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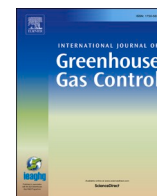
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# Feasibility, conditions, and opportunities for achieving net-negative emissions in the global cement industry

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## ABSTRACT

The cement industry possesses multiple options to decarbonize its operations, including material efficiency, energy efficiency, clinker content reduction, hydrogen utilization, bioenergy, and carbon capture and storage (CCS). By integrating bioenergy and CCS (BECCS), the industry could produce net-negative cement, surpassing the 2050 carbon neutrality pledge of the Global Cement and Concrete Association. In TIAM-FR, a bottom-up optimization model of the global energy system, we developed an explicit model of the global cement industry to analyze the potential contribution of BECCS to producing cleaner cement. We investigated the technical and policy conditions favorable to BECCS deployment and sustainability, considering different future biomass potentials, yields, rotation periods, and management costs. Our findings demonstrate that BECCS can significantly contribute to cement decarbonization, making it easier, quicker, and more cost-effective to achieve. However, the current bioenergy use and policy landscape falls short of meeting the 2050 target. Scaling bioenergy use from 3% of the global energy mix to more than 40%, along with strengthening global climate policies, is essential. By leveraging the potential of bioenergy substitution up to 80% and extensively invest in CCS processes, carbon neutrality in cement production could be advanced by 10 to 18 years, enabling the production of net-negative cement. Finally, we propose a technical roadmap for the decarbonization of the global cement industry.

## 1. Introduction

Cement is the second most consumed product globally in terms of tonnage, after water (“About Cement and Concrete,” 2022), with an estimated production of 4.3 Mt in 2018 (IEA, 2022) and an estimated growth of 40% by 2050 (GCCA, 2022). Cement is mixed with water and gravel to produce concrete, which is then used to build houses, bridges, roads, etc. The manufacturing process involves the decarbonation of limestone ( $\text{CaCO}_3$ ) above 900°C (Bataille et al., 2018) which delivers calcium oxide (CaO) – or clinker – while releasing carbon dioxide ( $\text{CO}_2$ ) – also denoted as process  $\text{CO}_2$  emissions. The clinker is then cooled, blended with aggregates such as limestone or gypsum, and ground into cement. The cement production process, and more precisely the calcination reaction, is particularly difficult to decarbonize as it requires high temperatures, for which cheap, “dense” fossil fuels are usually employed, generating massive amounts of combustion  $\text{CO}_2$ . Besides, cement plants are highly integrated processes, so that any modifications to one segment necessitate corresponding adjustments in other segments of the process (McKinseyandCompany, 2018). Furthermore, these

processes are usually designed for long periods of 40 years on average (IEA, 2020a; Liang and Li, 2012), compounding the risk of stranded assets.

Due to these specificities, the cement industry is included in the list of “hard-to-abate” industries (Kumar et al., 2024). In 2019, the cement industry was responsible for emitting 2.1-2.5 Gt $\text{CO}_2$  globally, of which 60% was process  $\text{CO}_2$ , and the remainder combustion  $\text{CO}_2$  (Bashmakov et al., 2022). The policies, end-use strategies, and technical measures for mitigating cementitious  $\text{CO}_2$  emissions have been assessed extensively in several reviews (Bataille et al., 2018; Habert et al., 2020; Korczak et al., 2022; Kumar et al., 2024; Rissman et al., 2020; Supriya et al., 2023), studies (Georgiades et al., 2023; Kim and Miller, 2023; Olsson et al., 2023; Pisciotta et al., 2023), and reports (CEMCAP, 2016; ECRA, 2017; JRC, 2023; McKinseyandCompany, 2018) quantifying the techno-economic performance of various measures, e.g., through the cost of  $\text{CO}_2$  mitigation, the levelized cost of producing one ton of cement, the potential GHG reduction, or their technological readiness level (TRL).

Regarding policies, the emergence of a global, fair, institutionalized

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policy framework has been called for (Balsara et al., 2021; Bataille et al., 2018; Busch et al., 2022; Nilsson et al., 2021; Rissman et al., 2020) to make the decarbonization of the global cement industry an achievable goal. Regarding demand-reduction strategies, substantial emissions savings of 12-36% could be made by, e.g., extending the lifespan of buildings and designed products, or refurbishing and remanufacturing (Creutzig et al., 2019; Grubler et al., 2018). Technically, the latest IPCC report (AR6) makes a highly confident assessment that material efficiency, cementitious material substitution, and fuel-switching measures are anticipated to reduce cement demand and emissions in the short term, while CCS is seen as the most effective measure to cut CO<sub>2</sub> emissions in the long run (Bashmakov et al., 2022). Using solid, liquid, or gaseous biomass in cement kilns shows the highest TRL of all fuel-switching measures to tackle energy-related emissions.

While bioenergy and CCS are mentioned as distinct strategies, they are poorly considered as a whole, although they could work in tandem to mitigate cement emissions more effectively by generating negative emissions (Cavalett et al., 2021). Combining bioenergy and CCS (BECCS) has been extensively studied in the power sector (Köberle, 2019; Minx et al., 2017) and acknowledged as a key technology to achieve the 1.5°C target (Riahi et al., 2023), although there is limited evidence regarding the industry sector. Hence, this paper aims to address the role of combined bioenergy and CCS (BECCS) in the global cement industry to help achieve the decarbonization of this sector.

In the technical literature, Cavalett et al. (2022) performed prospective life cycle assessments on two cement plants in Sweden and Germany and demonstrated a large potential for BECCS with negative carbon footprints of clinker for biomass substitution rates up to 80%. In contrast, (Yang et al., 2021) assessed the mitigation potential of BECCS in various industrial sectors and calculated CO<sub>2</sub> intensities for cement between 0.06 – for calcium looping – and 0.14 tCO<sub>2</sub>/t cement – for chemical absorption (post-combustion) and oxyfuel – with 50% biomass substitution. Tanzer et al. (2021) and Norton et al. (2019) also highlighted the importance of biomass rotation periods, i.e. the efficiency of biomass to absorb CO<sub>2</sub> during its growth, along with the recarbonation of demolished concrete, for providing net-negative concrete. Therefore, ensuring negative emissions in the cement industry appears to be a promising mitigation measure – albeit understudied (Tanzer et al., 2021; Yang et al., 2021) – subject to uncertainties regarding the biomass substitution rate and rotation periods.

Research based on energy system models helps design optimal pathways towards decarbonization of the cement industry (or any energy system), by assessing the competitiveness of the various measures while considering resource availability and demand, in a more holistic way and under different policy scenarios (Subramanian et al., 2018). Zhang et al. (2021) reviewed existing studies that have proposed optimal transition pathways for cement decarbonization and accounted for 16 studies carried out at the national level; they highlighted that existing research focused on energy efficiency measures, and to a lesser extent on fuel-switching measures. Obrist et al. (2021) studied an optimal decarbonization pathway for the Swiss cement industry by 2050. They concluded that CCS becomes competitive at a carbon tax above €70/tCO<sub>2</sub>. Although they modeled the input of biomass in the precalciner – a device used to enhance the efficiency of the decalcination process – equipped with carbon capture, they did not investigate the potential for negative emissions generation. The German cement industry was found to be decarbonized efficiently with a radical reduction of the clinker content of cement (Brunke and Blesl, 2014). This national model also includes biomass as an alternative fuel, albeit with a limited share of biomass in the fuel mix (biomass content remains constant at initial levels), and does not mention negative emissions opportunities. Lastly, the cement industry was found as a potential supplier of synthetic fuels, by capturing the CO<sub>2</sub> emitted from the decalcination of limestone, and making it react with low-carbon hydrogen (Farfan et al., 2019; Rumayor et al., 2022). Thus, research on the decarbonization pathways of the cement industry has focused primarily on national levels. More

specifically, Ren et al. (2023) reviewed the existing models including negative emissions strategies for the cement industry. It appears that only two national models – including theirs – concentrate on the assessment of negative emissions to decarbonize the cement industry, at a regional level also, i.e., China (Ren et al., 2023) and Japan (Watari et al., 2022). They both concluded that using negative emissions in the cement industry is critical to reach the net-zero target in this sector. Nevertheless, they highlighted sustainability concerns regarding biomass management, which could be even more substantial if studied at the global level.

At the global level, Edelenbosch et al. (2017) performed a cross-model comparison of cement decarbonization in integrated assessment models (IAM), namely DNE21+, IMAGE, TIAM-UCL, POLES, IMACLIM-R, MESSAGE, and GCAM. They highlighted a consensus for increasing material efficiency in this sector, but made no mention of carbon removal strategies. Van Ruijven et al. (2016) studied long-term projections of global cement demand and assessed the low-carbon pathways through different carbon tax policies. Their results show a massive roll-out of post-combustion capture units combined with up to 80% of bioenergy globally in 2050. Thus, emissions due to fuel combustion become net negative but do not compensate for the residual process CO<sub>2</sub> emissions, so the global CO<sub>2</sub> emissions generated from cement remain positive – approximately 500 MtCO<sub>2</sub>. However, the authors do not provide details on assumptions and technical feasibility behind this result. Later, van Sluiseveld et al. (2021) employed the IMAGE model and concluded that net-zero emissions are achievable in the cement sector, although the authors do not emphasize the breakthrough and provide few details on the feasibility of this outcome. In the report “Net Zero by 2050”, the IEA claims that “biomass and renewable waste [accounts for] 35%” of global thermal energy use in cement production while more than 80% of global cement production comes from CCUS<sup>1</sup>-equipped plants, and “constraints on the availability of sustainable biomass supplies prevent it from claiming a higher share” (IEA, 2021), thus preventing the production of net-negative cement. In the IPCC sixth assessment report (AR6), the IMP-Neg<sup>2</sup> scenario shows massive deployment of negative emissions from industry of more than 6 GtCO<sub>2</sub>.yr<sup>-1</sup> with little indication of what sectors generate these negative emissions. In addition, the IPCC highlights that there are “only a few scenarios which allow net-negative emissions for the industry” (IPCC, 2022).

In light of the existing literature and challenges, there is insufficient research regarding how negative emissions can be deployed in the cement industry on a global scale, and under what conditions they could roll out. It has been demonstrated that high biomass substitution rates and short rotation periods would be critical to achieve negative emissions. However, high biomass substitution rates are technically more challenging, and biomass is a resource that can require several decades before it can be used. Consequently, it can be legitimately assumed that future biomass cost and potentials as well as land availability would shape the use of biomass in the cement sector. Considering these parameters, the aim of this study is to assess the technical feasibility and potential contribution of carbon removals to decarbonize the cement industry through negative emission technologies. The scenarios are detailed in the following section, in which a novel modeling of the cement industry is proposed. Employing TIAM-FR, sensitivity analyses are carried out in the second section to assess the favorable conditions that would make the global cement industry not only net-zero but also a net-negative sector. This denotes that global cement factories would remove more CO<sub>2</sub> from the atmosphere than they emit, while producing cement. Addressing these research gaps, this research analyzes the real challenges that hinder the wide adoption of net-negative cement

<sup>1</sup> Carbon Capture Utilization and Storage (CCUS)

<sup>2</sup> Illustrative Mitigation Pathway (IMP) – Neg reflects a 1.5°C scenario with a high overshoot relying on extensive use of carbon dioxide removal.

strategies and proposes a roadmap for the transition of the global cement industry.

## 2. Method

The decarbonization pathway of the global cement industry is analyzed with a bottom-up optimization model through different scenarios, cases, and sensitivity analyses depicted in the following sections.

### 2.1. TIAM-FR

This analysis is carried out with TIAM-FR, the French version of the TIMES Integrated Assessment Model (TIAM). TIMES is a generator of partial equilibrium techno-economic models representing the energy system of a geographical area – or regions – on a long-term horizon. The TIMES framework is widely recognized and utilized in energy systems modeling designed to evaluate long-term energy scenarios and their environmental implications. TIAM-FR is the Mines Paris – PSL’s version of the global TIMES family models developed under the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (IEA).

TIAM-FR operates as a bottom-up optimization model, capturing the complexities of energy systems by representing various sectors, such as electricity generation, transportation, industry, agriculture, and residential. It considers a broad spectrum of energy technologies and resources, including fossil fuels, renewables, and nuclear power. The model incorporates 15 regions (Appendix A) and temporal resolution, allowing for a granular examination of regional and global energy

dynamics by the end of the century. For each user-defined milestone year, the model depicts the energy system with a detailed description of different energy forms, technologies, and end-uses, constituting the reference energy system (RES) (Fig. 1).

One of TIAM-FR’s strengths lies in its ability to assess the trade-offs and synergies between energy security and environmental sustainability, exploring different policy scenarios, technological advancements to understand their potential impacts on energy consumption, technical feasibility, resource dependency, greenhouse gas emissions, and overall system costs. Thus, TIAM-FR integrates economic, technological, and environmental factors to provide a comprehensive analysis of energy systems.

The modeling of the cement industry includes different options in addition to negative emissions that are presented in the following section.

In previous works, negative emission opportunities were implemented for the iron and steel sector of TIAM-FR (Andrade et al., 2024). This study revealed that this sector can become a net negative emitter by first employing electric routes and then biochar in Corex processes and biogas in DRI (Direct Reduction of Iron) processes while capturing and storing the CO<sub>2</sub> emitted to make net-negative steel. Noteworthy, the results highlighted that the unavailability of negative emissions could significantly affect the affordability of steel.

### 2.2. Modeling of cement in TIAM-FR

Usually, in bottom-up optimization models, cement demand is met by satisfying energy services to manufacture cement, such as process

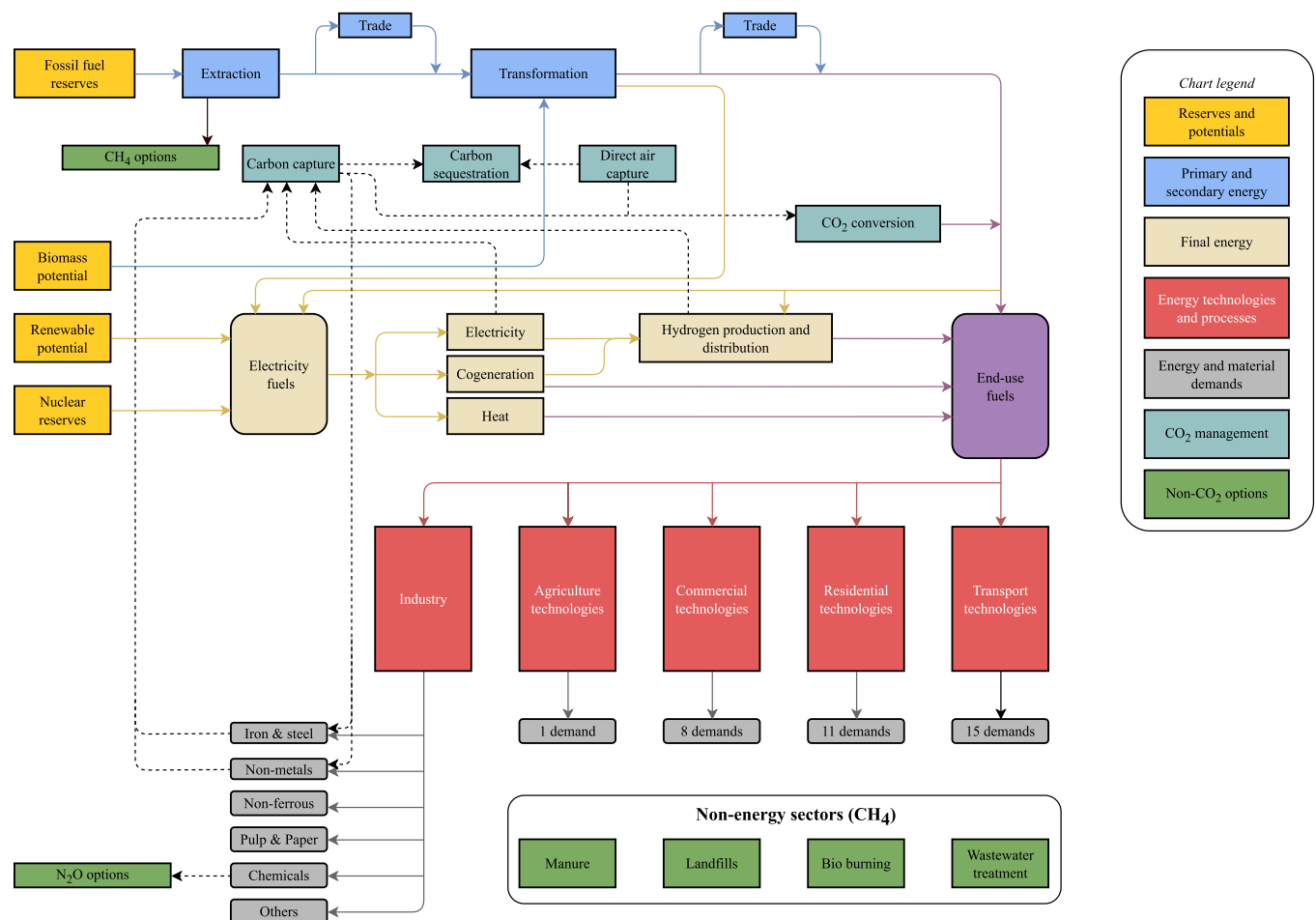


Fig. 1. Reference energy system of TIAM-FR.

heat, steam, machine drive systems, etc., which together make up a region-dependent energy intensity of cement (Fais et al., 2016). This representation is efficient to assess fuel-switching measures but cannot account explicitly for low-carbon investments such as CO<sub>2</sub> capture units, kiln electrification, and clinker reduction measures.

Fig. 2 represents the enhanced modeling of the cement industry in TIAM-FR developed in this study, from energy commodity inputs to cement demand. The cement industry is disaggregated into four steps. The first one computes the optimal fuel mix to feed cement plants, considering substitution rates detailed in Section 2.2.1. The second one processes energy and limestone to produce clinker, which is processed in the third step with other aggregates to produce cement. For the base year (2018), the global cement industry is represented according to IEA's energy balances (IEA, 2020b) for energy flows and cement demand. Regarding the clinker-to-cement ratio, several references were used (see Appendix B) to further calculate the statistic energy efficiency of the existing assets in 2018. The shares of aggregates (fly ash, blast furnace slags, limestone, and gypsum) are assumed to be proportionally distributed across regions compared to the global average (IEA, 2020c). Due to lack of data, the material efficiency, the operational cost, and the fixed cost are set for every region to 1.26 t<sub>limestone</sub>/t<sub>clinker</sub>, \$21.9 /t<sub>clinker</sub>, \$1.29 /t<sub>clinker</sub> (Griffin et al., 2013), but regional costs of limestone are taken from (Ferrari et al., 2019).

In 2018, coal and gas make up most of the global fuel demand for cement, at 64% and 17% respectively. The energy consumption of the global cement industry is disaggregated for each region of TIAM-FR according to type of energy; either solid fuel (coal, coke, pet coke, oven coke, municipal waste, biochar, wood biomass, pellets or torrefied pellets), gaseous fuel (natural gas, coke oven gas, liquefied petroleum gas, blast furnace gas, biogas or synthetic biomethane), or liquid fuel

(heavy fuel oil, or a predefined mix of fossil (resp. bio-based) diesel and gasoline. This choice is made as the type of kilns and burners in cement plants depend on the state of energy used, and other infrastructures such as storage tanks or pipelines that are difficult to consider in TIAM-FR. Heat and electricity are separated because these energy carriers cannot be used in conventional kilns, i.e. they require a substantial capital investment.

Emissions factors (EIA, 2022) are used to account for the emissions of fossil fuel combustion. The CO<sub>2</sub> emissions from biomass combustion are considered as climate-neutral. If the fuels are ultimately processed in cement plants equipped with carbon capture units, the amount of CO<sub>2</sub> captured is accounted at the same level of the RES. Once CO<sub>2</sub> is captured, it can be either stored in step 4 following the storage potentials of (Kearns et al., 2017) and the costs of transport and storage of (Smith et al., 2021), or it can be utilized in various CO<sub>2</sub> conversion processes including mineralization (NASEM, 2019), hydrogenation (Pérez-Fortes et al., 2016), Fischer-Tropsch (Albrecht et al., 2017; Zang et al., 2021) and methanation (Chauvy et al., 2021).

Assuming that the lifetime of cement plants is approximately 40 years (Cembureau, 2018a; IEA, 2020a), the remaining lifetime of current assets is evaluated in Appendix C for each region based on (IEA, 2020c).

2.2.1. Fuel-switching measures

Fuel-switching measures consist in employing low-carbon energies and energy carriers such as hydrogen, electricity and bioenergy instead of fossil fuels. To trace realistic transition pathways, fuel input shares are constrained to lower or upper bounds as detailed below. Between 2018 and 2025, the fuel shares in cement plants remain constant across regions, but these constraints are relaxed afterwards.

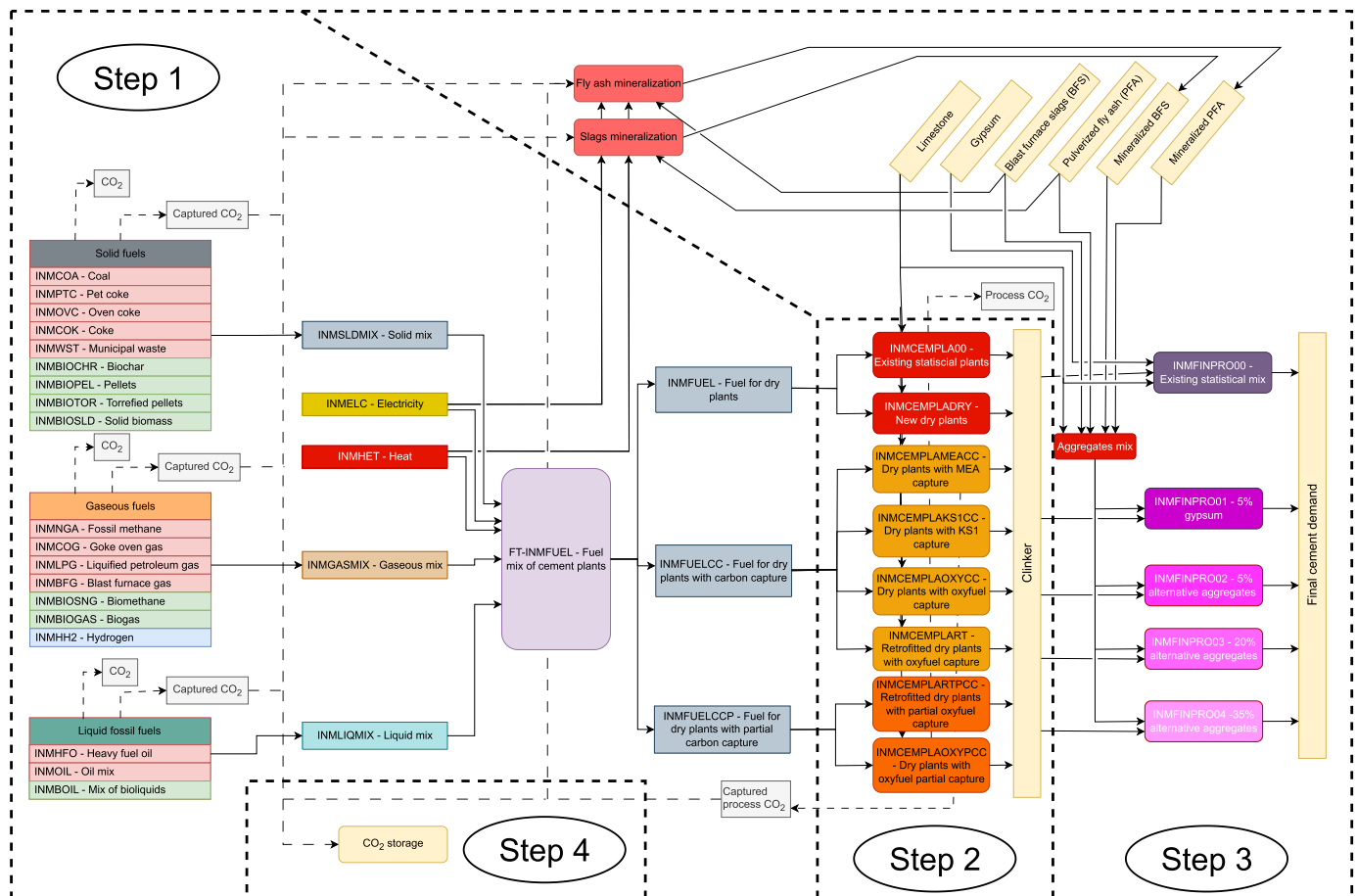


Fig. 2. Reference Energy System of the cement sector in TIAM-FR.

Firstly, the cement industry can substitute between solid, gaseous and liquid fuel by a factor of 33% every 10 years as of 2030 until 2050, i. e. each region is free to use 33% more or 33% less solid, gaseous, or liquid fuels as of 2030 onwards. Bioliquids, biomethane and biochar are considered as perfect substitutes for fossil gases, fossil liquids, and fossil solids respectively (Anand et al., 2023; Ardolino et al., 2021). Nonetheless, their substitution rate grows linearly until 100% in 2050 to ensure a realistically progressive replacement. As for solid biomass, pellets, and torrefied pellets, the substitution rate grows linearly until 80% in 2050, as it corresponds to the maximum rate found in the literature (Cavalett et al., 2022), and because these solid biofuels show a lower heating value (LHV) that cannot substitute coal products, while biochar can. Likewise, the biogas substitution rate is the ratio of its LHV of 6.5 kWh/m<sup>3</sup> compared to fossil gas (11 kWh/Nm<sup>3</sup>), which makes 59%. The small retrofitting investments required to convert a process consuming fossil fuels into a process consuming biofuels can be neglected (ECRA, 2017; McKinseyandCompany, 2018).

Secondly, for heat and electricity, an upper bound is set empirically for every region that corresponds to the maximum electricity share observed in 2018 multiplied by 133% to provide room for improvement. This constraint aims to reflect that the feasibility of changing the phase of the fuel employed in kilns is limited and requires costly adjustments (Turnell, 2000). The maximum input share of hydrogen is defined as 5%, 10%, and 15% of the gaseous mix respectively in 2030, 2040 and 2050 by pipeline (Di Lullo et al., 2021; Mahajan et al., 2022). Indeed, these energies cannot fully substitute fossil fuels, as burning hydrogen (H<sub>2</sub>) to generate high temperatures in the kiln requires significant capital investment; because of differences in heat transfers, the kiln and the burners needs to be redesigned (McKinseyandCompany, 2018). Likewise, electricity is not a perfect substitute for coal, gas, or liquids in existing kilns, although it is – and can be – used for other purposes in cement plants e.g., for grinding limestone, forklifts, or other electric devices. As for municipal waste, the maximum utilization rate of municipal waste in cement plants for all regions in 2025 onwards equals the maximum share of municipal waste observed in the base year – which is 7.3% in Eastern Europe – multiplied by 133% to allow for improvements.

All assumptions on fuel shares and fuel substitution rates are available in the Supplementary Materials.

### 2.2.2. Technological solutions

In addition to the existing wet and dry plants, new cement plants are available representing different types of kiln and different CO<sub>2</sub> capture types. The scope of the cement plant modeled includes limestone grinding, coal grinding – or fuel conditioning, pulp mill, heaters and pre-heaters, the kiln, the cooler, and clinker grinding. Two cases are distinguished for CO<sub>2</sub> capture: post-combustion and oxy-combustion. For post-combustion capture, two types of solvent are modeled, i.e. monoethanolamine (MEA) and KS-1. The former is the most common chemical for CO<sub>2</sub> capture, and has been used for decades, while the latter has gained interest as it requires less energy to regenerate, with a longer lifespan and a higher CO<sub>2</sub> uptake (DOE, 2017; Global CCS Institute, 2021; Ho et al., 2009), but at a higher cost (Griffin et al., 2013). Thus, dry kilns equipped with MEA-based post-combustion capture are distinguished from those equipped with KS1-based post-combustion capture.

The oxy-combustion technique is worth considering for the cement industry. This technique requires an Air Separation Unit (ASU) to provide the oxygen to the fuel, emitting almost pure CO<sub>2</sub>. Two options are available: either partial oxy-combustion, only to the calciner, or full oxy-combustion, to the whole kiln, thus covering both process and combustion CO<sub>2</sub> emissions. The partial capture covers approximately 60% of the emissions (ECRA, 2017; Griffin et al., 2013). Thus, dry kilns equipped with partial oxy-combustion capture are distinguished from dry kilns equipped with full oxy-combustion capture. The techno-economic assumptions were extracted from (CEMCAP, 2016; ECRA, 2017; Griffin

et al., 2013) and are gathered in Table 1 and Table 2.

The annual availability factor is set at 90% and material input is 1.26 t<sub>limestone</sub>/t<sub>clinker</sub> for every process. Any new capacities installed show a discount rate of 10%. Finally, retrofitting options for existing cement plants are included based on (Griffin et al., 2013), accounting for the energy penalty and additional costs of retrofitting an existing dry plant. The emissions from combustion CO<sub>2</sub> and the possible amounts of CO<sub>2</sub> captured are not shown here as they are endogenously determined according to the energy mix chosen by the optimization (see Sections 2.12.2 & 2.2.1). The amount of CO<sub>2</sub> captured from cement processes in 2030 is limited to existing projects and their announced operational date (Global CCS Institute, n.d.). Finally, the cost of transporting and storing CO<sub>2</sub> as well as storage potentials are assumed differently across regions based on (Smith et al., 2021) and (Kearns et al., 2017) respectively.

### 2.2.3. Clinker reduction measures

Different finishing processes are implemented in the model. They refer to the final process that converts clinker into commercial cement by blending clinker with a mix of aggregates. The conventional finishing process refers to the transformation of clinker into Ordinary Portland Cement (OPC), which consists in grinding and mixing clinker with gypsum, respectively by 95%wt and 5%wt (Fazio and Pennington, 2006). The finished cement is highly clinker-intensive, but an alternative finishing process consists in reducing the clinker-to-cement ratio and blending with alternative aggregates such as blast furnace slag, mineralized fly ashes, and mineralized steel slags. The model chooses the optimal mix of aggregates to be blended with clinker, and the clinker share in the final cement is comprised between 5% and 35% (Fig. 2).

### 2.2.4. Policies, biomass availability, and sensitivities

The decarbonization of the cement industry is studied in different policy and technical contexts. Table 3 summarizes the scenarios, cases, and sensitivities detailed in the following subsections and analyzed subsequently in Section 3.

### 2.2.5. Scenarios

Firstly, a reference scenario (REF) is designed to “provide a scale against which to compare mitigation scenarios” (Grant et al., 2020) incorporating the current pledges made by countries through their Nationally Determined Contributions (NDCs) (UNFCCC, 2023) (see Appendix D). The REF scenario projects global population and GDP growth according to the SSP2-4.5 scenario, i.e. towards a world limiting the global temperature below 3.0°C (IPCC, 2022). In this scenario, no global consensus emerges for fulling Article 6 or the Paris Agreement, such that there is no emissions trading system among the regions defined by the model.

Secondly, an ambitious scenario (NZ70) is considered to be

**Table 1**  
Techno-economic properties of cement plants (unit: ton of clinker).

Process Units	CAPEX [\$ /t]	FIXOM [\$ /t]	VAROM [\$ /t]	Lifespan [years]	Start
Wet process	392	22	1	32.5	2018
Dry process	415	22	1	32.5	2018
Dry process with MEA CO <sub>2</sub> capture	653	32	1.3	27.5	2030
Dry process with KS1 CO <sub>2</sub> capture	653	53	1.3	27.5	2030
Dry process with partial oxyfuel capture	653	38	1.3	27.5	2030
Dry process with oxyfuel capture	579	38	1.3	27.5	2030
Retrofitting existing plant with KS1 capture	253	54	1.3	27.5	2030
Retrofitting existing plant with partial oxyfuel capture	67	33	1.3	27.5	2030

**Table 2**  
Consumptions and emissions of cement plants (unit: ton of clinker).

Row Labels	Fuel	Oxygen	Process CO <sub>2</sub> emitted	Process CO <sub>2</sub> captured
Units	[GJ/t]	[t/t]	[kg/t]	[kg/t]
Wet process	5.17		556	
Dry process	3.90		556	
Dry process with MEA CO <sub>2</sub> capture	9.64		56	500
Dry process with KS1 CO <sub>2</sub> capture	8.24		56	500
Dry process with partial oxyfuel capture	4.57	0,16	222	334
Dry process with oxyfuel capture	5.27	0,26	56	500
Retrofitted existing plant with KS1 capture	8.24		56	500
Retrofitted existing plant with partial oxyfuel capture	4.57	0.16	222	334

**Table 3**  
Policy scenarios, biomass potentials, and sensitivity analysis.

Policy scenarios	Description	Socio-economics		
REF	All countries achieve their NDC and long-term pledges	SSP2-4.5		
NZ70	The REF scenario is reinforced by targeting net-zero emissions for all countries in 2070	SSP2-1.9		
CM0	The NZ70 scenario is reinforced by targeting net-zero cementitious emissions by 2050	SSP2-1.9		
<b>Biomass cases</b>				
High	High technical process and 25% conversion rate of harvested areas			
Mid	Low technical progress and 25% conversion rate of harvested areas			
Low	Low technical progress and harvested areas cannot be converted			
<b>Sensitivities</b>				
Biomass substitution rate (SR)	Solid biomass, pellets and biochar substitute for conventional coal and other solid fossil fuels	Min 25%	Max 80%	Increment 5%
Rotation periods (RP)	Consideration of the impact of long rotation periods on the absorption rate of atmospheric CO <sub>2</sub> by biomass	1 year	50 years	10 years

compared with REF, in which all countries and regions commit to the net-zero target by 2070 (all GHG included), in addition to their NDCs. If this target is really achieved, it will enable the world to contain climate warming below 1.5°C (Riahi et al., 2023). In this scenario, all regions of the model can trade CO<sub>2</sub> and non-CO<sub>2</sub> emissions as of 2030. Appendix E shows the cumulative regional caps of GHG emissions assumed across the 21<sup>st</sup> century. As of 2030, any GHG emission permits can be traded across regions.

To analyze more deeply the potential contribution of negative emissions for cement, the NZ70 scenario is enforced with by additional constraint on cementitious emissions (CM0) in which the global cement industry achieves carbon neutrality by 2050, as the Global Cement and Concrete Association (GCCA) has committed to this target (GCCA, 2022); in the meantime, the global net-zero target by 2070 remains effective. From 2030 onwards, a global GHG trade system is assumed, dedicated to cementitious emissions where some regions can achieve larger negative emissions than necessary in order to compensate the net positive emissions of other regions.

All scenarios are consistent with the second Shared Socio-economic

Pathway (SSP2) (Fricko et al., 2017), which is a middle-of-the-road scenario with moderate economic growth and improved education, health, and governance. In this SSP, there is a focus on increasing energy efficiency and expanding the use of low-carbon energy sources, but emissions reductions are limited, and greenhouse gas emissions decline. Global inequality increases, but at a slower rate than in other scenarios, and global population grows to around 9 billion by 2100. While the scenarios are driven by SSP2 economics, the associated climate scenario is different, i.e., the REF (resp. NZ70 and CM0) scenario features a 4.5 W/m<sup>2</sup> radiative forcing (resp. 1.9 W/m<sup>2</sup>), impacting the projections of demands (Fig. 3).

### 2.2.6. Cases

We explore the decarbonization of the cement sector by comparing the policy scenarios described in Section 0 with additional cases related to the availability, efficiency, and cost of land use. These ‘biomass’ cases were developed by (Kang, 2017; Kang et al., 2018) in the TIAM-FR model according to three potential levels. The conservative one, named *Low*, represents the most constraining case, forecasting moderate technical progress in land management, and does not allow for the conversion of other land areas except those already used in 2010. The *Mid* case allow for 25% of land use conversion, all other factors being equal. The optimistic case, named *High*, assumes the highest level of technical progress with a 25% rate for land use conversions. The potential, efficiencies, and costs for each biomass case are given in the Supplementary Materials.

### 2.2.7. Sensitivity parameters

We narrow the analysis by assessing the sensitivity of negative emissions in the cement industry to (1) biomass substitution rates and (2) biomass rotation periods, as these have been identified as crucial but uncertain parameters (see Section 0).

In sensitivity (1), the biomass substitution rate varies according to the type of biomass and the type of fuel it can substitute. In that sense, biomethane can substitute up to 100% of conventional natural gas and biochar can substitute up to 100% of coal or coke, as these are similar feedstock with different carbon content origins. Besides, biofuels are perfect substitutes for conventional fuels. However, solid biomass and pellets can substitute up to 80% of coal or coke, and biogas can substitute 59% of natural gas, because of their lower heating value. The substitution rate varies incrementally by 5 percent points to track tipping points.

In sensitivity (2), the biomass rotation periods vary from 1 year to 50 years, which comes down to assuming that the cement industry can grow trees – or other types of biomass – over up to 50 years to run the kilns. The data are taken from (Guest et al., 2013) for a 100-year carbon storage period in the atmosphere, with 10 years increment. Considering biomass emissions factors of 97 kgCO<sub>2</sub>/GJ for biomass (Cundall, n.d.), Table 4 shows the estimated emission factors for bioenergy depending on the rotation period.

## 2.3. Projection of global cement demand

As a bottom-up model is used, the interactions between the producers of cement and their consumers are not captured. Consequently, the projected demand for cementitious products is exogenous. In TIMES modeling, the material and energy demands (DEM) are driven by socio-economic parameters such as Gross Domestic Product (GDP), population (POP), and ratios of GDP per capita (GDPP), depending on the demand under discussion, as Equation (1) shows.

$$Demand_{r,t} = Demand_{r,t-1} \times drive^{elasticity_{r,t}} \quad (1)$$

The elasticity represents the degree of decoupling between the demand and its driver (Loulou and Labriet, 2008). For cement, GDPP was found to be a driver of demand (Neelis and Patel, 2006; van Ruijven

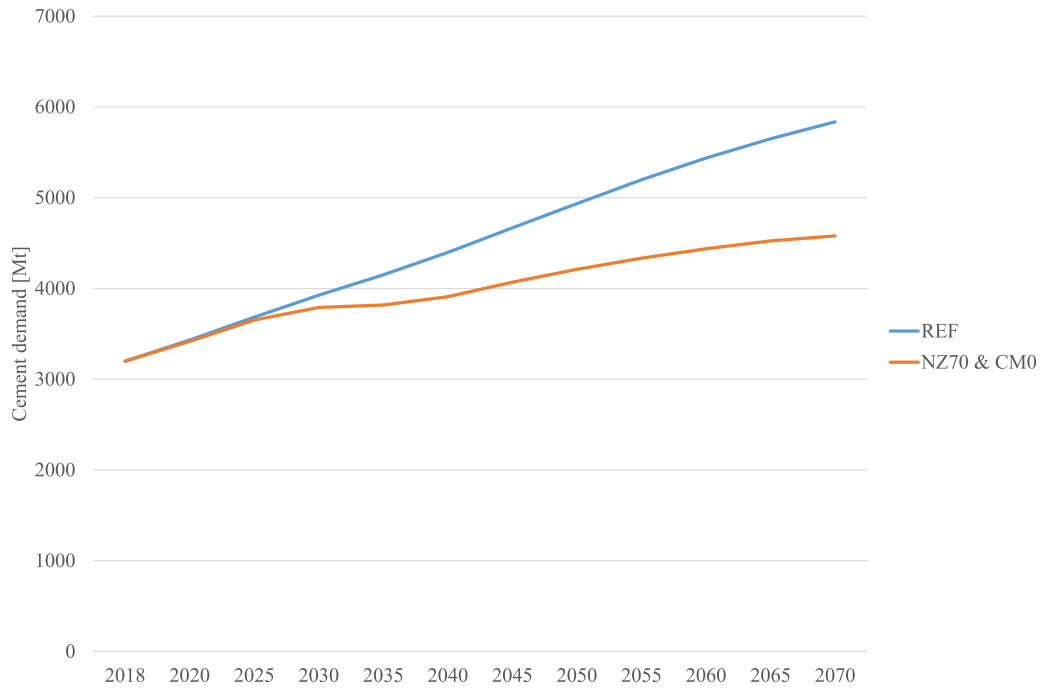


Fig. 3. Cement demand projections in TIAM-FR by policy scenario.

Table 4

Biomass emission factors based on rotation periods (Guest et al., 2013).

Biomass rotation years	GWP kgCO <sub>2eq</sub> / kgCO <sub>2</sub>	Wood, processing residues of wood, and logging residues of wood, biochar kgCO <sub>2</sub> /GJ
1	-0.99	1
10	-0.96	4
20	-0.92	9
30	-0.88	13
40	-0.84	22
50	-0.80	28

et al., 2016). To calculate these elasticities with Equation (2), the GDP and population projections are extracted from the IIASA SSP database for different SSPs, regions (r), and climate targets (CT). The database does not provide specific data on the energy consumption of cement; instead it is aggregated in the label *Final Energy | Industry*. Thus, the elasticity of the energy consumptions of cement to GDPP behaves the same way as the final energy demand of industry to GDPP. Besides, the regions r specified in the database do not match with the regions and countries of TIAM-FR, which need to be reallocated according to their location and economic development (see Appendix F).

$$elasticity_{SSP,CT,DEM}(t) = \frac{\frac{DEM_{SSP,CT,r}(t) - DEM_{SSP,CT,r}(t-1)}{DEM_{SSP,CT,r}(t)}}{\frac{driver_{SSP,CT,r}(t) - driver_{SSP,CT,r}(t-1)}{driver_{SSP,CT,r}(t-1)}} \quad (2)$$

With the estimated elasticities and the cement demand for the base-year of TIAM-FR (2018), the global cement demand is projected with Equation (3) for each region r of the model, depending on the SSP considered in the policy scenario (see Section 0).

$$DEM_{SSP,CT,r}(t) = DEM_{SSP,CT,r}(t-1) \times \left( 1 + \left( \frac{driver_{SSP,CT,r}(t)}{driver_{SSP,CT,r}(t-1)} - 1 \right) \times elasticity_{SSP,CT,r,DEM}(t) \right) \quad (3)$$

The resulting trends for the REF and NZ70 scenarios are given in Fig. 3. The REF scenario follows a SSP2-4.5 and the NZ70 and CM0

scenarios follow a SSP2-1.9.

### 3. Results and discussion

The transition of the cement industry is discussed according to the policies, biomass cases and sensitivities outlined in Section 2.3. and labeled accordingly (e.g. NZ70\_High 80%). Although we run the model until the 2100 horizon, the results presented in the following subsections cover the period until 2070, with updates every 5 years. This approach allows us to focus on the short and mid terms while considering any long-term potentials to ensure the sustainability of the proposed pathways.

#### 3.1. What impedes the carbon neutrality of the cement industry?

Regardless of the policy or biomass potential under consideration, the global cement industry consistently harnesses the full capacity of biomass for kiln firing. Therefore, when allowing a substitution rate of up to 80%, the cement industry seizes the opportunity and takes full advantage of it. This strategy enables the generation of significant carbon removals, which can be utilized to offset both residual cementitious emissions and other hard-to-abate industrial emissions (e.g. chemicals, pulp and paper, aluminum). Hence, imposing constraints on the biomass substitution rate makes the transition more expensive, reduces carbon removals, and consequently delays the achievement of carbon neutrality in the global cement industry. Fig. 4 illustrates, across REF and NZ70 scenarios, how the substitution rate influences the year at which the global cement industry reaches carbon neutrality (including non-CO<sub>2</sub> GHG) – CM0 scenarios are not plotted here since they purposely target net-zero by 2050. Across all substitution rates, the average delay of net-zero achievement between the REF scenarios and the NZ70 scenarios is 6, 4, and 3 years respectively for the *High*, *Mid*, and *Low* cases. However, the net difference is more substantial when comparing cases with low substitution rates. Besides, in the REF scenario, carbon neutrality is only achieved in 2050 or before with substitution rates above 45% in the *Low* and *Mid* cases, and 65% in the *High* case. This underlines the insufficiency of current climate policies and technical progress related to biomass use in cement kilns if the goal of the GCCA to reach net-zero by



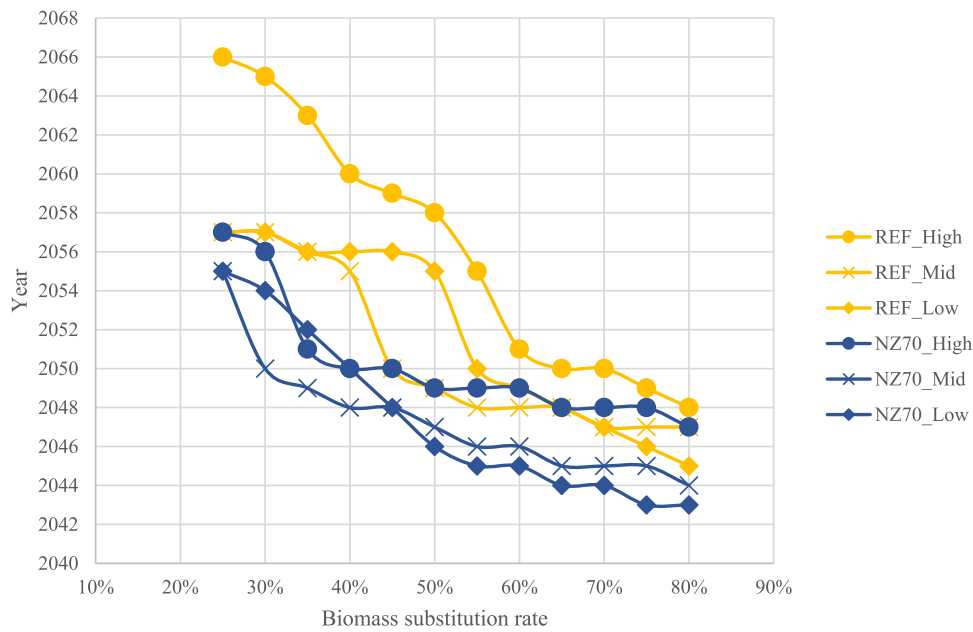


Fig. 4. Year when carbon neutrality is achieved as a function of biomass substitution rate for different policies and biomass potentials.

2050 is to be attained. However, in scenarios achieving global decarbonization in 2070, net-zero emissions for cement are achieved with biomass substitution rates higher than 40%.

Across all scenarios, the zero year is delayed by 10 to 18 years when comparing the lowest substitution rate (25%) with the highest (80%) for the same policy and biomass potential. Counter-intuitively, the cement industry achieves carbon neutrality earlier when the global biomass potential is more pessimistic, with an average difference of 4 years compared to more optimistic potentials. In other words, the global cement industry employs more biomass and generates more negative emissions when biomass management is constrained by lower potentials. However, the global generation of cumulative negative emissions from BECCS across all sectors is reduced in the *Low* and *Mid* cases, as

illustrated in Fig. 5. In the *Mid* and *Low* cases, respectively 16% and 32% fewer negative emissions are generated from BECCS in the power sector, which is partly compensated by direct air capture and some additional carbon removals from cement. Achieving higher amounts of negative emissions in the cement industry involves early investments to expand the capacities of dry plants equipped with CCS and powered with bio-energy. Therefore, the cement industry is more involved in removing carbon when fewer negative emissions from the power sector and bio-refineries are generated due to both costlier and scarcer land use.

Regarding the periods of biomass rotation, the sensitivity to the net-zero year is not significantly pronounced; at worse, it results in a delay of the target of up to 2 years. Fig. 6 illustrates the modest impact on the total amount of biogenic CO<sub>2</sub> captured from the cement industry for

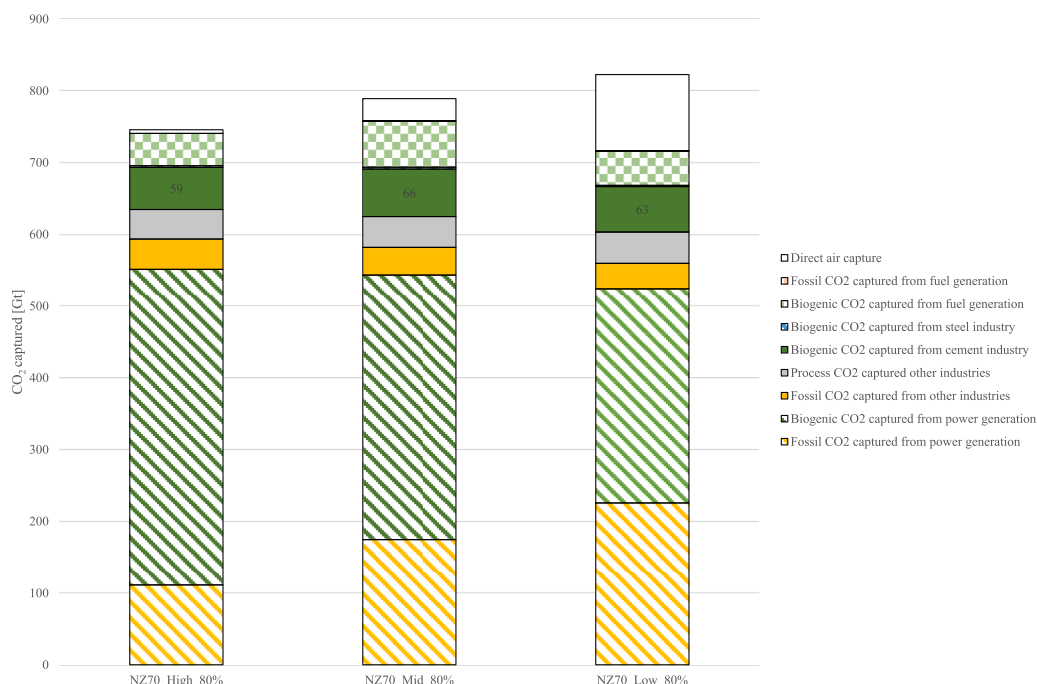


Fig. 5. Cumulative amount of CO<sub>2</sub> capture among sectors and across NZ70 cases with 80% substitution rates through the 2070 horizon.

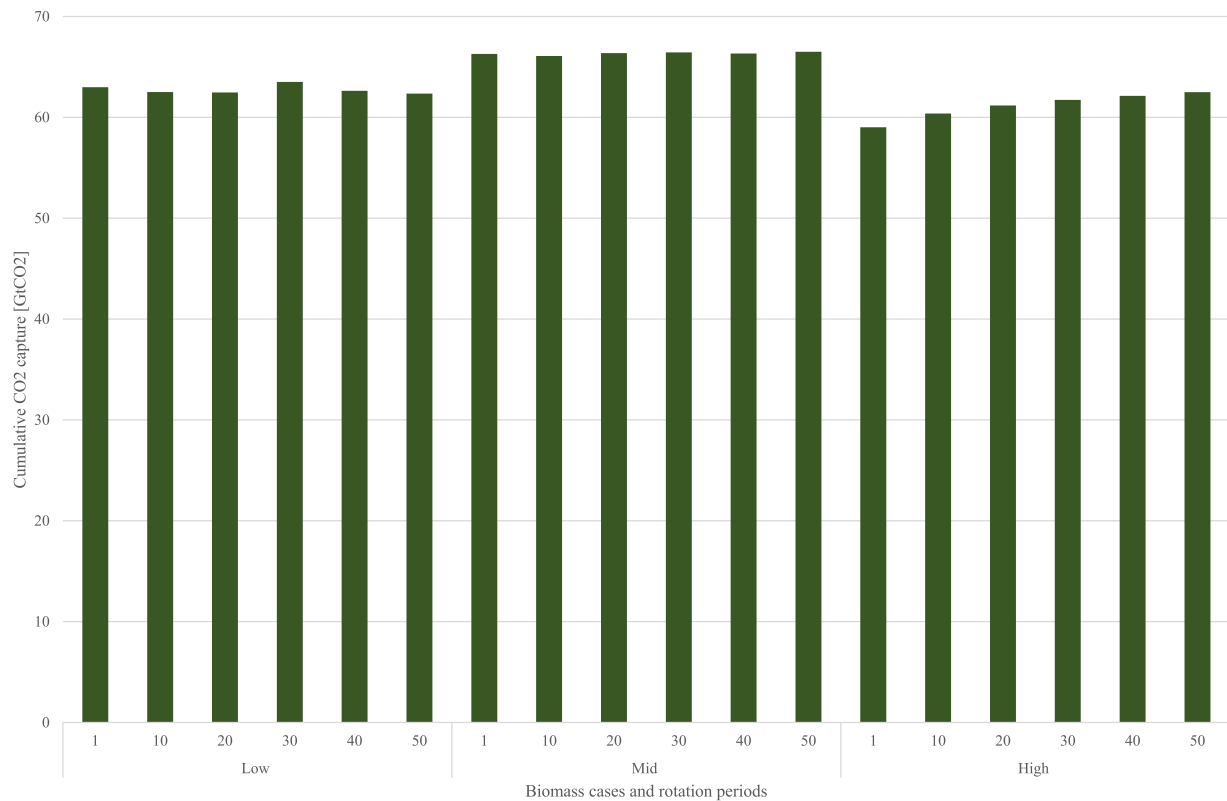


Fig. 6. Cumulative amount of biogenic CO<sub>2</sub> capture in a NZ70 scenario with 80% maximum substitution rate for different biomass cases and rotation periods.

different rotation periods across the three biomass cases. Notably, as the rotation period lengthens, cementitious carbon removals tend to increase. This pattern is similar to what can be observed regarding sensitivity to biomass potentials in Fig. 5. This emphasizes once again that constraining the entire value chain of biomass management initially impacts the use of biomass in other sectors, such as power generation. Consequently, this leads to a slight increase in BECCS use in the cement industry and additional capacities for direct air capture.

Overall, the carbon neutrality of the cement industry depends heavily on the policies adopted by major producers – and especially China. Indeed, the net-zero commitments or pledges by the US, Canada, Europe, Australia and New Zealand, Japan, South Korea, and China represent 83% of global cement production in 2060, according to our projections (see Section 2.4). In 96% of the scenarios analyzed, the cement industry becomes carbon negative in 2060 or earlier due to China's pledge to achieve net-zero CO<sub>2</sub> emissions in 2060, and Western nations by 2050.

### 3.2. How BECCS facilitates net-zero emissions in the cement industry

Fig. 7 shows how policies and sensitivities affect the achievement of net-zero emissions in the global cement industry by 2050 and shape the emissions profile. The positive emissions in NZ70 and CM0 decrease progressively and quite linearly, entailing continuous investments in fuel substitutions, carbon capture, and clinker content reduction. Conversely, in the REF scenario, emissions tend to stagnate from 2035 to 2045, but as bioenergy becomes more available, these emissions tend to decline more sharply and be offset for substitution rates superior to 60%.

Focusing on a 25% substitution rate, there are twice as many negative emissions in 2050 in NZ70 and CM0 compared to the REF scenario, and three times more positive emissions in the latter. There is no significant difference between CM0 and NZ70, except for slightly more carbon removals in the CM0 scenario in 2050, allowing it to reach net zero. Nevertheless, as the substitution rate increases, the CM0 scenario

achieves significantly more carbon removals compared to the NZ70 scenario, entailing a more efficient, cheaper energy system.

Thus, even with a 25% substitution rate, the cement industry can tackle “positive” CO<sub>2</sub> emissions sufficiently to ensure that these residual emissions are compensated by carbon removal. As a matter of fact, some countries and regions around the globe already use 25% or more solid biomass in the cement industry, namely South Korea, Europe, and Central and South America (IEA, 2020b). Therefore, our results suggest that even minor efforts on bioenergy use in the cement industry would allow the GCCA to comply with its net-zero commitment by 2050. Fig. 8 illustrates the gains of allowing for more bioenergy use in the cement industry, showing that the marginal cost of cement production is substantially impacted between 25% and 80% substitution rates. In the short term, the difference is not large but, in the long term, 80% biomass reduces the cement cost by 38%, according to these results.

### 3.3. Technologies, fuels, and cement composition: what changes for the cement industry?

Targeting net-zero CO<sub>2</sub> emissions by 2050 (as in the CM0 scenario), we depict the pathway outlined by our optimization exercise and compare it to the one proposed by the GCCA in their “Roadmap for Net Zero Concrete” (GCCA, 2022). Let us shift the focus to a scenario assuming a *High* biomass potential, as our socio-economic drivers are calibrated upon SSP2, providing results close to those found in the literature regarding biomass management (Popp et al., 2017). Furthermore, for the remaining analysis, we reasonably assume a 50% substitution rate, and 10-year biomass rotation periods to ensure both consistency and realism in biomass management.

The transition of the global cement industry accelerates as of 2035, with net emissions being reduced by 37% compared to 2030 (Fig. 9). This significant mitigation is accomplished by a combination of efforts including the retrofitting of existing assets with carbon capture and the introduction of bioenergy with a 16% penetration rate (Fig. 11). This

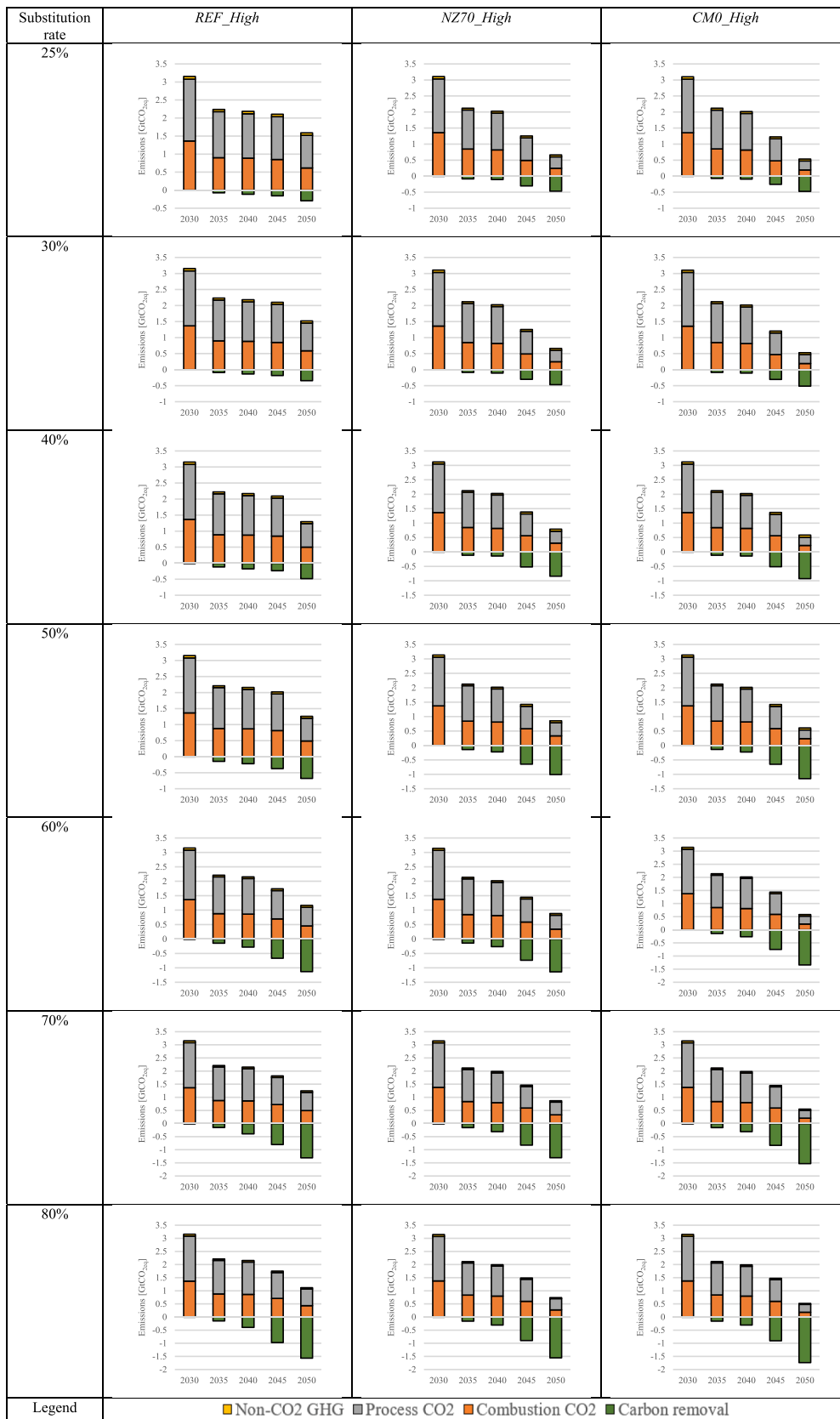


Fig. 7. Global profile of cement emissions in a NZ70 policy across different biomass cases and substitution rates.

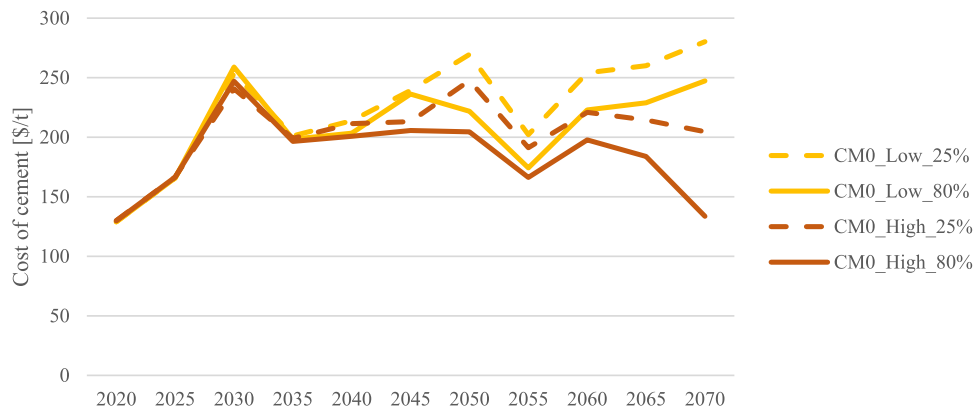


Fig. 8. Average global marginal cost of cement in the CM0\_High and CM0\_Low scenarios with different substitution rates.

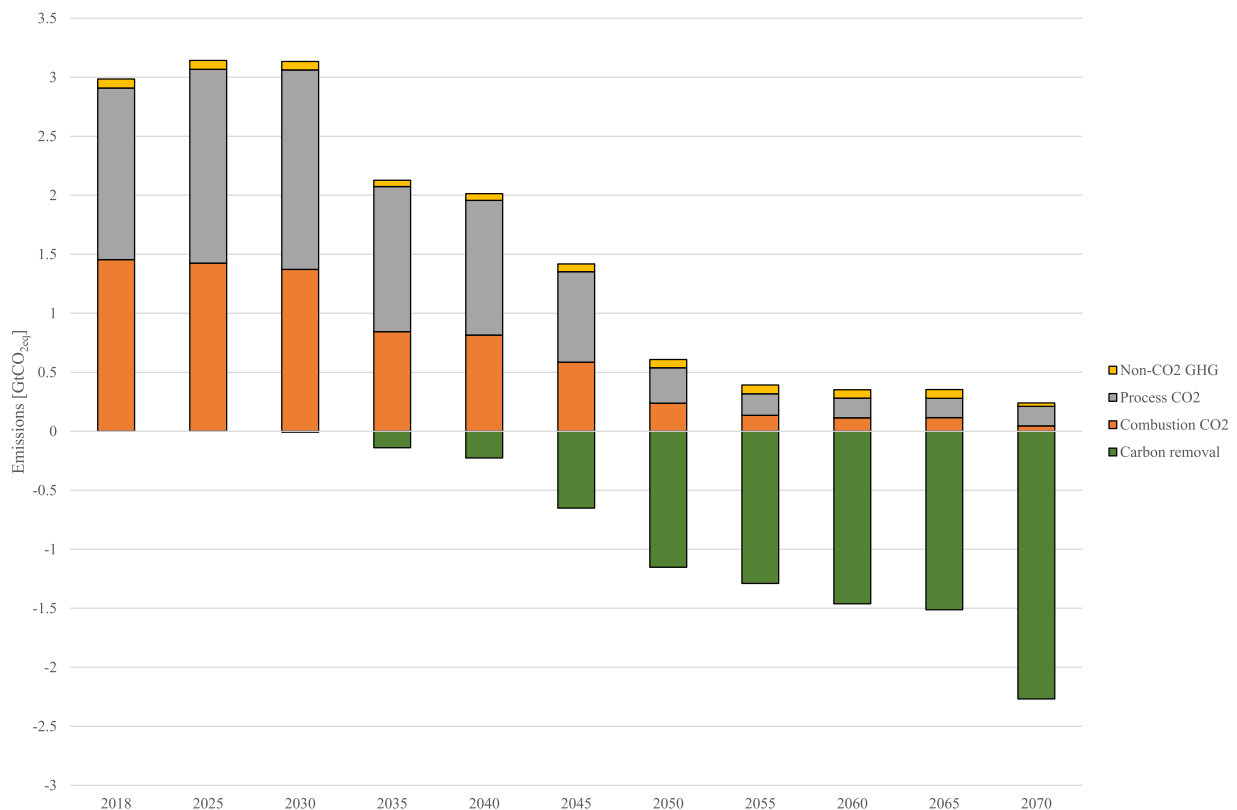


Fig. 9. Global cement emission profile for a CM0\_High\_50%\_10y scenario.

results in a total capture of 430 MtCO<sub>2</sub> of which 130 is biogenic (Fig. 10), allowing for some compensation in this sector. Noteworthy, capturing 430 Mt of CO<sub>2</sub> represents more than 430 carbon capture projects around the globe. Given the timeline, it requires a huge effort but remains in line with the ambitions stated by the GCCA.

In the mid term (2045-2055), carbon capture is deployed massively until the full equipment of carbon capture units is attained in 2055 for 50% substitution rate (Fig. 12). In the meantime, biomass use progresses to reach up to 50% of final energy consumption, dominated by solid biomass (Fig. 11). In a somewhat strategic approach, the cement industry leans towards investing in chemical capture units as the substitution rate grows, although chemical capture shows higher energy consumption compared to oxyfuel technology (roughly 40% more). This enables the generation of additional negative emissions by up to 1.2 GtCO<sub>2</sub> removed for a substitution rate of 50% but with 40% onwards, the negative emissions generated with chemical capture become more

cost-competitive than negative emissions generated by oxyfuel. These results indicate that the optimal technology mix depends on the biomass substitution rate assumed. In total, 3.4 GtCO<sub>2</sub> are captured from the cement industry in 2050, representing 2.5 times more than the ambitions of the GCCA.

In the long term (2060-2070), when the full potential of low-heating-value biomass is capped, biochar overtakes coal, allowing the removal of even more CO<sub>2</sub> rather than the avoidance of fossil emissions. The use of biochar instead of coal leads to massive negative emissions, with roughly 2 GtCO<sub>2</sub> removed. While coal is not phased out, offsets from BECCS compensate for coal emissions. However, fossil methane is completely replaced with biogas as of 2065. The cement composition undergoes no major changes, in contrast to the 11% emissions savings claimed by the GCCA. The industry tends to use the least clinker, opting for a mix of limestone and blast furnace slags recycled from the steel industry. A tiny part of this mixture is mineralized with CO<sub>2</sub> (as shown in

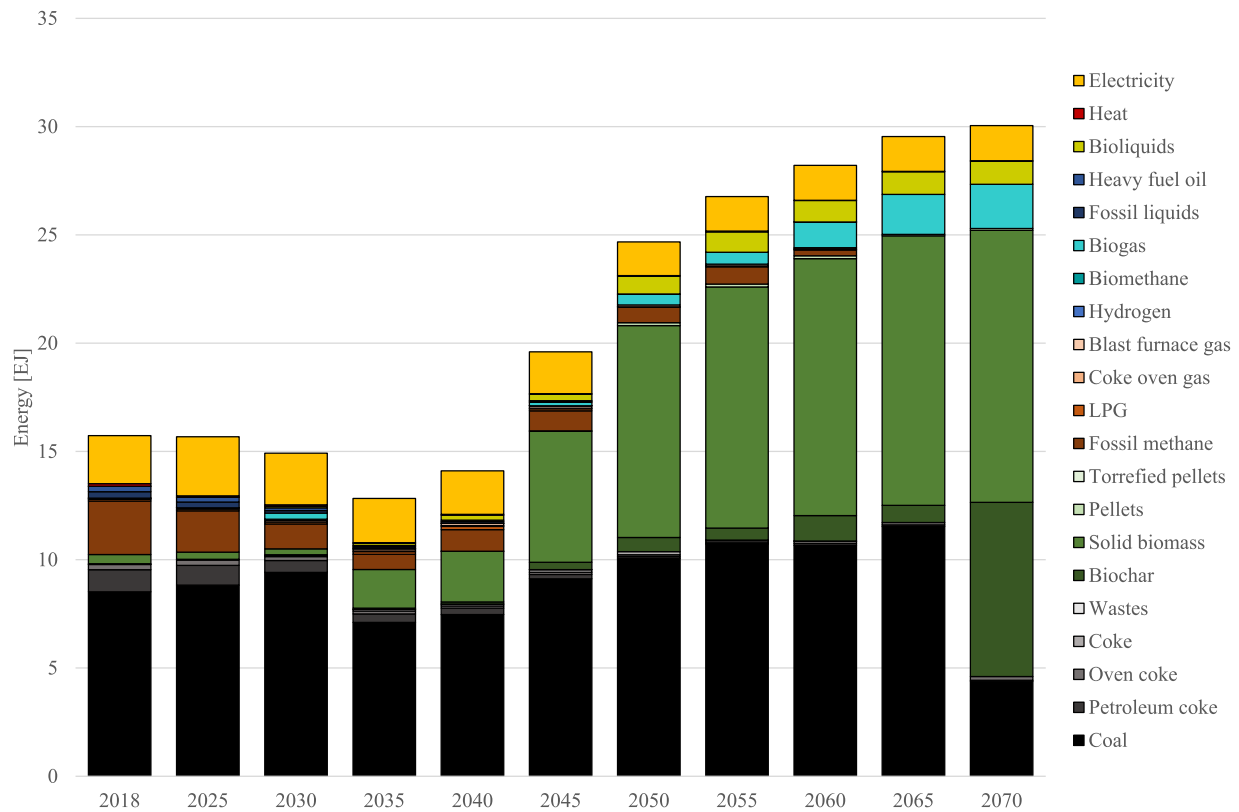


Fig. 10. Global profile of CO<sub>2</sub> capture in the cement industry for a CM0\_High\_50%\_10y.

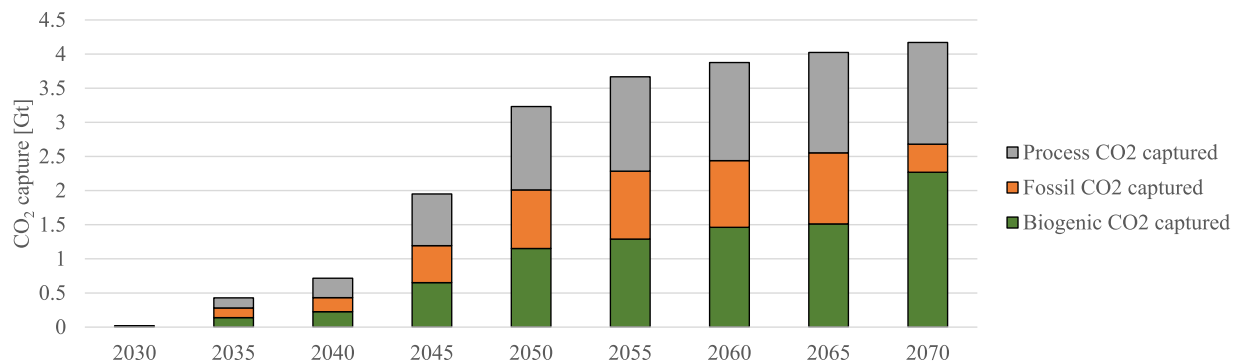


Fig. 11. Global energy consumption of the cement industry for a CM0\_High\_50%\_10y scenario.

Fig. 14).

Fig. 13

Thus, in the *CM0\_High\_50M\_10y* scenario, the global cement industry becomes net-negative in 2050 and beyond, which is much more ambitious than the target set by the GCCA. This optimal result from our study indicates the potential for the cement industry to become a net supplier of CO<sub>2</sub> permits globally. In particular, China generates the most negative emissions at 74% of the total for the 2030-2070 period – behind India (7%), and Africa (4%) – due to its enormous demand for cementitious products (72% of global production). Moreover, China capitalizes on this by becoming a net exporter of cementitious CO<sub>2</sub> permits, exporting three times more permits than it imports. This underlines large commercial opportunities for cement stakeholders if a global emissions trading system emerges, and at the national level, the cement industry could participate more thoroughly than expected in achieving emissions targets.

#### 4. Conclusion

This research underscores the opportunity for the global cement industry to become a carbon removal sector. Acknowledged decarbonization measures for this industry encompass strategies, including demand reduction, material efficiency, different fuel options like biomass or hydrogen, and technological changes like carbon capture and storage (CCS). By combining bioenergy and carbon capture and storage (BECCS), a cement plant can remove more CO<sub>2</sub> than it emits while producing cement, hence making the global cement industry a net-negative sector if deployed worldwide. In the literature, the BECCS technology applied to cement production emerges as promising yet understudied, contingent on uncertainties regarding biomass substitution rates and rotation periods, as well as concerns regarding the future of biomass management and availability. In studies projecting the future of the cement sector, the literature review reveals a focus on national models, with few studies focusing on industrial negative emissions strategies at the global scale. This research aims to assess the technical

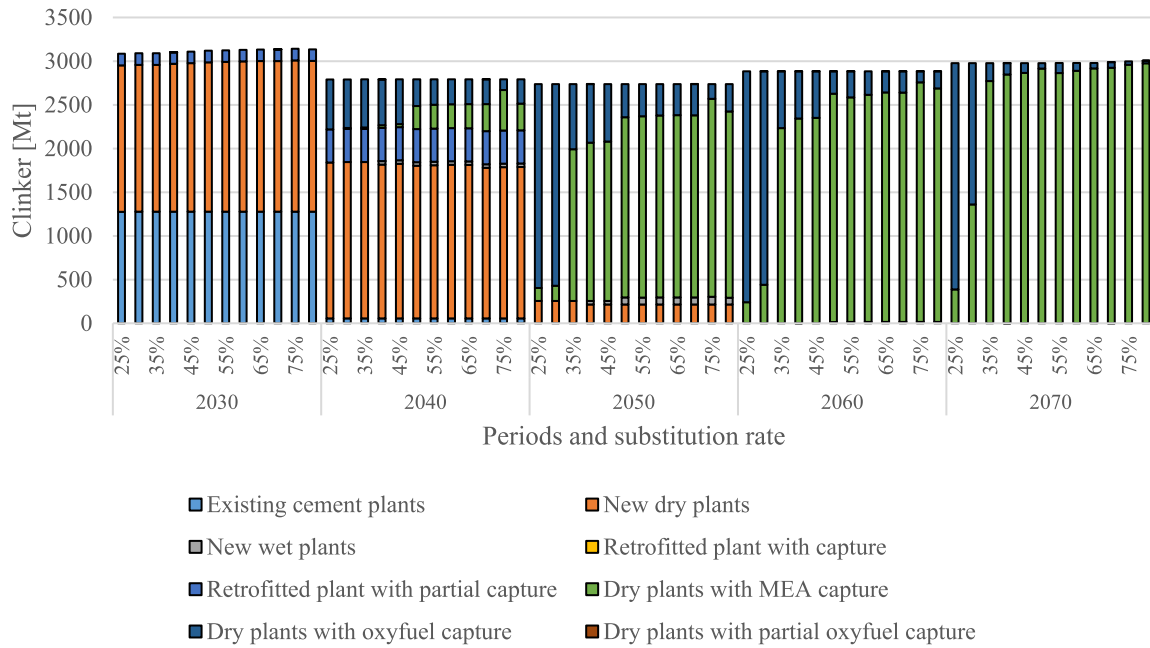


Fig. 12. Global clinker production for a CM0\_High\_10y scenario with different substitution rates.

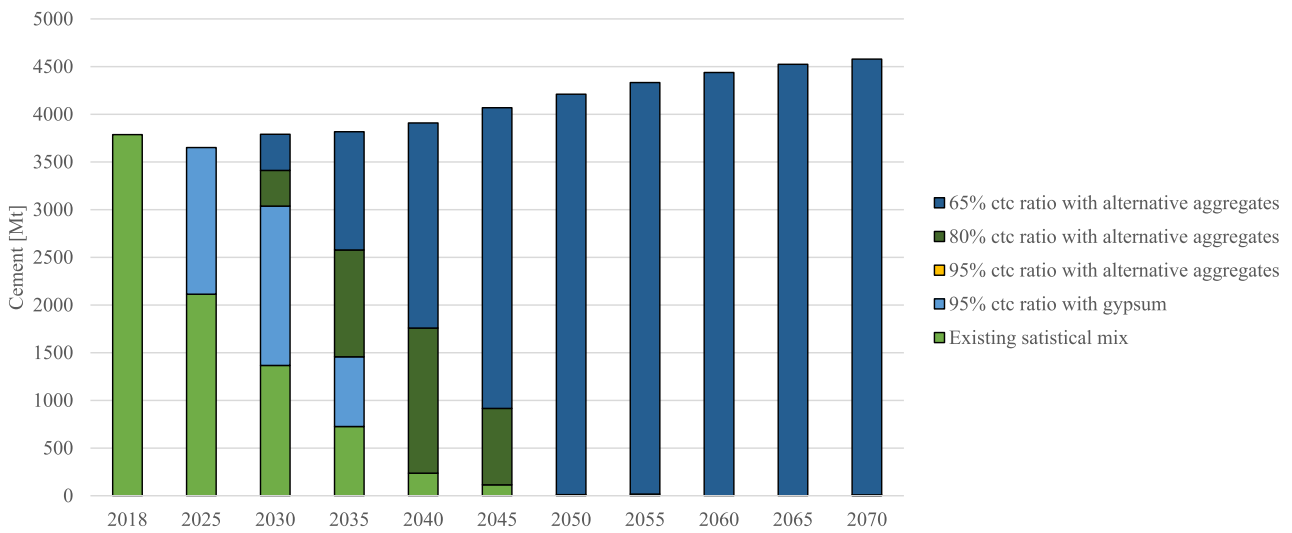


Fig. 13. Global profile of clinker-to-cement ratio for a CM0\_High\_50%\_10y scenario.

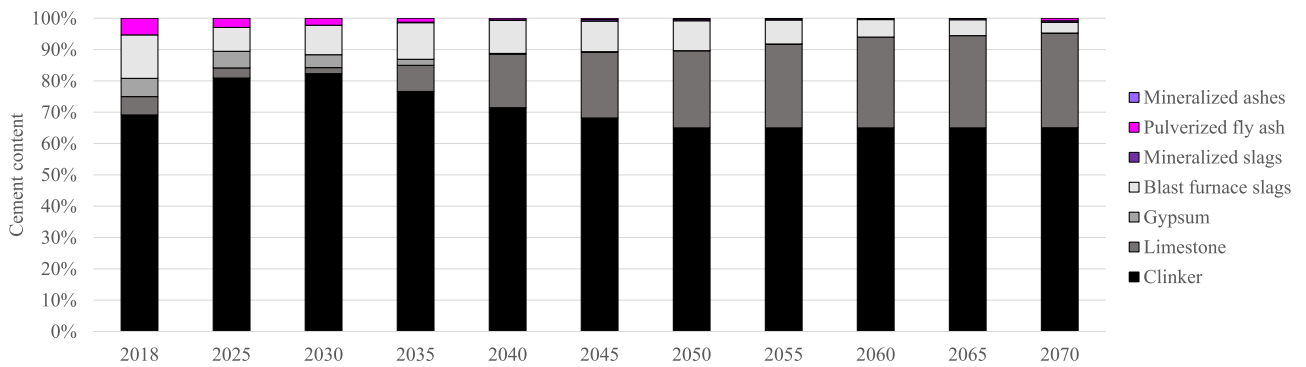


Fig. 14. Global cement content for a CM0\_High\_50%\_10y scenario.

feasibility and potential contributions of carbon removal to achieve global-scale decarbonization in the cement industry.

To this end, we explicitly model in TIAM-FR the production of cement across 15 regions with different energy use opportunities, technology investments, clinker-to-cement rates, and cement composition. Notably, the cement industry can employ biomass in different forms (solid, gaseous, or liquid) and combine it with dry kilns equipped with carbon capture units. Consequently, negative emissions opportunities are made available. Policy scenarios, biomass availability, and sensitivity analyses are explored, offering insights into the challenges and opportunities for widespread adoption of net-negative cement strategies globally.

Our analysis is conducted in a bottom-up manner, scrutinizing what combinations of policy, biomass potential, rotation period and substitution rate allow the global cement industry to reach net-negative emissions, assuming that the most pessimistic biomass potentials, costs, and efficiencies do not undermine the carbon neutrality of cement. However, current nationally determined contributions and pledges are not drastic enough to achieve cement decarbonization. Indeed, the decarbonization of the global cement industry hinges largely on the willingness of the Chinese cement industry to embrace decarbonization. According to our sensitivity tests, the decarbonization of the cement industry is significantly influenced by biomass substitution rates but shows limited dependence on biomass rotation periods. Nevertheless, considering rotation periods superior to 1 year – as it is frequently assumed in IAMs – seems unrealistic, but has a relatively low impact on the cement sector. Substantial improvements in biomass substitution rates would allow the global cement industry to reach net-zero, provided these rates are scaled to at least 40%. Biomass substitution rates appear more crucial in the cement sector in particular, as it is penalized by its process CO<sub>2</sub> emissions, unlike the power sector and the pulp industry. Hence, the cement industry must make more efforts to deploy bioenergy consumption combined with CCS and offset these process emissions.

Irrespective of the policy scenario and biomass potential, deploying BECCS in the cement industry emerges as a promising mitigation measure. The results suggest optimal deployment of solid biomass and pellets, complemented with biochar, achieving an almost fully bio-based solid energy mix. For gaseous biomass, fossil methane is phased out and replaced by biomethane. Importantly, neglecting the substitution of biomass in the cement industry could delay the achievement of the 2050 net-zero target announced by the GCCA by 10 to 18 years, according to our results. In the long run, adopting bioenergy in the final energy mix could prevent cement costs from rising. Overall, the decarbonization of the cement industry involves massive investment in BECCS. However, this strategy is not outlined in the GCCA roadmap, which merely mentions the potential emergence of carbon-negative concrete, offering limited indication of its feasibility.

In conclusion, we extend beyond the net-zero plan of the GCCA, proposing that the cement industry can evolve into a significant net-negative emitter, aiding other hard-to-decarbonize sectors by offsetting their emissions with cementitious CO<sub>2</sub> permits. Nonetheless, this would involve massive revamping of the current cement system. Future research should focus on the following.

Firstly, it is crucial to ensure that the 65% clinker-to-cement ratio becomes a standard by 2050 without compromising the quality of concrete in different structures and end-uses. Additionally, a comprehensive study of the other components of cement is needed to determine their influence on cement quality. In this study, recarbonation of CO<sub>2</sub> in

concrete structures was not considered. Assuming an ad hoc maximum carbonation of 105 kgCO<sub>2</sub>/t<sub>clinker</sub> (GCCA, 2022) and 4210 Mt of cement produced globally in 2050 (see Section 2.4), such recarbonation could bring an additional 440 MtCO<sub>2</sub> in savings. Besides, questions remain about the impact of climate change on existing and future concrete structures that could affect both the recarbonation process and cement demand.

Secondly, making the strategic decision to deploy significant CO<sub>2</sub> capture capacities for further storage is crucial. This necessitates assessing the technical operation involved in the simultaneous production of clinker along with the capture, collection, transport, and storage of CO<sub>2</sub> at both the local and regional scales. Concerns related to bio-methane substitution of fossil methane (Carvalho et al., 2023) and biochar for coal (Safarian, 2023) should be investigated and ensured. Following our results, the gigantic amounts of wood biomass required to process cement kilns after 2050 would have significant impacts on biodiversity, land, and water resources, which should be analyzed to assess the sustainability of the pathway we propose. Furthermore, the potential impact of climate change on biomass growth could pose a risk to the energy supply of cement kilns. While our findings indicate that pessimistic land use scenarios involve more bioenergy use in the cement sector, this counterintuitive result is highly dependent on the efficiency of other processes using bioenergy, such as biorefineries, power plants, steel, agriculture, etc. Further research is needed to bring more evidence into this result.

Finally, the current policies and long-term pledges prove insufficient to decarbonize the global cement industry by 2050, unless biomass represents more than 50% of the energy mix and is combined with CCS. This approach also requires the design of a global legal framework for CO<sub>2</sub> capture transport and storage.

#### CRediT authorship contribution statement

**Lucas Desport:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlos Andrade:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Damien Corral:** Data curation. **Sandrine Selosse:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

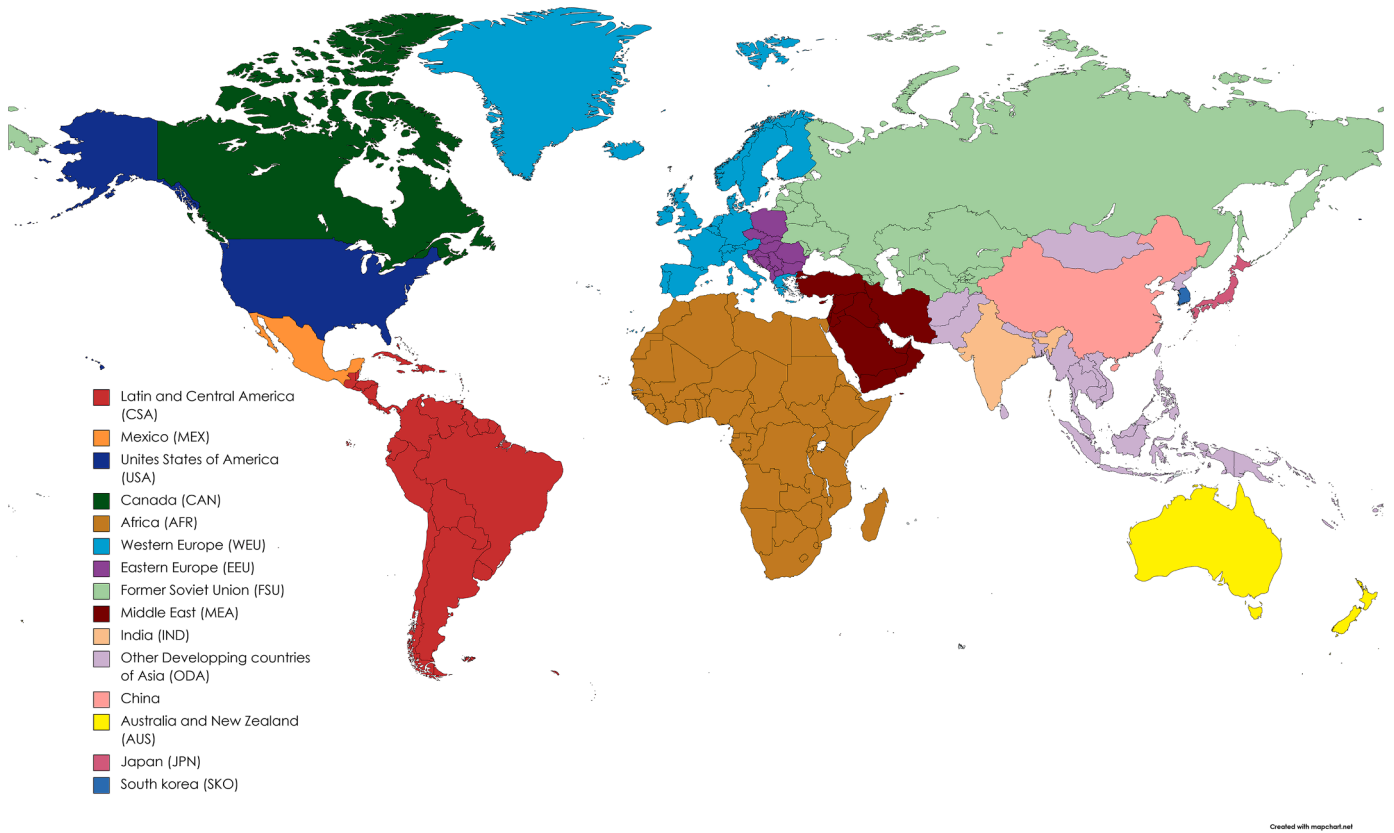
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#### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ijggc.2024.104280](https://doi.org/10.1016/j.ijggc.2024.104280).

Appendix A. Regions of TIAM-FR



Appendix B. Energy and cement demands, energy intensity, and clinker-to-cement ratios across regions

Region	Clinker-to-cement ratio	Reference
AFR	75%	(IEA, 2017)
AUS	84%	(Global Cement, 2022)
CAN	83%	(Cement Association of Canada, 2010)
CHI	65%	(IEA, 2020c)
CSA	71%	(Rowland, 2021)
EEU	82%	(IEA, 2017)
FSU	85%	(IEA, 2017)
IND	73%	(Rowland, 2021)
JPN	83%	(Taiheiyō Cement, n.d.)
MEA	80%	(IEA, 2017)
MEX	77%	(Rowland, 2021)
ODA	78%	(IEA, 2017)
SKO	92%	(Andrew, 2019)
USA	89%	(Rowland, 2021)
WEU	74%	(Cembureau, 2018b)

Appendix C. Remaining lifetime of existing assets across regions based on Fig. 1.14 of (IEA, 2020c)

AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU
26	26	22	28	24	27	21	27	18	26	24	26	26	21	27

Appendix D. NDCs recalibrated for the regions of TIAM-FR

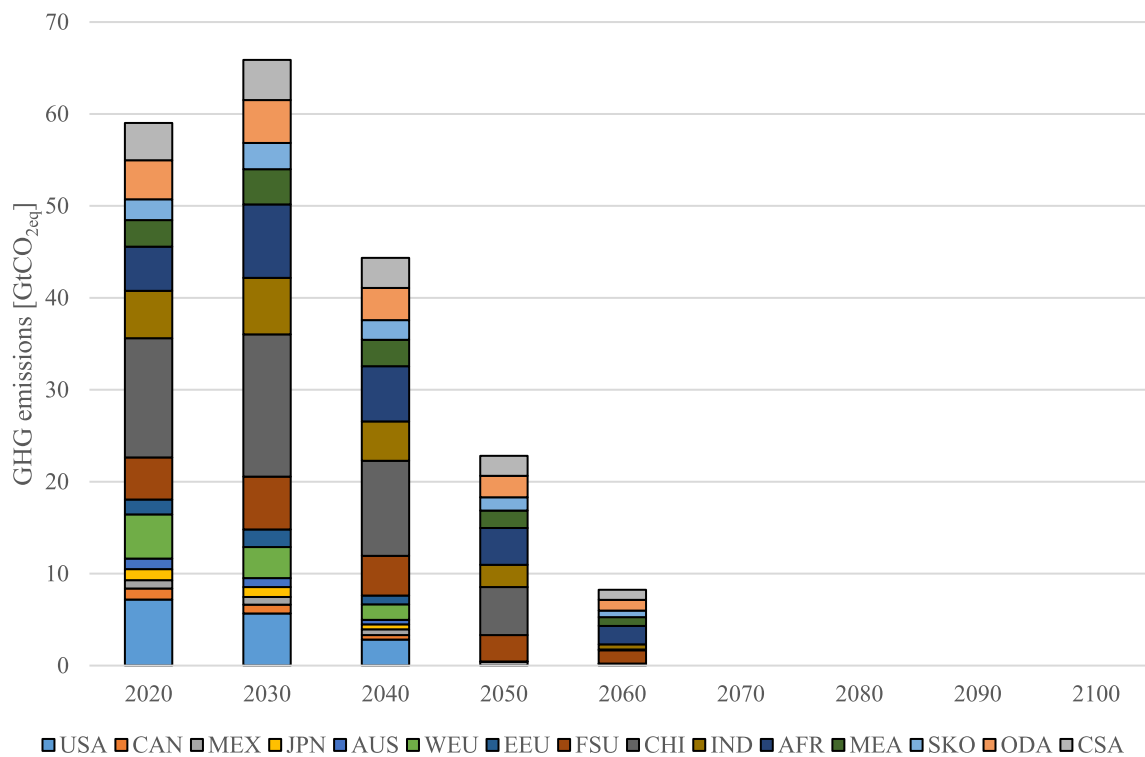
The NDCs are commitments made by countries under the Paris Agreement to reduce their greenhouse gas emissions and enhance their efforts to adapt to the impacts of climate change. NDCs are specific and quantifiable actions, policies, and measures that countries propose to take in order to



contribute to the global effort to combat climate change. As the name suggests, they are expressed by each country, while TIAM-FR aggregates countries into regions (see Appendix A). The table below thus shows the estimated targets of each region of TIAM-FR by compiling the national targets.

Region	Milestone year	Net GHG target [GtCO <sub>2,eq</sub> ]	Which GHG?
USA	2030	3.40	All GHGs
	2050	0	All GHGs
AUS	2030	0.55	All GHGs
	2050	0	All GHGs
CAN	2030	0.80	All GHGs
	2050	0	All GHGs
SKO	2030	0.62	CO <sub>2</sub>
	2050	0	CO <sub>2</sub>
JPN	2030	0.72	CO <sub>2</sub>
	2050	0	CO <sub>2</sub>
WEU & EEU	2030	2.77	All GHGs
	2050	0	All GHGs
IND	2030	5.05	CO <sub>2</sub>
	2070	0	CO <sub>2</sub>
CHI	2030	6.20	CO <sub>2</sub>
	2060	0	CO <sub>2</sub>
	2030	0.51	All GHGs
FSU	2030	6.34	All GHGs
ODA	2030	6.08	All GHGs
CSA	2030	3.55	All GHGs
AFR	2030	3.86	All GHGs
MEA	2030	4.40	All GHGs

Appendix E. GHG emissions cap in the NZ70 scenario in TIAM-FR



Appendix F. Region allocation between TIAM-FR and IIASA database

TIAM	IIASA database
AFR	Middle East and Africa
AUS	OECD

(continued on next page)

(continued)

TIAM	IIASA database
CAN	OECD
CHI	Asia
CSA	Latin America
EEU	Reforming Economies
FSU	Reforming Economies
IND	Asia
JPN	OECD
MEA	Middle East and Africa
MEX	Latin America
ODA	Asia
SKO	OECD
USA	OECD
WEU	OECD

## Data availability

I have shared a .xlsx file containing the main data used but the entire data used in the model cannot be given

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