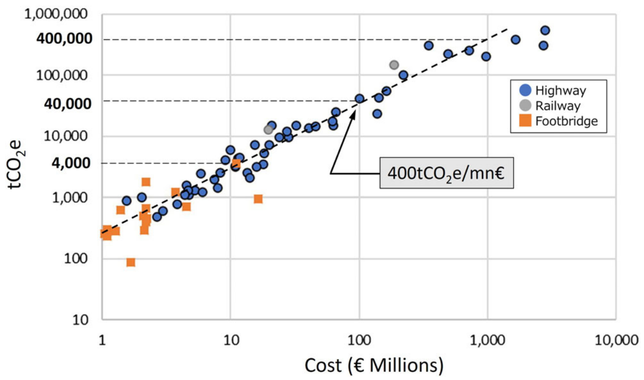

FIGURE 6 Relationship between CO_2 emission and bridge construction cost.[20]

concrete sector, benchmarked against construction cost. The 2020 indicators are 140 tCO_2/mn€ for the demand side and 260 tCO_2/mn€ for the supply side. The targets for 2035 are 70 and 130 tCO_2/mn€, respectively. These benchmarks incorporate emissions from both concrete and reinforcing steel, adjusted using *fib*'s estimated material ratios and economic assumptions, and are intended as guidance for national *fib* groups to define localized decarbonization targets. It is noted that while steel reinforcement is included in demand-side estimates, the treatment is less rigorous compared to concrete. This impression can be partly attributed to semantics (concrete vs. structural (reinforced/prestressed) concrete), but never the less the paper could benefit from expanding discussion by including steel decarbonization pathways and design-based reductions for reinforcing/prestressed materials. To use the ratios shown in Table 3 for the 2020 and 2035 demand-side benchmarks, the figures broken down into concrete and reinforcing steel are presented in Table 4. This visualizes the CO_2 emission reductions that the structure concrete demand side should contribute.

The above proposal utilizes a database of bridges in developed countries. Naturally, the benchmarks will fluctuate depending on the project type and economic conditions in each country, such as exchange rates and consumer prices. Incidentally, based on the limited data available from the author's company, the level for tunnels is around 250–300 tCO_2/mn€. The diagram shown in Figure 8 represents the circumferential direction of the pie chart as the proportion of CO_2 emissions for each country and region, while the radial direction shows CO_2 emissions divided by their respective GDP (Gross Domestic Product) converted to US dollars.[5] The global average is 434 tCO_2/mn\$. The divergence in trends between developed and developing countries suggests that a country's industrial structure, exchange rate against the US dollar, and consumer prices are larger factors. While CO_2 emissions from concrete structures built in different countries do not vary greatly, the indicator's denominator changes according to economic conditions, meaning that a different setting is required for each country.

This study presents a proposal for an indicator per million euros, though of course alternatives such as per ton, per cubic meter, or per square meter are also conceivable. Research specifically concerning building benchmarks has already been reported, utilizing CO_2 emissions per floor area.[21–23] However, based on roadmaps outlining reduction strategies, such as those presented by the GCCA or NIES, it is first necessary to clarify the contribution to demand-side reductions using the approach presented here. Thus, the demand side for structural concrete should independently set its 2020 benchmark according to each country's economic situation and the roadmap presented by relevant bodies. It should then manage its contribution, recognizing its liability scope, by ensuring alignment with the roadmap's pathway.

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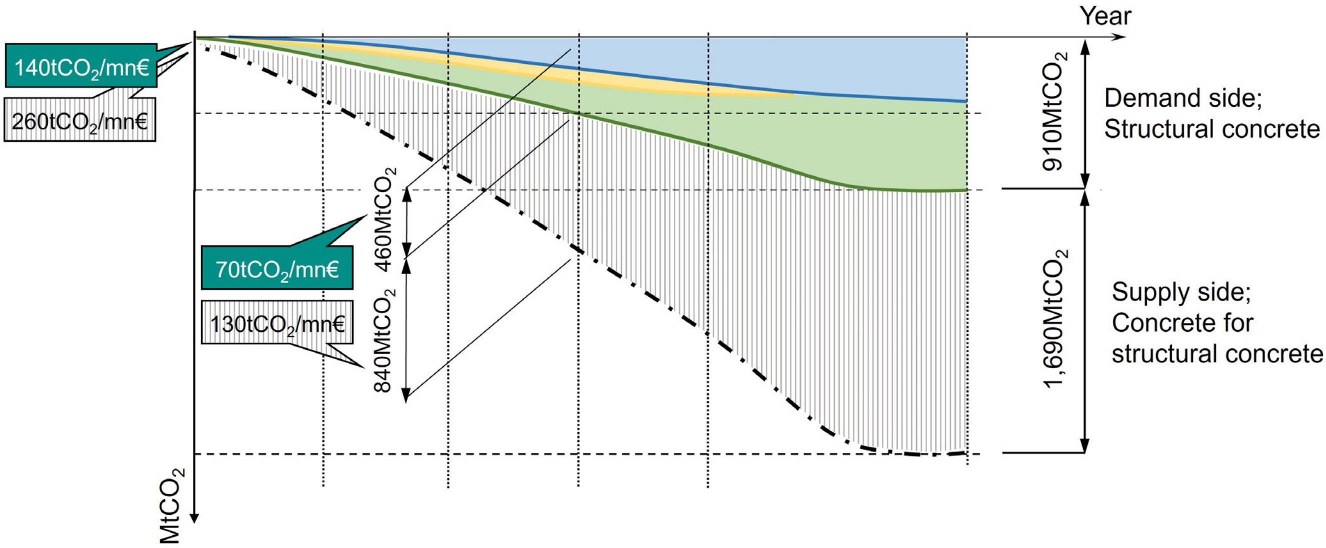

FIGURE 7 CO_2 emissions reduction targets for *fib* members and the corresponding supply side in the structural concrete sector.

TABLE 4 Breakdown into concrete and reinforcing steel and progress of benchmarks.

(CO_2/mn€)	2020			2035		
Demand side	140	Concrete	74 (53%)	70	Concrete	37 (53%)
		Re-bar + tendon	66 (47%)		Re-bar + tendon	33 (47%)

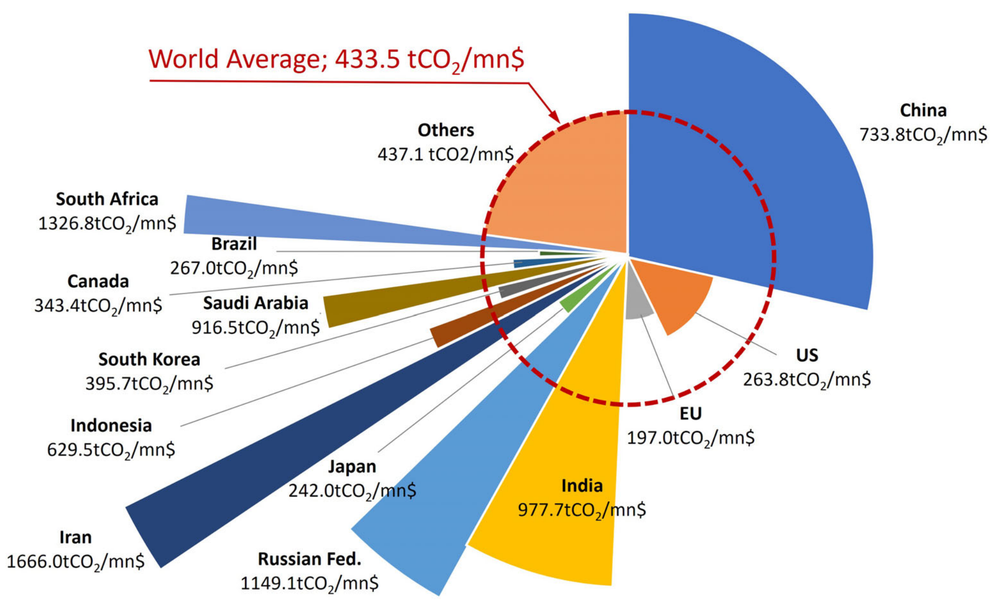

FIGURE 8 CO_2 emissions per 1 million USD of GDP for each country.

6 | MEASURES TO REDUCE CO_2 EMISSIONS FOR NEW AND EXISTING STRUCTURES

Measures to reduce new structures include the active use of low-carbon concrete and the ultra-high durability of structures. However, the substitution of by-products needs to be promoted with local production for local consumption, while recognizing the limits of supply. Reuse is also important, especially in terms of dismantling structures that are easy to disassemble, with a view toward remanufacturing.[24] There are limits to simply

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reducing the thickness of structural members, so creativity is needed to achieve significant weight reduction, as in the example of a bridge where the concrete in the lower structure was reduced by 50% through creative design of the superstructure.[25] These measures are decided at the design stage. Good communication between suppliers, designers, constructors, and the owner of the structure is essential, and all players must work with the same sense of purpose. In addition, standards for low-carbon concrete are gradually being established,[26–28] and its use can be expected to increase in the upcoming years. It should also be noted that precast products are easy to introduce with low-carbon concrete. Precast products, which account for 25% of structural concrete,[7] have great potential for reducing CO_2 emissions in terms of ease of adoption of low-carbon concrete, which is an urgent issue. In addition, they are an extremely effective construction method not only for accelerated construction but also for making up for the global shortage of manpower. It is essential to increase the ratio of precast concrete even further and contribute to reducing CO_2 emissions as soon as possible.

Measures for reducing existing structures should prioritize extending the life of structures and changing their functions rather than demolition, and maintenance and reinforcement should be carried out using low-carbon materials. And setting up a platform like the Dutch National Bridge Bank[29] is also effective for promoting reuse. Research conducted in Germany indicates that there exist construction periods where indirect CO_2 emissions due to construction activities having an impact on social activities are larger than the CO_2 directly emitted by the construction work itself.[30] This is the user carbon that applies to the infrastructure referred to as user's utilization of infrastructure in the module B8.[31] Since conservation work is carried out according to the needs of the owner, the CO_2 emissions referred to as this user carbon, which are caused indirectly by traffic congestion and detours due to the conservation, must be reduced under the liability of the owner. To achieve this, it is effective to choose to shorten the construction period as much as possible. In the case of infrastructure, in the policy decision-making process of prioritizing structures to be conserved, it is necessary to solve the optimization problem of a multi-objective function, such as the importance, conservation cost and CO_2 emissions, and the economic loss and CO_2 emissions when the function is lost. Research has already commenced on sustainability-centered decision-making for existing structures,[32] multi-criteria decision analysis,[33] and probabilistic approaches to budget allocation in seismic regions.[34] These studies are urgently needed from a carbon neutrality perspective.

7 | STRATEGY AND CHALLENGES FOR THE DEMAND SIDE

The contributions shown above are a rough analysis. As previously mentioned, it is important for companies to demonstrate to stakeholders that actual reductions are being achieved through CO_2 emission reduction measures. In the future, accurate figures will be calculated in detail by each country and organization. However, this will take time. The purpose of this study is to establish early on what strategies to adopt from among the limited measures available on the demand side. Efficient design can be started immediately. And it has become clear that significant expectations are being placed on this strategy. The use of low-carbon concrete is effective, but it is advisable to start with precast concrete, which is easier to adopt. Furthermore, research is needed on the development and evaluation of precise analytical tools that take into account differences in concrete mixes, climate conditions, and environmental factors regarding the CO_2 sink of concrete. The goal is to incorporate this approach into the EU Taxonomy. This will take time, so it is essential to begin immediately. *fib*, the international association for structure concrete, should explicitly communicate these matters to its members as *fib*'s strategy, thereby serving as a sound guide for strategy development for each country and organization. By doing so, *fib*'s goal of halving CO_2 emissions on the demand side by 2035 and achieving net zero by 2050 is not impossible.

From now on, companies will have to disclose their CO_2 emissions not only for Scope 1 and Scope 2, but also for Scope 3 as non-financial information. CO_2 emissions from corporate activities will be aggregated and disclosed for each scope on an annual basis. However, companies grow. Even if they are becoming more low carbon, their total CO_2 emissions may increase if their sales increase. And if this continues, the company's stakeholders will not be satisfied. As shown earlier, in order to resolve this dilemma, Benchmarks based on 2020 should be defined and presented for each structural type. Indicators could consider CO_2 emissions per square meter of structure, per ton, per cubic meter, or per construction cost. Of course, the effect of rising consumer prices needs to be removed from construction costs. Then, the results of the reduction from this benchmark will be shown to

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stakeholders as an indicator, and the path of the contribution amount on the demand side proposed in Figure 7 will be visualized.

Another issue is carbon credits. Reducing CO_2 emissions through low-carbon concrete is difficult to prove. At this stage, measures to reduce CO_2 emissions will be certified by Environmental Product Declaration (EPD) and the reduction amount will be demonstrated by scientific reasons. In response, structure owners will set internal carbon pricing and pay designers and builders for their efforts. This provides an incentive for the use of new low-carbon technologies. Carbon pricing is linked to carbon taxes and border environmental taxes In Europe, where the carbon credit market is well-established, prices range from €60 to €80 per tCO_2. In contrast, Japan's credit market will commence operations in 2026, but its carbon taxation system remains underdeveloped, resulting in a low carbon price. Appropriate carbon pricing is essential for advancing the development and adoption of low-carbon and decarbonization technologies, in order to reduce CO_2 emissions from concrete as swiftly as possible.

United Nations Environment Programme (UNEP) has been saying since an early stage that economic growth and the use of natural resources and environmental impact can be decoupled.[35] In other words, it is the decoupling of economic growth and climate change. In addition, the World Economic Forum has shown through data that GDP and GHG emissions are decoupled in developed countries.[36] The driving force for achieving decoupling, which is to reduce CO_2 emissions while achieving economic growth, is new technology related to low-carbon and decarbonization of concrete. The demand side, which bears the responsibility for achieving a quarter of the overall reduction target, has a major responsibility.

8 | CONCLUSIONS

The results of this study can be summarized as follows.

1. By comparing the GCCA and Japan's NIESs' roadmaps for concrete to achieve carbon neutrality by 2050, this study clarified the contribution of demand side (designers, builders, and owners) and supply side (cement and concrete producers) to reducing CO_2 emissions. It was found that the demand side is expected to contribute one-quarter of the total reduction.
2. The pathway to net zero of NIES in Japan expects a contribution of 25% and 2.9 $MtCO_2$ on the demand side of structural concrete. The larger expected reductions are material-efficient design and more intensive use
3. The GCCA roadmap expects the demand side of structural concrete to contribute to a reduction of 22%, or 480 $MtCO_2$. The reduction measure is efficiency of design and construction. This ratio is almost the same as the NIES study.
4. Based on the GCCA roadmap, the reduction in CO_2 emissions from concrete and reinforcing steel in structure concrete was estimated. This is equivalent to 910 $MtCO_2$. Since reinforcement steel accounts for 47% of CO_2 emissions in structural concrete, research is needed to clarify the contribution of demand-side reductions in reinforcement steel. It is important to start as soon as possible with efficiency of design and construction and the active use of low-carbon concrete.
5. For designers and builders, the setting of internal carbon pricing by the structure owner, and payment for the reduction achieved, provides an incentive for the development and adoption of low-carbon and decarbonization technologies to be.
6. Progress towards decarbonization is monitored using benchmark indicators, and disclosed to stakeholders alongside the total annual CO_2 emissions. It is crucial to consistently demonstrate adherence to the pathways outlined in the referenced roadmap. This is essential for decoupling, which is to reduce CO_2 emissions while achieving economic growth.
7. New research themes for structure concrete to be addressed by *fib* include quantitative methods for assessing carbon sink, methods for evaluating the integrity of dismantled components for reuse markets and establishing a component platform and optimization problems for multi-objective functions for policy decision-making.

Each country and organization should define a benchmark, such as 400 tCO_2/million € in 2020, and then use the ratios shown in this article to manage the contribution of demand-side CO_2 reductions on a roadmap. Strategies should be developed using measures appropriate for each country or organization. It is important for international associations such as *fib* to authorize the definition of benchmarks and the concept of the contribution of concrete and reinforcing steel on the demand side to the reduction of CO_2 emissions.

By clarifying the amount of reduction contribution on the supply and demand sides this time will, for example, facilitate communication between *fib* and GCCA, promoting the realization of concrete carbon neutrality as soon as possible. Once the data that

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has not yet been organized is clarified, it will be possible to make more detailed calculations. At that time, it would be a great help if this research could be used to derive specific figures for the amount of CO_2 emissions that demand sides should reduce, and to update them.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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APPENDIX A

The supplementary explanation for the calculations in Figure 5 is as follows.

According to GCCA data, the amount of CO_2 emitted by concrete in 2050 is 3800 $MtCO_2$. Given that the reduction contribution from the demand-side lever "efficiency of design and construction" is 22%, this quantity is calculated as follows:

$$3800 MtCO_2 \times 0.22 = 840 MtCO_2.$$

On the supply side, the calculation is as follows:

$$3800 MtCO_2 \times 0.78 = 2960 MtCO_2.$$

As 57% of this concrete is used for structurals, the respective calculations are:

$$\text{Demand side}: 840 MtCO_2 \times 0.57 = 480 MtCO_2.$$

$$\text{Supply side}: 2960 MtCO_2 \times 0.57 = 1690 MtCO_2.$$

CO_2 emissions from structural concrete on the demand side also include those from reinforcing steel, in addition to the concrete itself. Assuming this quantity is 0.9 times that of the concrete, as shown in Figure 4,

$$480 MtCO_2 \times 0.9 = 430 MtCO_2$$

is estimated. Therefore, the total CO_2 emissions from structural concrete that the demand side should reduce are as follows:

$$480 MtCO_2 + 430 MtCO_2 = 910 MtCO_2.$$

Consequently, the total CO_2 emissions from structural concrete that should be reduced by both the demand and supply sides can be calculated as follows:

$$910 MtCO_2 + 1690 MtCO_2 = 2600 MtCO_2.$$

The respective contribution ratios for reductions on the demand and supply sides become:

$$940 MtCO_2 / 2600 MtCO_2 = 0.35, \text{and}$$

$$1690 MtCO_2 / 2600 MtCO_2 = 0.65.$$

These ratios can be used to divide the structure concrete benchmark between the demand and supply sides to provide respective management indicators up to 2050.

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