



NDC ASPECTS

Technological Pathways towards Paris-compatible Steel, Cement and Petrochemicals (Deliverable D3.1-I.2 Report)

Annex 2 of Deliverable 3.1

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Executive Summary

The direct and indirect greenhouse gas (GHG) emissions of the industry sector amounted to 34% of the total anthropogenic GHG emissions in the year 2019. About 42% of the direct and indirect GHG from the industry sector arise from only three industrial sectors: the steel, cement and chemicals sectors (own elaboration based on IPCC, 2022). Despite the significance of these sectors for reaching the goals of the Paris Agreement, current Nationally Determined Contributions (NDCs) of major emitter countries do not include specific GHG reduction targets for the energy intensive industry sectors. It is therefore desirable to identify GHG reduction levels for these industrial sectors that are consistent with the goals of the Paris Agreement as well as corresponding sectoral pathways in order to inform future NDCs.

The main objective of the work conducted in WP3 “Sectoral Modelling” of the NDC ASPECTS project was to support the potential revision of existing NDCs of the Paris Agreement’s parties, as well as the development of new NDCs for the post 2030 period through conducting quantitative analyses of possible ambitious transformation opportunities in the industry sector. This report is part of the Deliverable D3.1: *Report and academic article manuscripts on opportunities and constraints in Industry, Transport, Buildings and AFOLU* of the NDC ASPECTS project and covers the work conducted in Task 3.2 “Sectoral Modelling for Industry”. The scope of the work was the energy-intensive industry, more specifically the three most CO₂-intensive industrial subsectors: steel, cement and chemicals. Key results of the work conducted are sectoral technology transformation pathways. As a basis for the development of the pathways, key mitigation options have been identified and characterized in all three sectors.

Steel

The bulk of emissions of (conventional) steel production is induced by the reduction of iron oxide through the use of coke and coal during the production of primary steel. Alternative, (almost) CO₂-neutral technology routes for primary steel production such as the hydrogen-based DRI route (H₂-DRI) have been developed and are expected to make a transformation of the steel industry to near-zero emissions possible in the coming decades, from a technical perspective. In the context of the NDC ASPECTS project the question arises whether the steel transformation expected from the current ambition of the steel industry is compatible with the Paris Agreement and – if this is not the case – which options exist to enhance ambitions and to achieve a Paris-compatible transformation pathway for the global steel industry.

The main objectives of the work conducted therefore were:

- › Objective 1: Assess the current ambition of the steel industry with regards to decarbonization in light of the Paris Agreement
- › Objective 2: Identify opportunities to raise the ambition and develop Paris-compatible global steel decarbonization pathways
- › Objective 3: Analyze the potential role and impacts of global DRI trade

The main method applied to achieve these objectives was the development and comparison of mitigation pathways for the global steel industry. A major focus of the work conducted for the steel sector was an analysis of the potential role and impacts of global DRI trade (Objective 3). This is reported in a paper manuscript by Bilici et al. (submitted) who describe two quantitative Paris-

compatible global mitigation pathways – the *domestic* and the *DRI-trade* pathways – which differ with regards to the role of global DRI trade (no global DRI trade assumed in *domestic*). These two pathways have been contrasted to a *current ambition* pathway in this report, which reflects the current ambition of the sector.

The *current ambition* is based on the IEA SDS scenario (IEA, 2020) while the *domestic* pathway has been synthesized from existing regional climate neutrality scenarios and roadmaps. The *DRI-trade* pathway is derived directly from the *domestic* pathway by applying rules that substitute parts of domestic hydrogen-based DRI production with DRI imports and allocate the DRI production to world regions with low production costs for green hydrogen. All pathways feature a regional break-down that allow insights for major emitter countries as well as emerging economies. For the synthesis of regional technology pathways on a global level and for the quantification of the emissions, costs and energy related impacts, the WISEE-EDM Global Steel Model has been developed and used.

The CO₂ emissions of the *current ambition* pathway in 2050 are about 1.4 Gt of CO₂ and the cumulative CO₂ emissions of this pathway amount to 66 Gt CO₂ in the period from 2020 to 2050 and are set to increase further in the time afterwards. The *domestic* pathway achieves near zero emissions in 2050 and implies cumulative CO₂ emissions of 51 Gt between 2020 and 2050. As defined by the scenario design, the *DRI-trade* pathway differs from the *domestic* pathway precisely in them locations of the production of hydrogen-based DRI (H₂-DRI) and features the same CO₂ emissions as the *domestic* pathway. According to the rules defined, global DRI trade starts in the late 2020s and grows significantly to a trade volume of 430 Mt DRI/year in 2050.

For the assessment of the *current ambition* with regards to decarbonization in light of the Paris Agreement, the pathway's cumulative emissions have been compared to CO₂ budgets allocated to the steel industry by two approaches. The first is a “sectoral grandfathering” approach which allocates 49 Gt CO₂ to the steel industry, based on its today's share of 7% of total emissions from the energy and industry sectors and a CO₂-budget of 700 Gt CO₂ for all of the energy and industry sectors in the period 2020-2050 that allows to stay below 1.7 °C with a probability of 67% (IPCC, 2022). The second approach assesses CO₂ budget allocations to the steel sector in scenarios from the IPCC AR6 scenario database.

Figure 0.1 (left) shows, that cumulative emissions of the *current ambition* can only be considered Paris-compatible (Objective 1) if the steel industry is granted a large share of the remaining CO₂ budget, compared to other sectors, as is the case in only very few scenarios. Figure 0.1 (right) shows, that the *domestic* global pathway building on regional net-zero studies can be much more robustly be assessed being compatible to the Paris Agreement.

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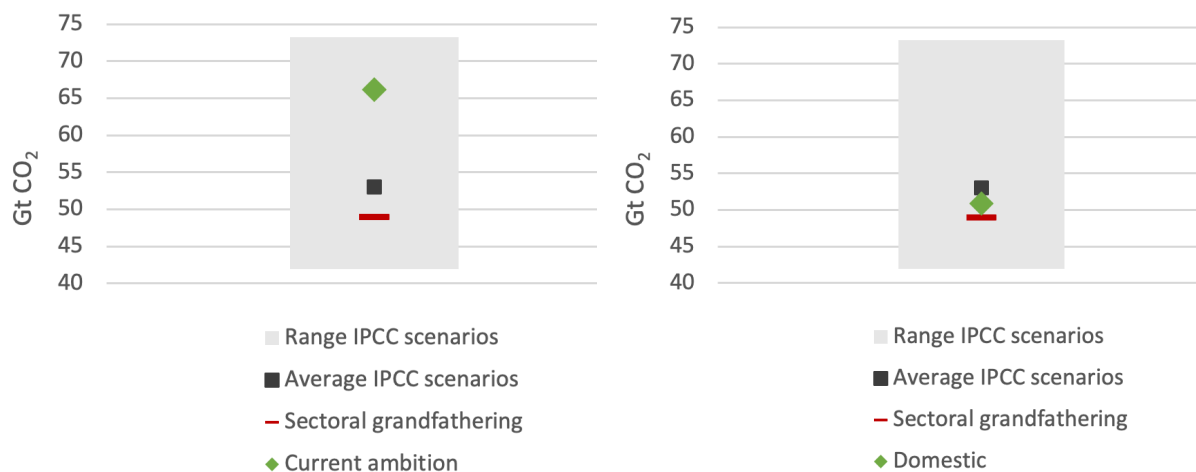


Figure 0. 1: Comparison of CO₂ budgets allocated to the global steel industry with cumulative emissions of the *current ambition* (left) and *domestic* (right) pathway

The opportunities for raising the ambition and developing Paris compatible global steel decarbonization pathways (Objective 2) are identified through comparison of the *current ambition* and the *domestic* pathways. Figure 0.2 shows that both pathways basically feature the same set of mitigation options. However, their implementation levels differ between both pathways. In particular, unabated steel production is avoided almost completely by 2050 in the *domestic* pathway but not in the *current ambition* pathway.

The potential role and impacts of global DRI trade (Objective 3) are assessed through comparison of the *domestic* and the *DRI-trade* pathways. Of the 570 Mt/year of CS produced with H₂-DRI in 2050 in the *domestic* scenario, 415 Mt/year are produced from imported DRI and the remaining 155 Mt/year domestically as H₂-DRI in the *DRI-trade* scenario. Global DRI trade implies a shift in hydrogen consumption around the globe and more than 26 Mt/year of hydrogen consumption shifts to Australia, Brazil and South Africa in 2050, according to the scenario. On the other hand, hydrogen consumption by the steel industry in DRI-importing regions such as China, India and the EU decreases by 75% on average. Consequently, DRI trade could have a significant impact on energy system transformation in both exporting and importing countries.

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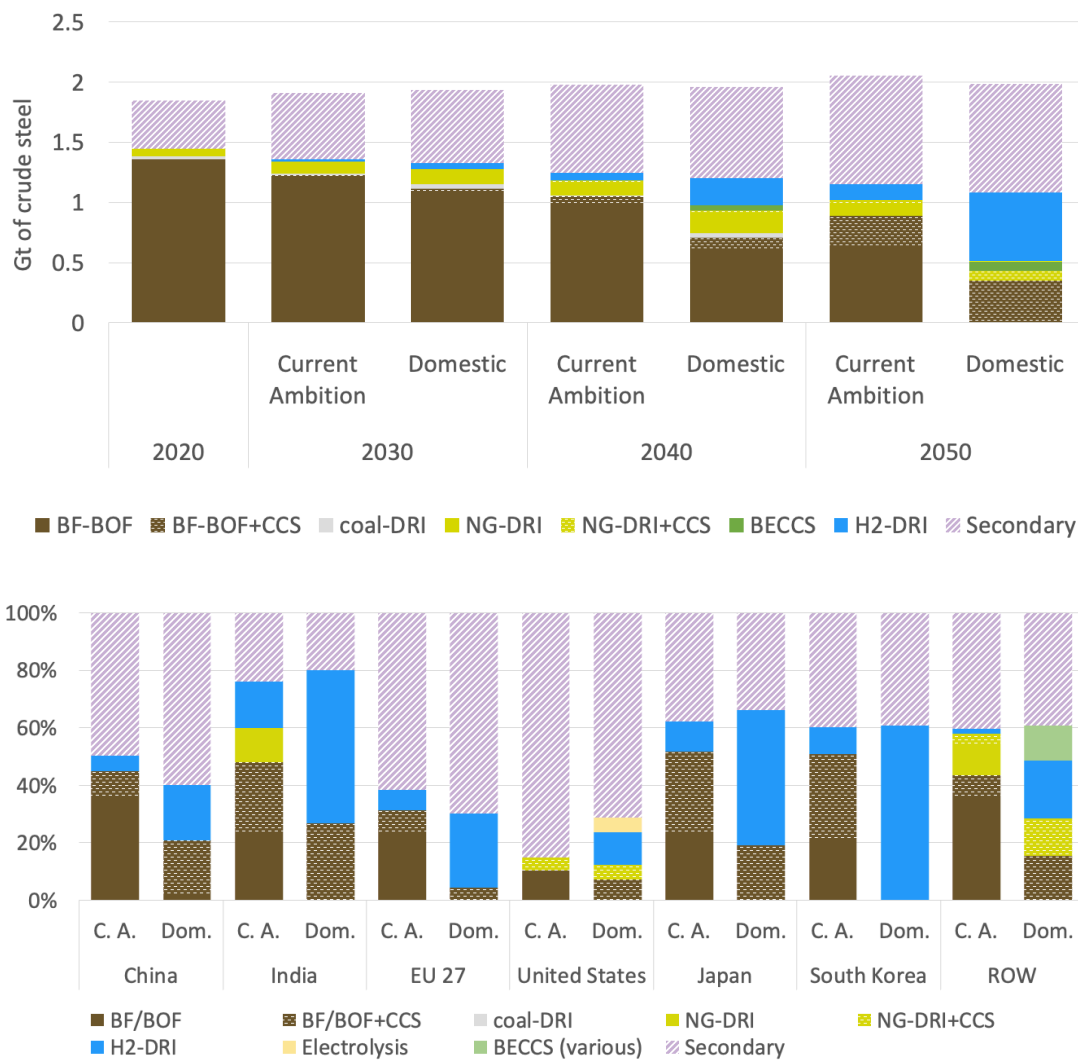


Figure 0.2: Global crude steel production per production route in the *domestic* pathway, compared to the *current ambition* pathway: globally (top) and regional break-down for 2050 (below)

Figure 0.3 shows that specific steel production costs increase in all cases compared to 2020, but stronger in the *domestic* pathway and the *DRI-trade* pathway than in the *current ambition* pathway. The higher costs in the latter two pathways are due to a faster upscaling of mitigation options such as H2-DRI and CCS, which have higher specific costs than the BF-BOF route. Figure 0.3 also shows that part of the cost increase can be dampened by global DRI trade. Compared to the *domestic* scenario, global DRI trade generates cost savings of more than 45 billion dollars annually and globally in 2050, because it facilitates more H2-DRI being produced in countries with low-cost renewable electricity generation. The savings represent nearly 4% of the annual production costs in 2050.

The mitigation costs for the CO₂ reduction that goes beyond the *current ambition* would be about 149-159 \$/t CO₂ in the *domestic* pathway and could be reduced to about 111-141 \$/t CO₂ if global DRI trade is considered (*DRI-trade* pathway).

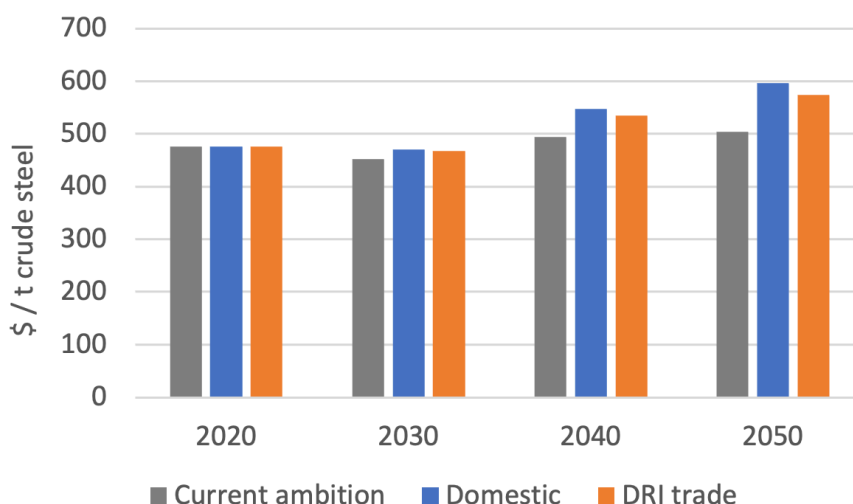


Figure 0.3: Global average specific crude steel production costs in the three pathways

Cement

Cement is responsible for about 7% of global CO₂ emissions from the energy and industry sectors (IPCC, 2022).¹ Almost all of the direct emissions related to the sector are generated through the production of cement clinker and about 2/3 of these emissions result from the chemical reaction by which cement clinker is produced from limestone. Nevertheless, strongly reduced levels of CO₂-emissions or even climate neutrality of the cement sector are deemed possible. Broadly speaking, key strategies are: 1) reducing the amount of clinker required to achieve the same performance of concrete structures, 2) reducing CO₂ generation during clinker production through thermal efficiency, fuel switch and use of decarbonated raw materials, 3) capture and storage of CO₂ generated during clinker production.

Several cement industry associations have developed roadmaps for CO₂ mitigation for their respective regions. It has, however, not yet been assessed whether the current ambition of the cement industry reflected by these roadmaps is compatible with the Paris Agreement.

Against this background, the purpose of the work conducted was to

- › assess whether current decarbonization ambitions for the cement sectors on the global level and in major emitter countries (China, EU, India, USA) are in line with the Paris goals and to
- › identify levers for acceleration of cement decarbonization and to assess their impacts.

The main approach chosen to achieve the objectives was the development and comparison of mitigation pathways for the major emitter countries China, EU, India and USA. For the elicitation of the current ambition of the cement industry a quantitative analysis of existing roadmaps (*current ambition*) with regards to their cumulative CO₂ emissions in the time period 2020 to 2050 was conducted. For the identification of levers for further acceleration of cement decarbonization we conducted a comparative analysis between the mitigation levers in these roadmaps and derived pathways with *increased ambition*, based on the comparison. For the quantification a model has been

¹ When including both, fuel-related and process-based CO₂ emissions of cement production.

developed and used which provides a unified analytical structure to represent and compare the different national roadmaps.

The pathway's cumulative emissions have been assessed against a regional break-down of a Paris-compatible CO₂ budget for the global cement industry. The global budget was derived by comparison of three approaches ("sectoral grandfathering"; cumulative emissions of the cement sector of Paris-compatible scenarios from the IPCC AR6 scenario database; cumulative CO₂ emissions implied by the global cement roadmap of the GCCA (2021)). The regional break-down of the global budget was conducted by three different allocation methods ("Grandfathering", "Immediate per capita convergence", "Equal cumulative per capita emissions"). For the global level, we conclude that staying below cumulative emissions of (about) 50 Gt CO₂ is an ambitious and Paris-compatible mitigation target for the global cement industry and that the roadmap of the Global Cement and Concrete Association (GCCA, 2021) is in line with this target.

The regional allocations of budgets, however, differ largely, depending on the allocation method. The very high level of current absolute and per-capita cement use of China strongly influences the picture and generates a huge range of arguable budgets for all countries. Figure 0.4 shows that for China, India and the EU27, the emissions implied by the roadmaps fall into the bandwidth of budgets spanned by the three allocation approaches. Hence, in all these cases, there are perspectives according to which each roadmap is or is not compatible to the Paris Agreement. The picture is clearest with regards to the roadmap for the USA, which is (almost) compatible to the Paris Agreement, according to all allocation methods applied.² Due to the dependence of the assessment of Paris-compatibility on the allocation method chosen, debates about burden-sharing among countries' cement sectors for reaching the global target may be difficult. This highlights a strong need for further international cooperation on this matter.

Table 0.1 shows the mitigation levers for which an increase in ambition is suggested in the *increased ambition* pathways (for more information see cement chapter of this report). The resulting reduction of cumulative emissions between the *current ambition* and the *increased ambition* pathways appears to be modest in China (11%), EU27 (11%) and the USA(8%) – see figure 0.4. In these cases, the decrease of emissions can be accelerated to some degree in the *increased ambition* pathways, but only gradually and to increasing extents over time as all mitigation levers require time for their (additional) upscaling. As a consequence, large shares of the cumulative emissions are already emitted before a massive (additional) scale-up of mitigation options can be achieved.

The case of India is different as cement demand increases strongly in both pathways and the *current ambition* pathway of India is somewhat delayed, compared to the other analyzed regions. As a consequence, additional mitigation efforts that are scaled up massively after 2030 have higher impacts, leading to a reduction of cumulative emissions by 29% in the *increased ambition* pathway, compared to the *current ambition* pathway. The global south – here represented by the case of India – requires special attention due to its expected strongly rising demand for concrete buildings. Additional CO₂ mitigation through an *increased ambition* appears to be highest in India, compared to

² It should be noted, however, that the calculations of the cumulative emissions of the roadmap for the USA includes several crucial assumptions, as the information provided in the roadmap was not conclusive with regards to all mitigation levers, in particular CCS. See main part of the report for further information.

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the other major emitters analyzed, suggesting that any efforts beyond what is already planned would have the highest mitigation impact in the global south.

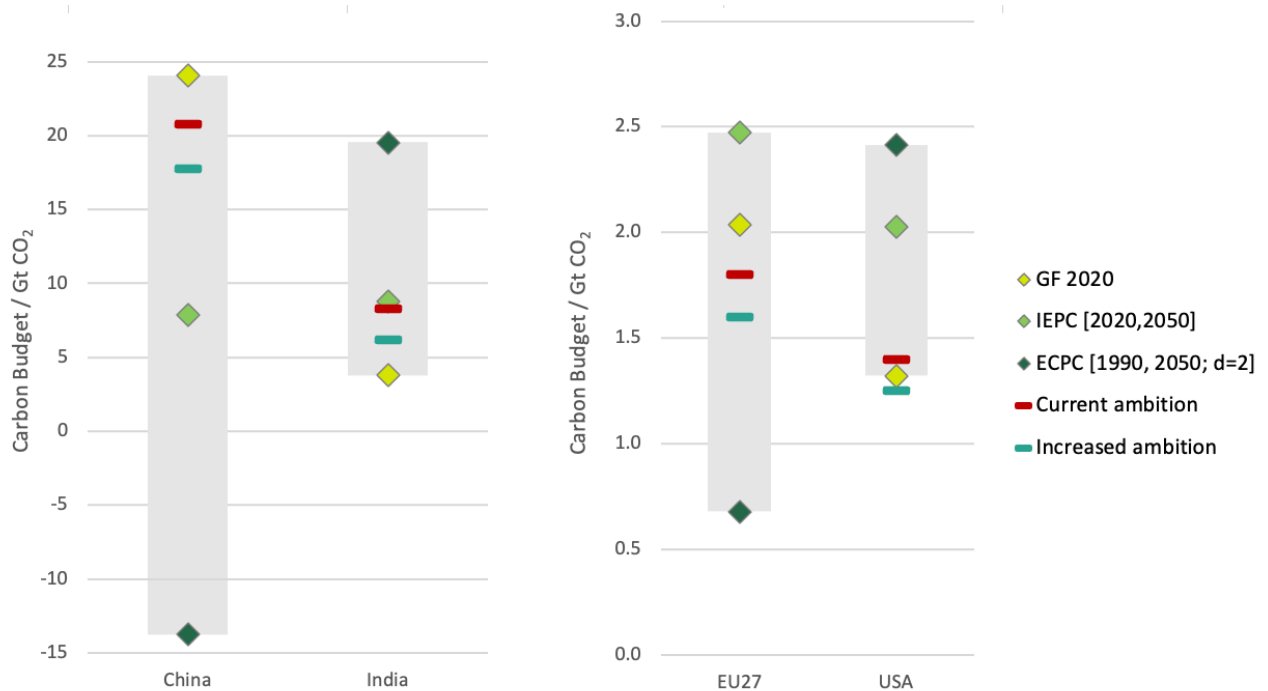


Figure 0.4: Carbon budgets allocated to cement sectors of world regions according to various approaches compared to cumulative CO₂ emissions implied by regional *current ambition* and *increased ambition* pathways. Note: GF=“Grandfathering”; IEPC=“Immediate per capita convergence”; ECPC=“Equal cumulative per capita emissions”

Table 0.1: Mitigation levers for which an increase in ambition is suggested in the increased ambition pathway for the respective country

	China	India	EU27	USA
Concrete demand per structure		X	X	
Binder intensity of concrete		X		
Use of decarbonated raw materials		X		X
Clinker factor	X			
Waste-based fuels	X	X	(X)*	X
Biomass fuels	X	X	X	X
CCS	X	X	(X)*	X

*Minor increase of ambition for 2030 only, based on recent developments and announcements.

The cumulative emissions of the *increased ambition* pathway rank similar to those of the *current ambition* pathway (see Figure 0.4); i.e. the assessment of the Paris-compatibility does not change substantially between the pathways for any of the allocation approaches. From a technical point of view, a further increase of the mitigation ambition beyond the *current ambition* of major emitters seems thus possible. The identified potential for increasing the ambition is however not essential for the assessment of the pathways' credibility in light of the Paris Agreement. The main focus for policy makers and stakeholders with regards to the cement and concrete industries should therefore be on implementation and realizing the existing pathways and creating the relevant enabling policies, while further discussions about targets appear to be secondary.

Figure 0.5 shows the contributions of the analyzed mitigation levers related to overall CO₂ mitigation achieved in the *increased ambition* pathways of the analyzed cases. CCS is the mitigation option with the highest single mitigation impact, according to our analysis. The findings thus support the sector's current strong focus on this mitigation option. However, the analysis furthermore reveals that material efficiency – saving concrete and binders – is beneficial in multiple ways: on the one hand it has the potential to directly reduce clinker demand and associated CO₂ emissions considerably. On the other hand, material efficiency has indirect effects through facilitating a faster upscaling of other mitigation options: it allows a greater reduction in the clinker factor and a greater increase in the share of alternative fuels and CCS in the remaining cement production plants, as fixed absolute amounts of limited resources (SCMs, suitable waste, CO₂ infrastructure) can still be used and higher relative application rates can be achieved if overall cement demand is reduced.

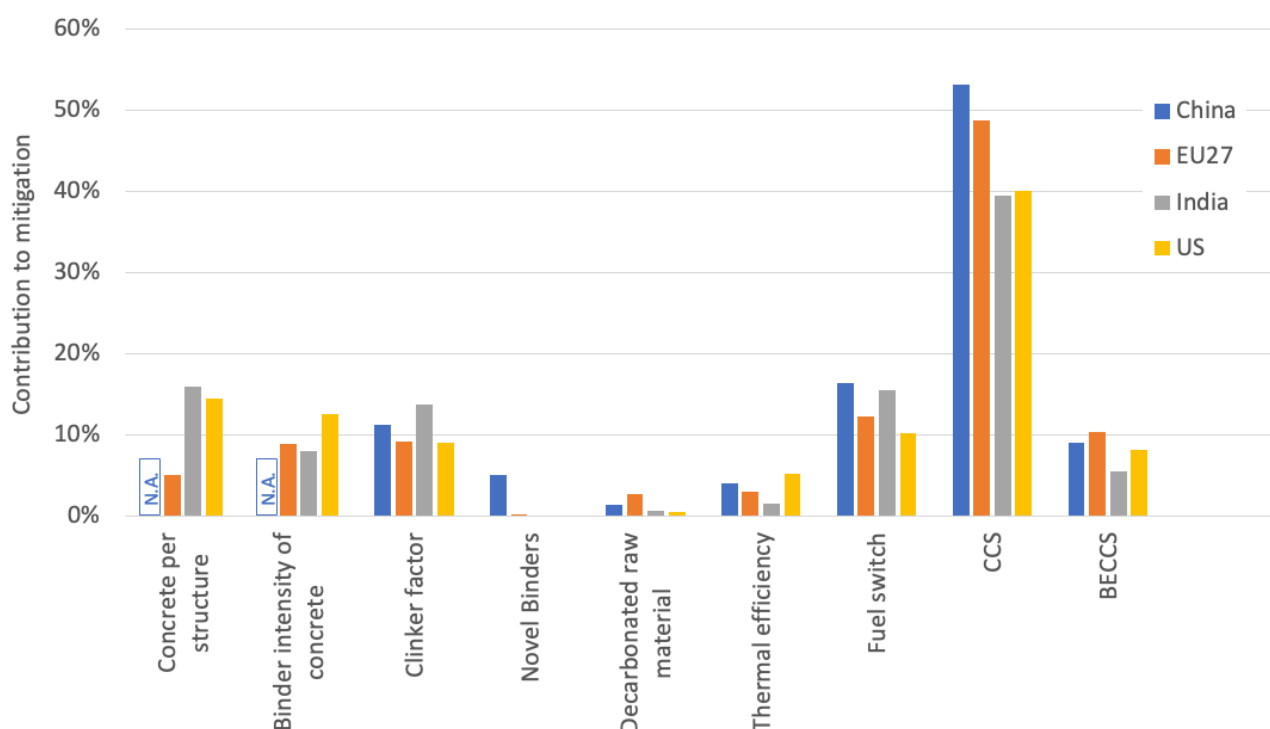


Figure 0.5: Contributions of the analyzed mitigation levers related to overall CO₂ mitigation achieved in the *increased ambition* pathways of the analyzed cases.

Petrochemicals

According to the IPCC (2022) the direct³ energy- and process-related CO₂ emissions from the global chemicals and petrochemicals sector made up approximately 9.9% of the total global direct industrial CO₂ emissions in 2019. The petrochemical sector produces a broad range of intermediary and final chemical products from mineral oil and natural gas. The materials produced by the petrochemical industry, including plastics, rubbers and fertilizers have become pervasive in our societies and everyday lives. The role of the petrochemicals sector in mitigating climate change therefore becomes most apparent when considering Scope 3 emissions, i.e. the provision of its (fossil) feedstock and the fate of its carbon-based products.

While the total portfolio of final products made from petrochemicals is large, these are produced from a much smaller number of key primary chemicals (IEA, 2018). The scope of the exercise covers the most important material flows and processes to produce five key primary chemicals also referred to as high value chemicals (HVCs): ethylene, propylene, benzene, toluene and xylene.

The petrochemical sector is closely intertwined with the fuel sector and its products are partly substitutable, offering a very wide range of possible futures. Mitigation technologies covering specific parts and aspects of the production value chain have been described before and scenario studies have been conducted based on modelling. To the perception of the authors, the debate could benefit from an analytical lens in the form of conceptual building blocks for understanding the complex transformation of the petrochemicals sector at an intermediate level in-between single mitigation technologies and full-blown scenarios.

Against this background, the work conducted derived three defossilized archetypical production routes, which are qualitatively described and characterized, in addition to the currently dominant fossil fuel integrated route. The process routes are illustrated and characterized in terms of necessary mitigation technologies, feedstock and energy use, carbon efficiency, their interaction with other sectors along the value chain, as well as geographical aspects. Each archetypical process route has its own limitations and shortcomings, which are also presented. The routes are thus not to be understood as stand-alone systems, rather, they carve out different core elements of an encompassing defossilized petrochemicals production system as a means to analytically decompose its complexity.

The *current fossil fuel integrate route* is described for setting the scene and as a reference point for the portfolio of intermediary products which is required in the subsequent petrochemicals value chain. The *synthetic fuel integrated production route* shares a strong resemblance to the current fossil system in that it presumes a retained strong connection to the fuel industry. The fuel industry is assumed to have transformed, now producing renewable Fischer-Tropsch fuels, and the chemical industry can make use of its by-products. Also similar to the current system is the use of these fuel by-products in steam crackers. The *green methanol-based production route* instead is a new type of petrochemical production route, no longer strongly linked to the production of fuels. In this system, naphtha is no longer the central input commodity for the production of petrochemicals. The new platform chemical is methanol, produced from renewable CO₂ and H₂. MtO (Methanol to Olefins) and MtA (Methanol to Aromatics) technologies are used to produce HVCs out of it. Finally, the *carbon looping production route* highlights how the carbon can remain in-loop, avoiding losses and thus reducing the need for new input feedstock. Electrified steam crackers are used as well as methanol-based processes,

³ i.e., the Scope 1 CO₂ emissions

interacting in a way that makes use of the processes by-products. Technologies for chemical recycling of by-products and plastic wastes are the characterizing elements of this route.

These production routes take complementary roles in a future petrochemicals production system: the *synthetic fuel integrated production route* makes high-value use of green naphtha, a by-product from renewable fuel production. The *green methanol-based production route* is a comparably energy-efficient route to provide additional carbon from renewable sources and to convert it into HVCs. The *carbon looping production route*, finally, aims at re-using carbon already in the techno-sphere to a large extent in order to limit CO₂ emissions, save renewable resources and reduce the renewable energy demand of the petrochemicals system.

The development and characterization of the production routes revealed that these are different with regards to yield shares of the different HVCs, as well as with regards to the production of other by-products such as butadiene. If major disruptions of the downstream polymer industry are to be avoided, the design of future petrochemicals systems need to take these differences of yields into account to achieve a balanced portfolio, overall. It became furthermore apparent, that the routes differ with regards to energy demand in terms of energy amounts, energy carriers and location of the energy demand. Furthermore, their possibility to make use of existing capacity stock and infrastructure as well as requirements for nearby facilities such as waste-management differs as well. The transformation will hence in all likelihood play out differently across different geographies, while regional developments will interact on a global market for feedstock and HVCs.

To illustrate how the routes could be combined in the transformation of specific sites towards a future defossilized chemical industry, the report describes two future scenarios of two different fictional chemical clusters in short narratives. The first fictional cluster described represents an existing cluster that manages to undergo a transition from a conventional fossil system to a fully decarbonized system, whereas the second cluster is a greenfield development within the new renewable resource economy that has formed.

Gender aspects

Gender impacts of industrial decarbonization are a marginalized topic that is under-researched and often under-represented in discussions of the transformation of energy-intensive industries. Through desk research, impacts of industrial decarbonization could be found along all seven gender dimensions. They include impacts related to paid and unpaid work, aspects of a just transition of industrial communities, access to decision-making processes along the value chain, conflicts of interest related to workers' protection and environmental conservation, and the dominance of "masculinist" paradigms of industrial production and growth-centered economic organization. In order to ensure a successful and just transition for all, gender aspects need to be taken into account more broadly and deeply in analysis and discussion of industrial decarbonization.

1 Introduction and overview

The direct greenhouse gas (GHG) emissions of the industry sector amounted to 24% of the total anthropogenic GHG emissions in the year 2019, which increases to 34% if indirect emissions are included (IPCC, 2022). The direct and indirect GHG emissions of the industry sector have increased from 8.6 Gt in the year 2000 to 20 Gt in the year 2019, according to IPCC (2022). This trend needs to be reversed and emissions need to drop significantly in the coming decades in order to reach the goals of the Paris Agreement. About 42% of the direct and indirect GHG emissions of the industry sector arise from only three industrial sectors: the steel, cement and chemicals (own elaboration based on IPCC, 2022). Despite the significance of these industrial sectors for reaching the goals of the Paris Agreement, current Nationally Determined Contributions (NDCs) of major emitter countries do not include specific GHG reduction targets for the energy intensive industry sectors.⁴ It is therefore desirable to identify GHG reduction ambition levels that are consistent with the goals of the Paris Agreement as well as corresponding sectoral pathways in order to inform future NDCs.

The main objective of the work conducted in WP3 “Sectoral Modelling” of the NDC ASPECTS project was to support the potential revision of existing NDCs of the Paris Agreement’s parties, as well as the development of new NDCs for the post 2030 period through conducting quantitative analyses of possible ambitious transformation opportunities in the industry sector. In order to do so, mitigation options were identified, the current ambition for GHG reduction was assessed and opportunities for increasing the ambition were identified.

This report is part of the Deliverable D3.1: *Report and academic article manuscripts on opportunities and constraints in Industry, Transport, Buildings and AFOLU* of the NDC ASPECTS project and covers the work conducted in Task 3.2 “Sectoral Modelling for Industry”. It thereby complements Deliverable D3.1-I.1, the academic article manuscript by Bilici et al., as submitted to the Journal of Cleaner Production in June 2023, which is currently⁵ under revision. The main purpose of this report is to document the work conducted and the results achieved in Task 3.2 which are not covered by the above-mentioned academic article manuscript.

The scope of the work conducted in Task 3.2 was focused on the energy-intensive industry, more specifically the three most CO₂-intensive industrial subsectors: steel, cement and chemicals. Since the prime purpose of this report is the documentation of the work conducted and of the results, it does not feature a full-fledged introduction to the transformation of the industry sector or the industrial sub-sectors analyzed. The interested reader is referred to existing literature for this purpose, such as (Agora Energiewende & Wuppertal Institute, 2021; IEA, 2022), for example.

Key results of the work conducted are sectoral technology transformation pathways, based on the state of the art in research and technology and in line with the long-term climate protection goals of the Paris Agreement. The main focus of the work was on steel, in alignment with other work conducted in the project as well as with the topics of the sectoral conversations held in WP1. For the steel sector (chapter 2) two quantitative Paris-compatible global mitigation pathways have been derived through modelling, and contrasted to a current ambition pathway. All pathways build on existing studies and feature a regional break-down that allows insights for major emitter countries as well as emerging economies. Key results of the analyses of the steel sector are included in the academic article

⁴ The NDCs of the major emitters China, EU, India and USA were checked in the version available on the website of the UNFCCC (<https://unfccc.int/NDCREG>) in October 2023.

⁵ At the date of submission of this report: Oct 30th 2023.

manuscript draft by Bilici et al. (submitted) that is part of the same Deliverable as this report.

For the cement sector (chapter 3), existing roadmaps for the major emitters China, India, EU27 and USA have been quantified, assessed and cross-compared to identify further potential for increased ambitions. Quantitative pathways with increased ambition have been derived through this comparison and own modelling, and assessed.

With regards to the chemicals sector (chapter 4), the analysis focusses on the petrochemicals subsector, which is the most extensive and complex chemicals subsector. The aim of the work done for the petrochemicals sector has been to provide an analytical lens and conceptual building blocks for understanding the transformation of (selected relevant parts of) the petrochemicals sector on an intermediary ground in-between single mitigation technologies and full-fledged scenarios. For this purpose, three defossilized archetypical production routes have been proposed, which are qualitatively described and characterized. These production routes feature different key mitigation technologies and take complementary roles in a future petrochemicals production system. It is furthermore illustrated how the routes could be combined in the transformation of specific sites towards a future defossilized petrochemicals industry through two narratives of two different fictional chemical clusters.

As a basis for the development of the pathways, key mitigation options have been identified and characterized in all three industrial sectors. In particular the chapter on the cement industry features an extensive assessment of the contributions of different mitigation options to the overall mitigation achieved.

Finally, gender aspects of the industry transformation have been investigated through desk research (chapter 5).

2 Steel

2.1 Introduction

According to the IPCC (2022), the steel industry responsible for 7% of total CO₂ emissions of the energy and industry sectors globally. The bulk of emissions of (conventional) steel production is induced by the reduction of iron oxide through the use of coke and coal during the production of primary steel. Alternative, (almost) CO₂-neutral technology routes for primary steel production have been developed to high technology readiness levels (TRLs) already and are expected to make a transformation of the steel industry to near-zero emissions technically possible in the coming decades. A range of roadmaps and scenario studies have been conducted on the global level (e.g. Bataille et al., 2021; IEA, 2022; MPP, 2021; Yu et al., 2021) as well as on regional levels (e.g. J. Chen et al., 2021; Hall et al., 2022; Hasanbeigi et al., 2023; Material Economics, 2019) that describe transformation pathways for the global or respective regional steel industry towards net-zero.

As outlined in the introduction, current NDCs of major emitter countries do not explicitly set CO₂ reduction targets for the steel industry and do not elaborate on corresponding measures and pathways. But, because of the high relevance of the steel industry for achieving the goals of the Paris Agreement, steel specific targets and measures should be included in future NDCs, ideally. The question then arises, which ambition level and which measures should be included. Industry associations, whose primary role is to advocate the interests of their members and who have established knowledge about their sectors, will likely have an important voice in this. In the opinion of the authors, future NDCs should be at least as ambitious as the targets set by the (steel) industry itself.

Against this background, in the context of the NDC ASPECTS project the question arised whether the steel transformation expected from the current ambition of the steel industry is compatible with the goals of the Paris Agreement and – if this is not the case – which options exist to enhance ambitions and to achieve a Paris-compatible transformation pathway for the global steel industry.

Therefore, the first two objectives of the work conducted were:

- › Assess the current ambition of the steel industry with regards to decarbonization in light of the Paris Agreement
- › Identify opportunities to raise the ambition and develop Paris compatible global steel decarbonization pathways

One mitigation technology that plays a key role in scenarios and roadmaps for the steel industry is hydrogen-based iron reduction, which has been the subject of many project announcements including first investment decisions by big steel companies in the recent years. In contrast to hot metal from the blast furnace, the direct reduced iron (DRI) produced in a shaft furnace exists in a solid state and can be transported at reasonable costs over long distances. This enables spatially decoupling the production step of iron reduction from that of steelmaking. In principle, DRI hence could be produced in global “sweet spots” which are rich in both iron ore resources and renewable energy and subsequently be shipped to steelmaking sites around the world. Such global DRI trade is increasingly discussed and – if realized at scale – may have major impacts on the global steel production network as well as on the energy systems of both DRI exporting and DRI importing countries. Therefore, the third objective of the work conducted was to

- › Analyze the potential role and impacts of global DRI trade

Parts of the quantitative analyses of the steel sector conducted during Task 3.2 of the NDC ASPECTS project have been described in Bilici et al. (submitted). Bilici et al. (submitted) focuses on the third objective – analyzing the impacts of global DRI trade – in particular and describes two Paris-compatible decarbonization pathways for the global steel industry which differ with regards to the role of global DRI trade. Those parts of the work described by Bilici et al. (submitted) are not repeated at length in this report, but references are made where appropriate, instead.

2.2 Methodology

2.2.1 Approach

In order to achieve the above-mentioned objectives, three quantitative pathways for the global steel industry and for the time period 2020 to 2050 have been developed through synthesis and adaptation of existing pathways:

- › *Current ambition*: reflects the current ambition of the global steel industry, including a regional break-down. It goes beyond a stated policies scenario and reflects what industry actors currently aim to achieve, if policy frameworks and market conditions are created accordingly.
- › *Domestic*: a Paris-compatible pathway for the global steel industry compiled from regional pathways which are Paris-compatible, according to the underlying studies
- › *DRI-trade*: Identical to *domestic* with regards to steel making, but assuming that global trade of DRI is taking place

The technology pathway of the Sustainable Development Scenario (SDS) of the IEA (2020) has been chosen as the *current ambition* pathway as the World Steel Association, whose members represent 85% of the global steel production⁶, makes strong reference to it in its climate policy paper (World Steel Association, 2021).

The regional technology pathways which are synthesized into a global picture for the *domestic* pathway have been identified through desk research and the pathways as well as amendments to the pathways have been discussed with country partners of the NDC ASPECTS projects in the cases of China, EU27, India and South Africa. They have been selected from various regional net-zero studies that are either focusing on the steel industry explicitly or contain a Paris-compatible development of the steel industry as part of a broader study. If no such roadmaps could be found, quantitative roadmaps are derived from qualitative roadmaps of the government for the steel industry or based on expert views.

The reason for using regional studies as a starting point for the *domestic* and *DRI-trade* pathways is that these regional studies are expected to reflect expertise on regional factors that can influence steel sector transformation (such as level of development, resource endowments, economic and political factors) that could not have been elicited in the same level of detail in the scope of the NDC ASPECTS project and therefore might have been overlooked in a purely global view.

For the synthesis of regional technology pathways on a global level and for the consistent quantification of the emissions and energy related impacts of all pathways the WISEE-EDM Global Steel

⁶ <https://worldsteel.org/about-us/who-we-are/>

Model (GSM) has been developed and used. The model is briefly described below in section 3.2.2 and at greater detail in Bilici et al. (submitted) and on the I2AM-Paris platform⁷.

As a basis for the pathway development and analysis and as introduction to mitigation options in the steel industry the main mitigation options are briefly outlined.

2.2.2 Global Steel Model (GSM)

The WISEE-EDM Global Steel Model (GSM) compiles regional technology pathways into a global picture and quantifies the related regional and global energy consumption, CO₂ emissions and costs based on a technology database. The model represents 11 regions explicitly (see figure 2.1) which today cover 92% of global steel production. The EU27 is represented as one region in the GSM. Furthermore, the rest of the world (RoW) is represented as one additional region.

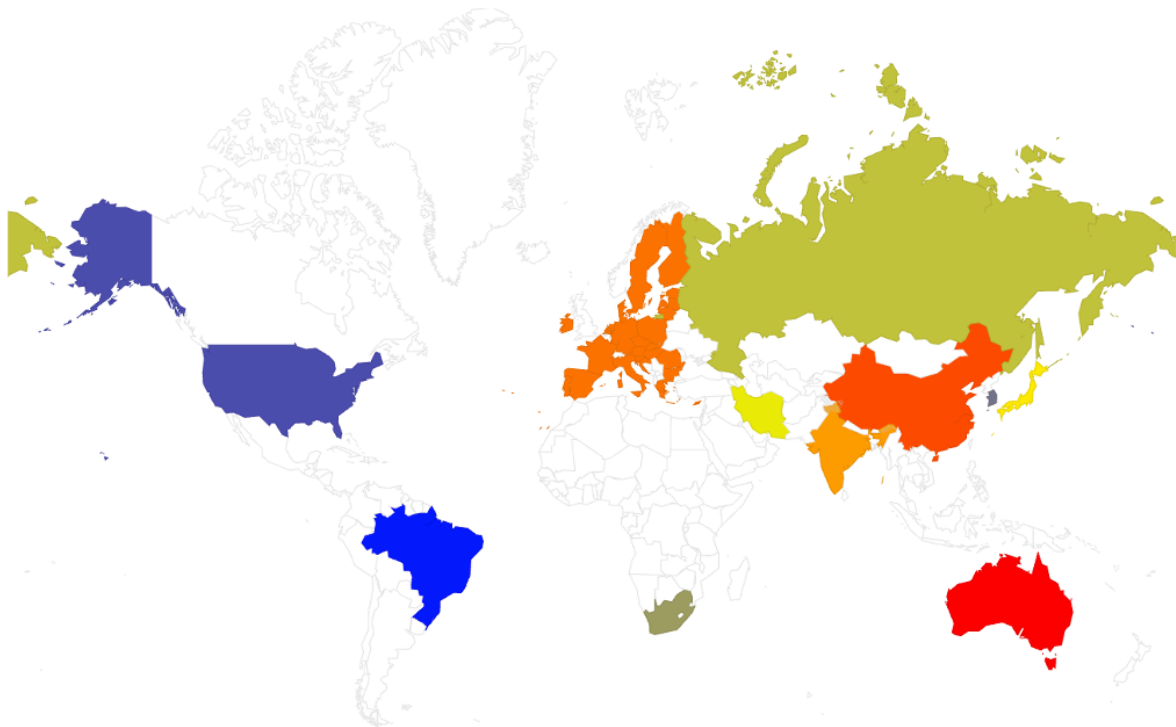


Figure 2.1: Regions explicitly represented in the GSM: Australia, Brazil, China, EU27, India, Iran, Japan, Russia, South Africa, South Korea, USA

On the technological side, the model allows to separate iron production from crude steel production, i.e., iron (DRI) may be produced either for domestic consumption or for export and steel may be produced from imported DRI. The model differentiates 21 Technologies (see section 2.3 for a brief outline of the process routes):

⁷ https://www.i2am-paris.eu/detailed_model_doc/wisee-globalsteel

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- › 14 technologies for primary steel production: blast furnace (BF)/ basic oxygen furnace (BOF); BF/BOF+CCS⁸; Smelting Reduction (SR); SR+CCS; DRI/Electric Arc Furnace (EAF) with coal, bioenergy, natural gas or H₂ used for DRI production and with or without CCS; DRI / submerged arc furnace (SAF) /BOF with bioenergy, natural gas or H₂ used for DRI production and with or without CCS; Alkaline electrolysis (AEL) + EAF; Molten Oxide Electrolysis
- › 3 technologies for iron (DRI) production for export: DRI with natural gas or hydrogen; AEL
- › 2 technologies for production of steel from imported iron (DRI): EAF; SAF/BOF
- › 2 technologies for production of secondary steel: EAF with fossil fuels or bioenergy used as carbon

For sake of clarity technologies are aggregated sometimes in the figures, in particular the DRI/EAF and DRI/SAF/BOF routes are typically subsumed and only differentiated according to the energy carrier used, e.g. as H₂-DRI and NG-DRI.

The quality of iron ore pellets is also considered by the model. The required quality (Fe content) of the ore matters for the choice between different DRI-based production routes. In the DRI-EAF route the iron ore is not melted and thus no slag is formed that facilitates the removal of impurities from the iron. Therefore, this route requires the use of high-quality iron ore pellets (DR-grade). In the DRI-SAF-BOF route, in contrast, an additional reduction process (SAF) is included that allows to reduce impurities through slag formation. Hence, low quality iron ore pellets (BF-grade) can be used in this process. As DR-grade pellets have a minor share (10%) in the pellet market, the investment decisions in DRI-based steelmaking processes are adjusted accordingly in the model to respect the limited availability of DR-grade pellets.

The technological system boundaries reflected in the model are shown in figure 2.2: coke ovens and industrial power plants of integrated steel sites are included in the calculations, while steel finishing processes (e.g. hot rolling) are not included the model scope. Parameters (e.g. costs) for electricity and hydrogen production external to the site are exogenous input parameters to the calculations, taken from the literature.

⁸ The abbreviation CCS stand for Carbon Capture and Storage

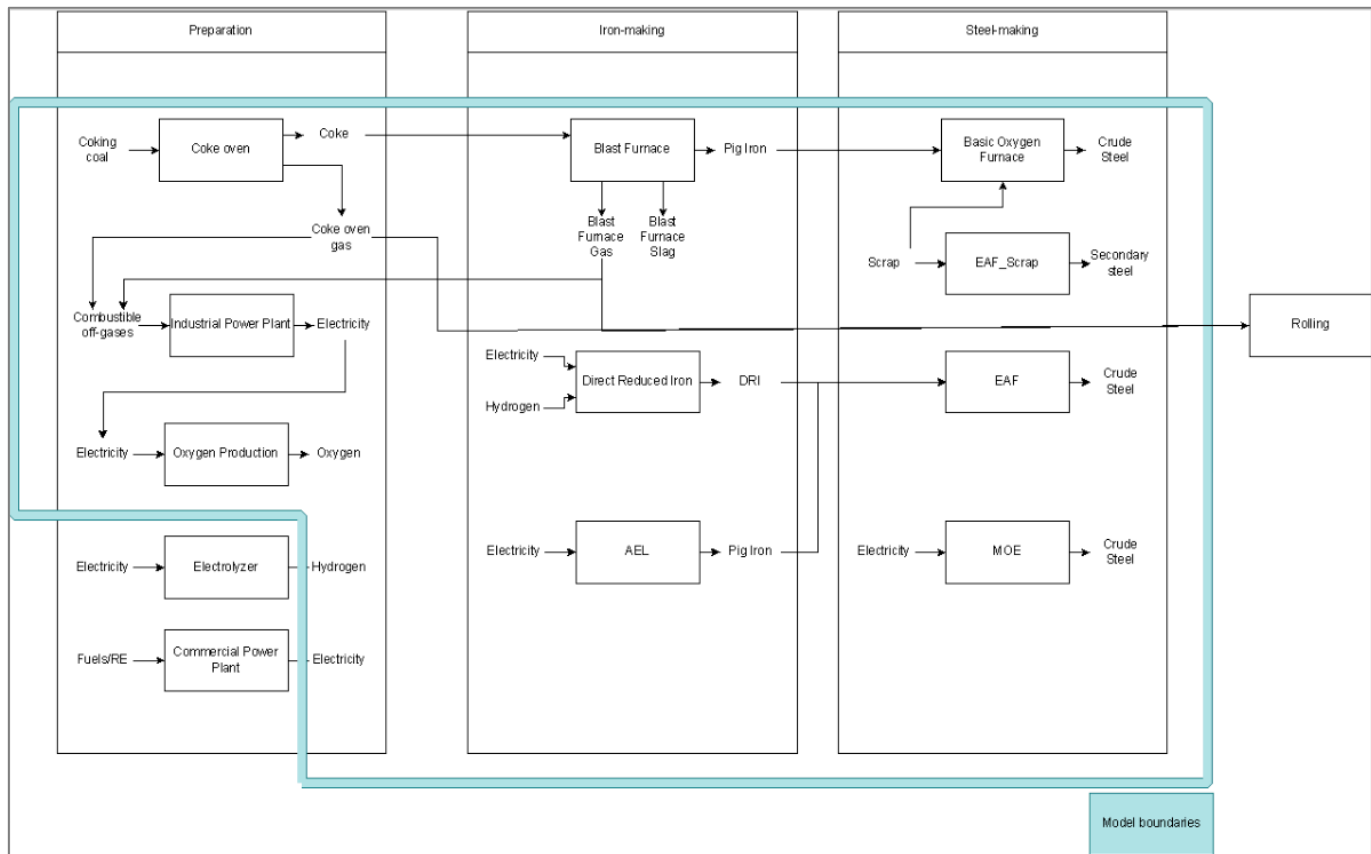


Figure 2.2: Technological system boundaries of the steel making processes in the GSM

2.3 Mitigation options

The main process routes used in the GSM and in the developed pathways are briefly outlined in the following. A more comprehensive and detailed description as well as quantitative process parameters are provided in Bilici et al. (submitted).

The integrated Blast Furnace – Basic Oxygen Furnace (BF-BOF) steel mill is the dominant production route for primary steel globally, today (see figure 2.4 below). In this route, the iron ore is reduced and smelted in a BF with coal being the primary energy source and CO₂ resulting as the by-product of the reduction of iron ore. The hot metal from the BF is subsequently processed to crude steel by oxygen blowing in the BOF.

An alternative to the primary BF-BOF route is the direct reduction of iron ore to iron in vertical shaft furnaces. A wide range of reducing gasses, including natural gas, coal-derived syngas or hydrogen can be used, out of which natural gas and coal-derived syngas are used in industrial scale plants, today. A (future) use of H₂ in this route would allow an emission-free production of primary iron as the by-product of the chemical reaction is (only) H₂O, instead of CO₂, as is the case for reducing gases including carbon. This process results in solid direct reduced iron (DRI) which can be processed to steel either in an electric arc furnace (EAF) or be melted in a submerged arc furnace (SAF) and then further processed to steel in a BOF.

Iron ore can also be directly reduced by electricity in electrolysis processes. Electrolysis routes can be considered carbon-free and therefore climate-neutral. However, compared to other mitigation options discussed here, their current TRLs are low.

Besides producing primary steel from iron ore, the production of secondary steel from scrap is another option and widely established today. As the iron included in scrap is already reduced, the energy-demand for the process is much lower than for primary steel. The dominant route for secondary steel production is processing scrap in an EAF, which is powered by electricity. The use of secondary steel is limited by global scrap availability⁹ on the one hand and its suitability for certain applications on the other hand.

Another option for reducing CO₂ emissions from the steel making process is to capture and permanently store (or use) the CO₂ (CCS). CCS can be combined with all previously mentioned process routes, in principle. In this report, the use of Monoethanolamine (MEA) scrubbing post-combustion capture with a capture rate of 90% is assumed.

Finally biogenic carbon can be used and substitute fossil carbon in the previously mentioned routes. However, for technical reasons this is not possible for all fossil carbon. If the use of biogenic carbon is combined with CCS, the capture and storage of biogenic CO₂ is accounted for as a negative CO₂ emission in this report.

2.4 Sectoral pathways

2.4.1 Current ambition

The *current ambition* pathway has been compiled from the production volumes and technology pathways of the IEA SDS scenario (IEA, 2020), but the GSM has been used to calculate resulting energy demands, CO₂ emissions and costs in order to use technology data that is consistent with the *domestic* and the *DRI-trade* pathways. In the IEA SDS scenario and hence in the *current ambition* pathway the global crude steel production increases from 1.85 Gt crude steel in 2020 to 2.05 Gt/year in 2050, see figure 2.3. Figure 2.4 shows the production volumes of different production routes on the global level in the same time period. The share of secondary steel increases from 22% to 35%, globally. For the production of primary steel, H₂-DRI and CCS play a (very) small role already in 2030 and scale up afterwards, with CCS being more prominent than H₂-DRI in the year 2050. It becomes apparent that significant shares of unabated primary steel production remain by 2050. Figure 2.5 shows the regional break-down of the shares of different steel production routes in the year 2050 in the *current ambition* scenario.¹⁰

⁹ Since the year 2000 the global steel production has more than doubled (<https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/>). Therefore, the mass of steel products produced in the past and being available as scrap today after having reached their end of life is much lower than the current production levels of crude steel.

¹⁰ Here and in some other figures Brazil, Iran, Russia and South Africa are included in the RoW, for sake of clarity of the figure.

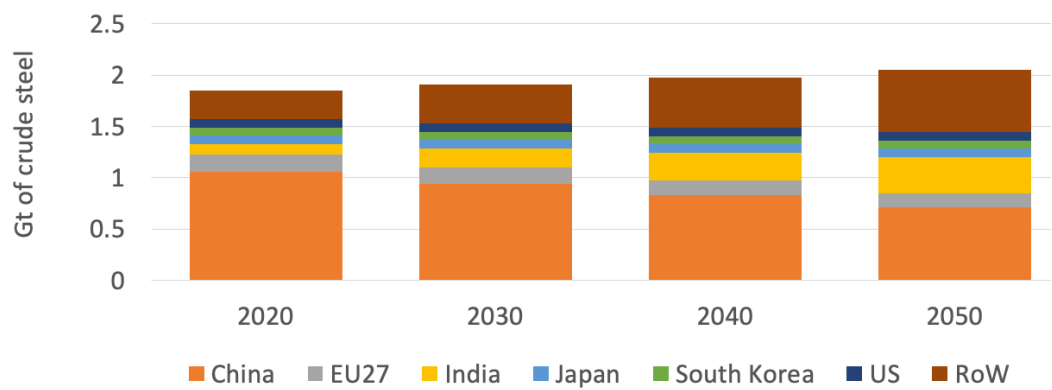


Figure 2.3.: Global crude steel production per region in the *current ambition* pathway

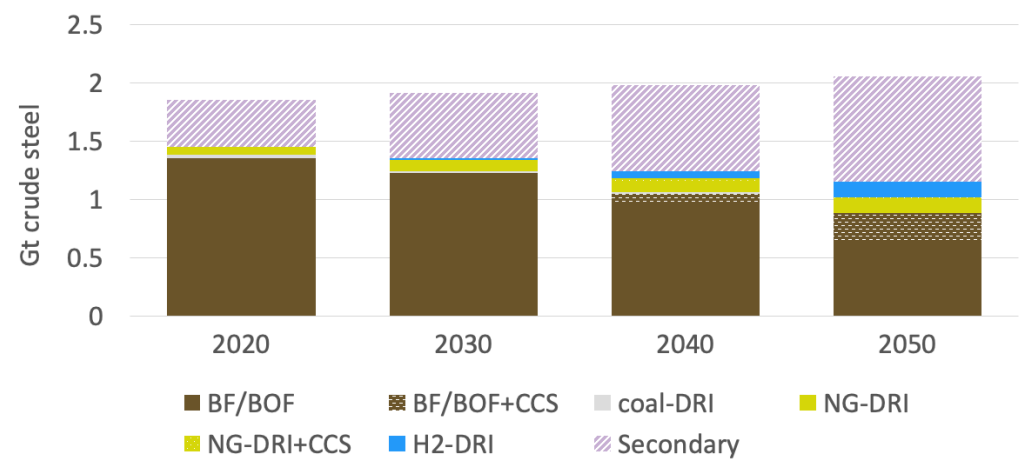


Figure 2.4.: Global crude steel production per production route in the *current ambition* pathway

Technological Pathways towards Paris-compatible Steel, Cement and Petrochemicals

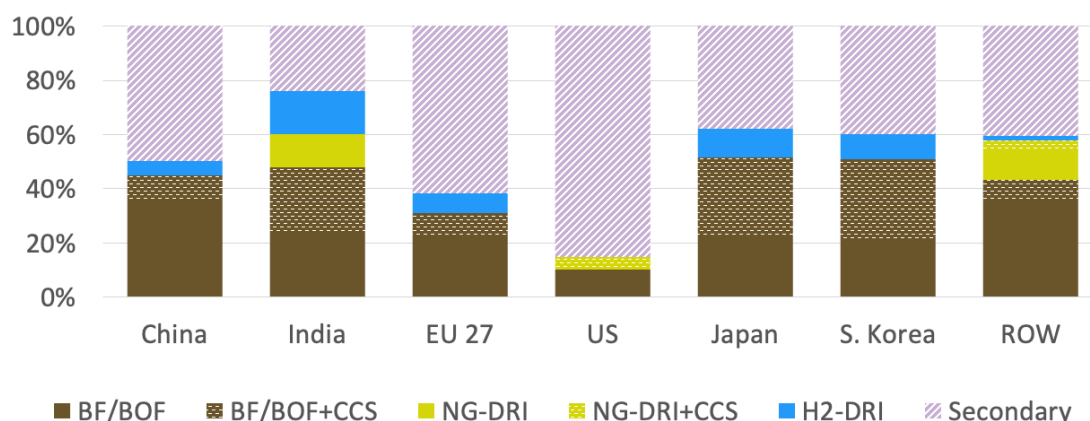


Figure 2.5: Shares of steel production routes in main steel production regions in the year 2050 in the *current ambition* pathway

The CO₂ emissions associated with the *current ambition* pathway are shown in figure 2.6. In 2050 about 1.4 Gt of CO₂ emissions remain, mostly in China, India and RoW (see figure 2.7). The relevance of these regions for remaining emissions is a direct consequence of their high production volumes in 2050 (figure 2.3) and the shares of unabated primary steel production in these regions – mostly using the coal-fired BF-BOF route (figure 2.5). The cumulative CO₂ emissions of this pathway reach 66 Gt CO₂ in 2050 and are set to increase further in the time afterwards.

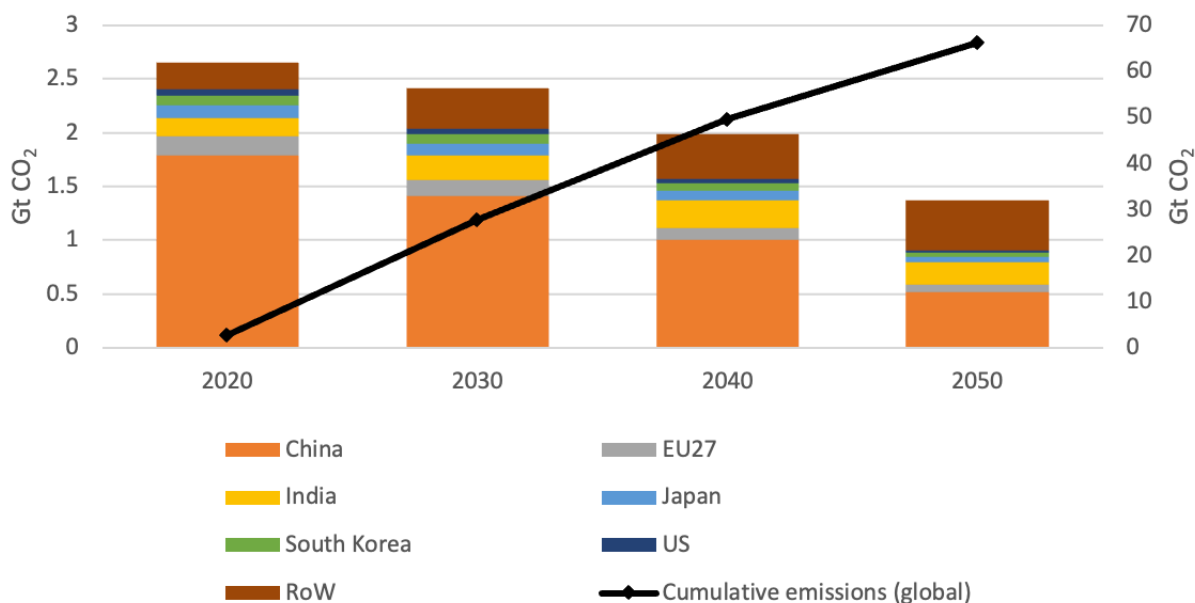


Figure 2.6: Regional annual CO₂ emissions (columns, left axis) and global cumulative CO₂ emissions (line, right axis) of the *current ambition* pathway for the steel industry

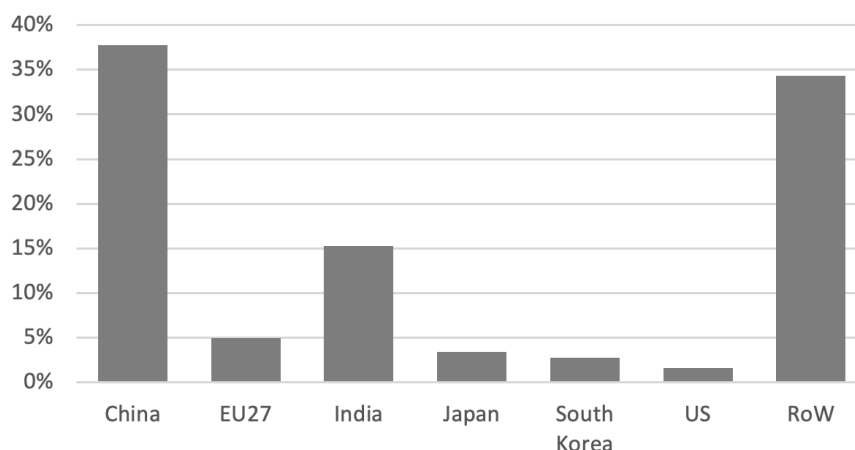


Figure 2.7: Regional shares of annual emissions of the steel industry remaining in the year 2050 according to the *current ambition* pathway.

2.4.2 Domestic pathway and DRI-trade pathway

The *domestic* and the *DRI-trade* pathways as well as their development are described in detail in Bilici et al. (submitted). Both paths are based on the IEA NZE scenario (IEA, 2021b) for the development of global steel production, which rises accordingly to 1987 Mt crude steel by 2050. The global and regional technology pathways and the CO₂ emissions of the *domestic* pathway are derived from a synthesis of regional roadmaps and are displayed below in figures 2.9, 2.10. and 2.11. The *DRI-trade* pathway is identical to the *domestic* pathway except that global DRI trade starts in the late 2020s, resulting in a global trade volume of 25 Mt DRI/year in 2030 and rising to 430 Mt/year in 2050. China, India and RoW are the regions with the largest DRI imports, accounting for more than 100 Mt in each region in 2050. Australia, Brazil and South Africa are the DRI-exporting regions, with Australia being the largest exporter with an annual export of 290 Mt/year in 2050.

2.5 Assessment of pathways

2.5.1 Assessment of the *current ambition* pathway

The first objective of this report is to assess the current ambition of the steel industry with regards to decarbonization in light of the Paris Agreement. In order to do so, the cumulative CO₂ emissions implied by the *current ambition* pathway are compared to a Paris-compatible CO₂-budget for the global steel industry. Deriving a Paris-compatible CO₂-budget for the global steel industry is a challenging task as there is no process agreed to decompose the global climate goal into regional or sectoral emission targets. In this study, this is achieved by two sub-steps: 1) defining a global CO₂ budget that is in line with the goals of the Paris agreement; and 2) allocating a share of this budget to the steel industry.

For the definition of a Paris-compatible global CO₂ budget we refer to IPCC (2021), which provides a relation between global CO₂-budgets and increases of the global average temperature. According to this, a total remaining CO₂-budget of 700 Gt CO₂ for the Energy and Industry sectors would allow to stay below 1.7 °C – i.e. “well below 2°C” – with a probability of 67%. Based on these considerations, we use 700 Gt CO₂ as “Paris compatible” budget for the global Energy and Industry sectors.

There are no commonly agreed rules for allocating this CO₂ budget to specific sectors. One simple approach could be a “sectoral grandfathering”; i.e. the budget is allocated to sectors according to their today’s share of emissions. Another approach is using global Integrated Assessment Models (IAMs) to identify an optimal allocation of a global CO₂ budget to sectors. Figure 2.8 compares budgets for the global steel industry from these two approaches to the cumulative CO₂ emissions implied by the current ambition pathway (see section 2.4.1). The sectoral grandfathering approach allocates 49 Gt CO₂ of the total budget to the steel industry, based on its today’s share of 7% of total emissions from the Energy and Industry sectors (IPCC, 2022). The assessment of IAM’s CO₂ budget allocation to the steel sector is based on scenarios from the AR6 scenario database that fulfill two conditions: the total CO₂ emissions from the Energy and Industry sectors stay below 700 Gt CO₂ in the period 2020 – 2050 and the emissions of the steel sector are made transparent (i.e. they are reported and the values are above zero).¹¹ The scenarios include cumulative emissions in a bandwidth of 42 to 73 Gt CO₂, with an average of 53 Gt CO₂. The cumulative emissions of the *current ambition* pathway of 66 Gt CO₂ are within the bandwidth of results from Paris-compatible scenarios from the IAMs¹², but higher than their average value and higher than the budget allocated to the steel industry by the sectoral grandfathering approach. This result does not allow for a clear-cut assessment of the Paris-compatibility of the *current ambition* pathway. It shows however, that the *current ambition* pathway can only be considered Paris-compatible if the steel industry is granted a large share of the remaining CO₂ budget, compared to other sectors, as it is envisioned only by three scenarios from one single model of the analyzed set. Ideally, a robust and highly credible Paris-compatible steel decarbonization pathway should imply cumulative CO₂ emissions of no higher than 49 Gt CO₂ until net-zero CO₂ emissions are achieved.

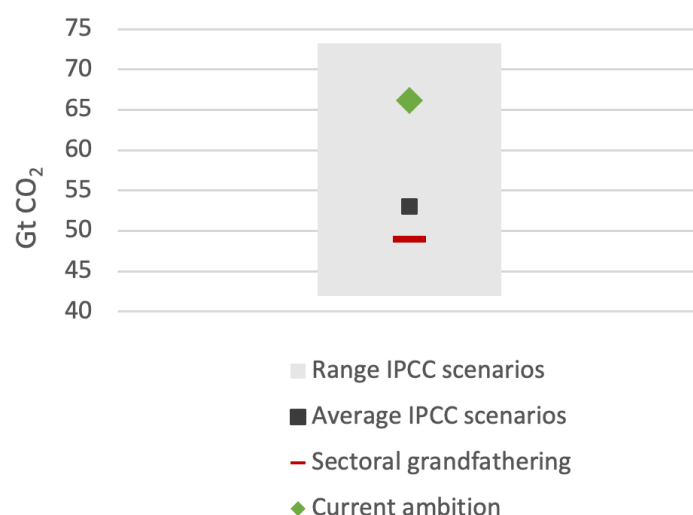


Figure 2.8: Comparison of CO₂ budgets allocated to the global steel industry with cumulative emissions implied by the *current ambition* pathway

¹¹ This results in 18 scenarios based on three models (IEA Energy Technology Perspectives Model; Mc Kinsey 1.0; IMAGE3.2) being taken into account.

¹² Two models (IEA Energy Technology Perspectives Model; IMAGE3.2) report cumulative CO₂ emissions of the steel industry in the time period 2020 to 2050 that are below 66 Gt CO₂ in all their scenarios included in the analysis, while Mc Kinsey 1.0 reports cumulative emissions for the steel industry that are above 66 Gt CO₂ in all included scenarios.

2.5.2 Assessment of the *domestic* pathway

Figure 2.9 shows the technology pathway of the *domestic* pathway, compared to the *current ambition* pathway. Due to the slightly increased material efficiency in the domestic pathway, the available amount of scrap allows to cover slightly higher shares of crude steel production by secondary steel. No new installations of unabated primary steel take place in this pathway after 2030, globally, according to the regional scenarios underlying this pathway. As a consequence, (almost) no unabated crude steel production remains in 2050, globally leading to a drastic reduction in CO₂ emissions. The *domestic* pathway features a stronger shift towards the H₂-DRI-routes, compared to the *current ambition*. Figure 2.10 highlights the regional differences between the two pathways.

In the *domestic* pathway the annual emissions are reduced to near-zero (34 Mt CO₂, globally) until 2050 and the cumulative CO₂ emissions amount to 51 Gt CO₂ in the period 2020 to 2050 (figure 2.11). Figure 2.12 relates this amount to the CO₂ budgets allocated to the steel industry through a sectoral grandfathering approach and by Paris-compatible scenarios developed by IAMs (see previous subsection). The cumulative emissions of the *domestic* pathway are below the average of the IPCC scenarios and roughly in line with the sectoral grandfathering approach. Based on this, we conclude that the *domestic* pathway is consistent with the Paris-agreement. Bilici et al. (submitted) furthermore discuss the emissions reductions achieved in the *domestic* pathway as compared to other global steel scenarios from other studies.

The *DRI-trade* pathway described in Bilici et al. (submitted) is identical to the *domestic* pathway from a steel production technology point of view (while the DRI production partly takes place in different world regions). The implied CO₂ emissions are hence identical to the *domestic* pathway (within the scope chosen for this analysis).

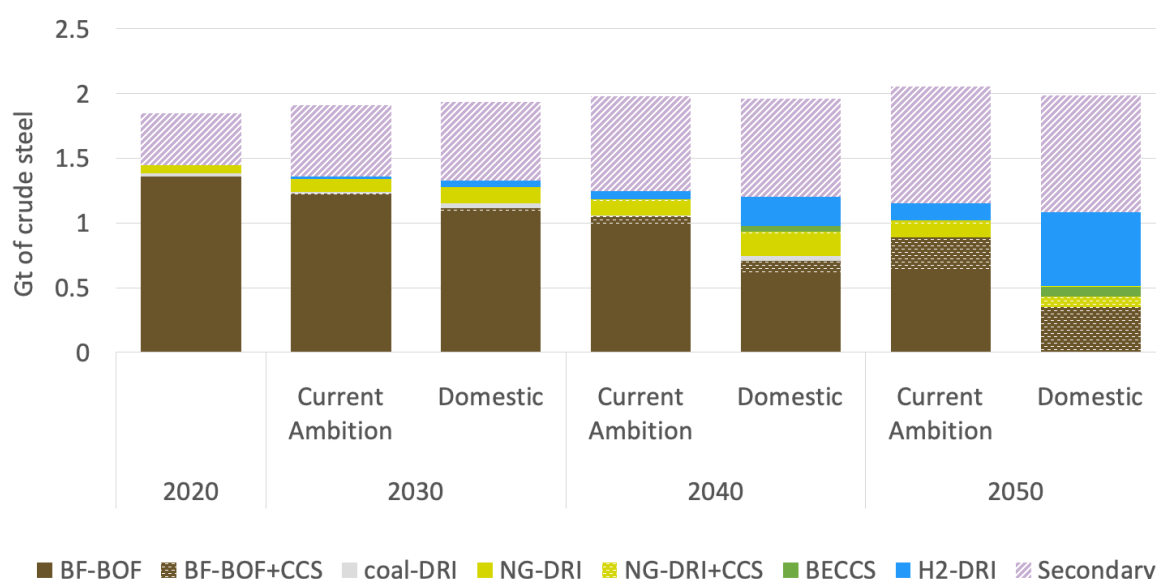


Figure 2.9: Global crude steel production per production route in the *domestic* pathway, compared to the *current ambition* pathway.

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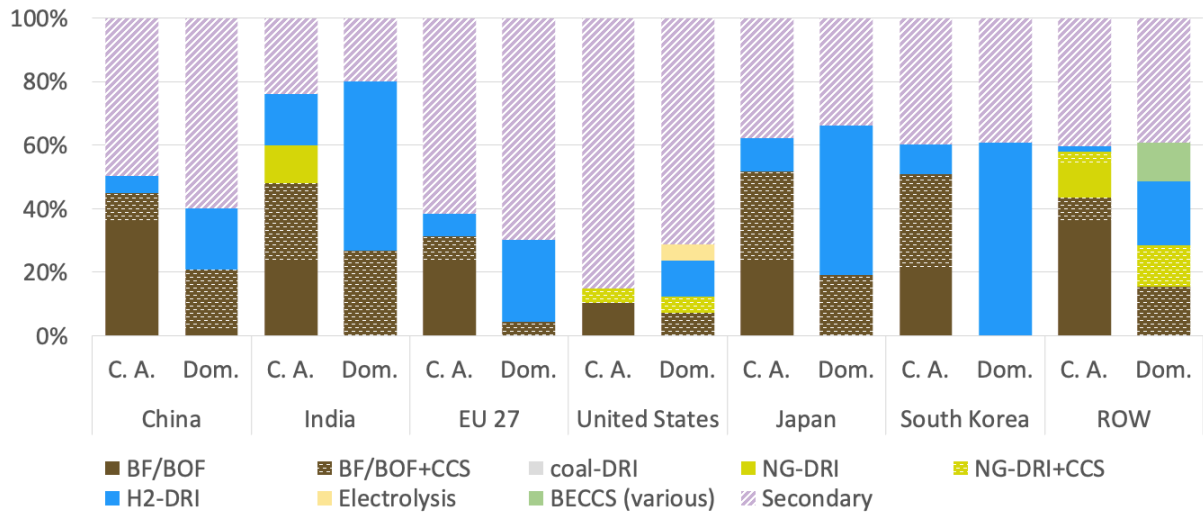


Figure 2.10: Shares of steel production routes in main steel production regions in the year 2050 in the *domestic* pathway (Dom.) compared to the *current ambition* pathway (C.A.)

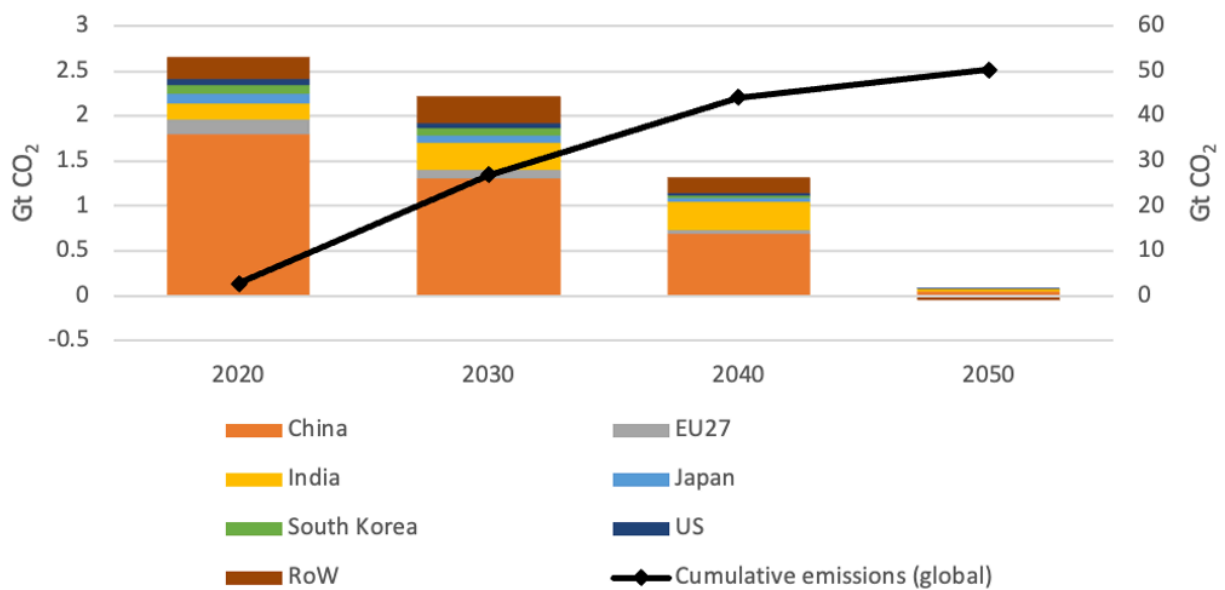


Figure 2.11: Regional annual CO₂ emissions (columns, left axis) and global cumulative CO₂ emissions (line, right axis) of the domestic pathway for the steel industry

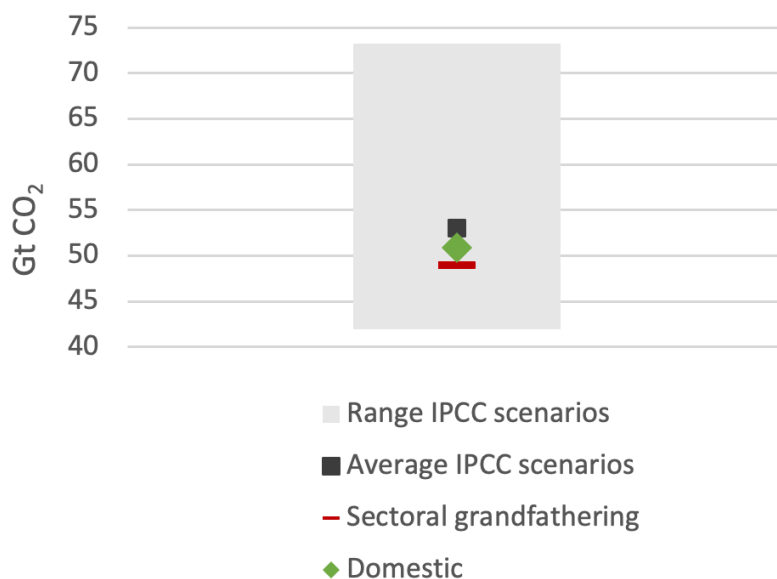


Figure 2.12: Comparison of CO₂ budgets allocated to the global cement industry with cumulative emissions implied by the *domestic* pathway

2.5.3 Assessment of DRI trade

The third objective of this report, i.e. the analysis of the potential role and impacts of global DRI trade have been the focus of Bilici et al. (submitted) and the main impacts of global DRI trade in terms of energy demand and costs have been laid out in detail in this paper, including regional perspectives. Until the year 2050, global DRI trade allows to relocate the production of 430 Mt DRI per year to regions with abundant renewable electricity and availability of low-cost hydrogen, facilitating cost savings of more than 45 billion dollars annually in 2050. A notable consequence is the shift of the consumption of more than 26 Mt of hydrogen to Australia, Brazil and South Africa which implies significant additional demand for green electricity in those countries. DRI trade could have significant impacts on the energy system transformation in both, exporting as well as importing countries.

2.5.4 Assessment of mitigation costs

In complement to the analyses conducted by Bilici et al. (submitted), figure 2.13 compares the global average specific crude steel production costs across the three pathways. It can be seen that specific steel production costs, including capital costs as well as operational expenses, increase in all cases, but stronger in the *domestic* pathway and the *DRI-trade* pathway, compared to the *current ambition* pathway, due to a faster upscaling of mitigation options such as H₂-DRI and CCS, which have higher specific production costs than the BF-BOF route. Figure 2.13 also shows that the cost increase can be dampened by global DRI trade due to a more cost-efficient regional allocation of global DRI production (see Bilici et al., submitted). Compared to the *domestic* pathway, global costs are reduced by more than 45 billion dollars annually in 2050 in the *DRI-trade* pathway. The annual cost savings increase over the period from 2020 to 2050 with increasing trade volumes and cumulate to 535 billion dollars, over the whole period.

Figure 2.14 compares the CO₂ mitigation costs for the emissions reduction that goes beyond the current ambition scenario. I.e. the specific additional CO₂ savings of the *domestic* and *DRI trade* pathways are set into relation to their additional specific costs, respectively compared to the *current ambition*.

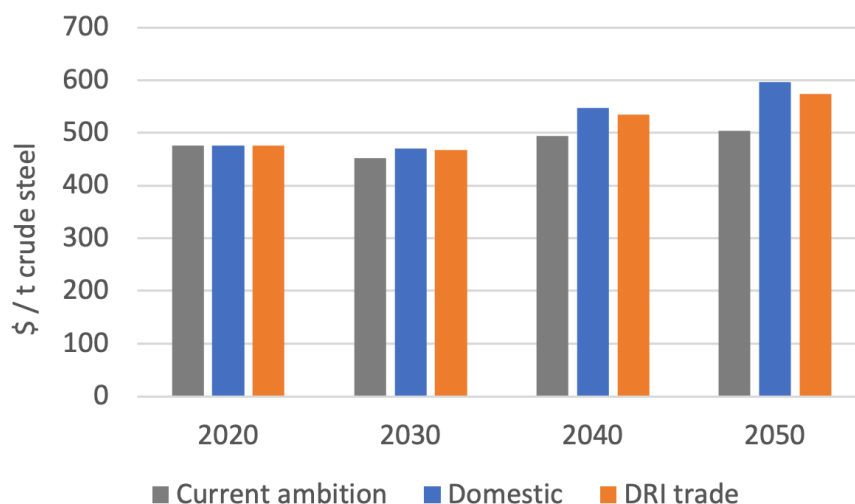


Figure 2.13: Global average specific crude steel production costs in the three pathways

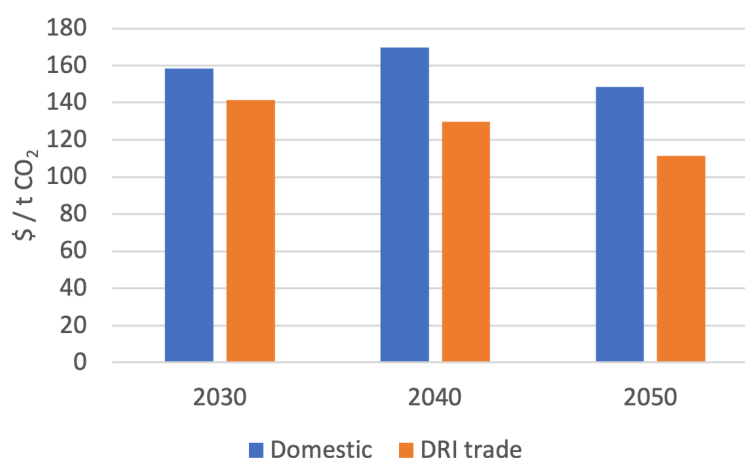


Figure 2.14: Global average CO₂ mitigation costs of the domestic and DRI trade pathways for CO₂ mitigation that goes beyond the *current ambition* pathway

2.6 Conclusions for steel

The cumulative CO₂ emissions of a pathway for the future development of the steel industry according to its *current ambition* (reflected by the IEA SDS scenario) amount to 66 Gt CO₂ until 2050. About 1.4 Gt CO₂ of annual emissions would remain in 2050, 38% of which in China, 15% in India, 34% in the “Rest of the world” (RoW; in particular Africa, South America and South-East Asia) and 13% in the EU27, the USA, South Korea and Japan combined. This amount of cumulative emissions is not compatible to the Paris agreement goals – here operationalized as staying below 1.7°C with a probability of 66% – except a large part of the remaining CO₂ budget for the energy and industry sectors is allocated to the steel industry to an extent that is only considered in a few scenarios by IAMs.

A Paris-compatible global steel decarbonization pathway (“*domestic*”) has been developed, which

achieves near-zero steel production by 2050 and features cumulative emissions of about 51 Gt CO₂. The mitigation used in this pathway are basically identical to the ones used in the *current ambition* pathway. The main differences to the *current ambition* pathway concern faster deployment of mitigation options such as CCS and hydrogen-based DRI production. A further increase of the ambition level for the reduction of CO₂ emissions of the steel industry is therefore not dependent on (additional) technological break-through technologies, but on suitable policy frameworks and market conditions. The increased ambition, however, comes with an increase of specific steel production costs of about 18% in the year 2050, in the global average. The CO₂ avoidance costs for the CO₂ emissions reduction that goes beyond the current ambition scenario would be about 149-159 \$/t CO₂ over the period 2030 to 2050.

The increase in costs can be dampened by global DRI trade. Cost savings through global DRI trade increase over time with increasing DRI trade volumes and amount to more than 45 billion dollars annually in 2050, compared to the *domestic* scenario (in which all additional CO₂ mitigation towards net-zero steel production is achieved domestically in each region). Global DRI trade lowers costs because it facilitates more hydrogen-based DRI being produced in countries with low-cost renewable electricity generation and large renewable energy potential. Accordingly, CO₂ mitigation costs could be reduced to about 111-141 \$/t CO₂ in the period from 2030 to 2050 if global DRI trade is considered. These savings would dampen the increase of specific steel costs to 14% in 2050, compared to the *current ambition* pathway.

Under the DRI trade scenario, more than 26 Mt/year of hydrogen consumption would shift to DRI-exporting countries with large, low-cost renewable energy resources, namely Australia, Brazil and South Africa. This implies significant additional demand for green electricity in those countries. On the other hand, hydrogen consumption of the steel industry decreases by 75% on average in DRI-importing regions such as China, India and the EU. Consequently, DRI trade could have significant impacts on the energy system transformation in both, exporting as well as importing countries and should hence be analyzed in further studies and be incorporated in global and regional energy system scenarios.

3 Cement

3.1 Introduction

Cement is responsible for about 7% of global CO₂ emissions of the energy and industry sectors (IPCC, 2022).¹³ Almost all of the direct emissions related to the sector are generated through the production of cement clinker, the main “ingredient” to cement that is responsible for its ability to bind gravel and sand into stable and durable structures. About 2/3 of the emissions related to clinker production result from the chemical reaction by which cement clinker is produced from limestone and the remainder is related to fuels used to heat the raw material up to 1450 °C. A sufficiently high transfer of thermal energy needs to be achieved, in order to produce the required chemical compounds. These high-heat requirements limit the variety of suitable non-fossil energy sources.

Despite these challenges, strongly reduced levels of CO₂-emissions or even climate neutrality of the cement sector by 2050 are deemed possible by many, and various roadmaps towards this goal have been presented by industry associations, researchers and non-governmental organizations for the global, regional and national levels (Cao et al., 2021; Cembureau, 2020; Favier et al., 2018; GCCA, 2021; IEA/CSI, 2018; Material Economics, 2019; PCA, 2022; RMI & CCA, 2022).

As outlined in the introduction and similar to the steel industry (see chapter 2), current NDCs of major emitter countries do not explicitly set CO₂ reduction targets for the cement industry and do not elaborate on corresponding measures and pathways. But, because of the high relevance of the cement industry for achieving the goals of the Paris Agreement, specific targets and measures should be included in future NDCs, ideally. The question then arises, which ambition level and which measures should be included. Industry associations, whose primary role is to advocate the interests of their members and who have established knowledge about their sectors, will likely have an important voice in this. In the opinion of the authors, future NDCs should be at least as ambitious as the targets set by the (cement) industry itself.

While the roadmaps provided by industry associations are clearly ambitious, it has not yet been assessed whether the current ambition of the cement industry reflected by these roadmaps is compatible with the goals of the Paris Agreement. Against this background, the first purpose of this report section is to

- › assess whether current decarbonization ambitions for the cement sectors on the global level and in major emitter countries¹⁴ (China, EU27, India, USA) are in line with the Paris goals.

In line with the main objective of the NDC ASPECTS project – to provide guideline for enhanced NDCs – the second purpose of this report section is to

- › identify levers for acceleration of cement decarbonization and to assess their impacts in major emitter countries.

3.2 Methodology

3.2.1 Approach

The main approach chosen for the elicitation of the current ambition of the cement industry is a

¹³ See also for a discussion of various estimates of the cement industries share of global CO₂ emissions: <https://www.linkedin.com/pulse/co2-emission-from-cement-industry-whats-best-estimate-claude-lorea>

¹⁴ For sake of simplicity we use the terms “countries” and “national” in a broad sense also including the EU27.

quantitative analysis of existing roadmaps with regards to their implied CO₂ budget in the time period 2020 to 2050. The analysis is based on roadmaps that have been developed by national cement associations as these roadmaps are assumed to best reflect the current ambition of the sector (in a particular region or country). For the quantification a model is used to replicate the pathways described in the roadmaps, where required to fill gaps in the information provided by the roadmaps. The model is described below in section 3.2.3 and in more detail in the appendix.

Currently there is no commonly agreed view on sectoral Paris-compatible CO₂ budgets, neither on a global level nor on the level of countries. In order to assess the current ambition of the cement industry reflected in global roadmaps, we suggest a Paris compatible global CO₂ budget for the cement sector based on a combination of results of Paris-compatible pathways from Integrated Assessment Models (IAMs) and a sectoral grandfathering approach towards the remaining global CO₂ budget for anthropogenic emissions.

Concerning the national level, it needs to be considered that various approaches for allocating a global budget to countries exist, based on different considerations of a fair allocation. Thus, there cannot be a widely-agreed and politically accepted clear-cut answer to the question whether a CO₂ budget used by the cement industry of a particular country is in line with the Paris goals, or not. We therefore relate the cumulative emissions by national roadmaps to a range of CO₂ budgets derived from different allocation methods.

For the identification of levers for further acceleration of cement decarbonization we focus on the major emitter countries China, EU27, India and USA only, as the global level covers very diverse countries that strongly differ with regards to current deployment levels of mitigation options as well as context. For these major emitter countries, a comparative analysis between their roadmaps is made to identify possible levers for further acceleration of decarbonization of the cement sector and to propose possible levels of enhanced ambition. Different context conditions such as state of socioeconomic development, availability of industrial by-products for use in the cement industry etc. are respected and discussed as far as possible within the scope of this study. In order to quantify the effects of an increased ambition the above mentioned and below described “WISEE-EDM Cement National” model is used to quantify CO₂ emission trajectories of pathways that include an increased ambition for the cement sector. The model thereby provides a unified analytical structure to represent and compare the different national roadmaps.

The contributions of single mitigation options to the mitigation achieved by the various national pathways are presented using waterfall diagrams. These are derived by isolating effects of single mitigation options by assuming only a single parameter (or a set of intertwined parameters) would change between the base year 2020 and the target year 2050 and then relating these isolated contributions to the overall mitigation achieved in the respective pathway.¹⁵ Finally, the interdependencies between different mitigation levers are discussed and quantified in a simplified way in section 3.5.

In order to provide a knowledge base for the above-mentioned analyses, section 3.3 provides an introduction to the mitigation options considered.

¹⁵ Normalizing the effects of single mitigation options to the overall mitigation level achieved across all options is required due to strong interdependencies between options, see section 4.4.5.

3.2.2 Scope

The analysis focuses on Scope 1 emissions, i.e. direct emissions at the cement plant including fuel related and process-based emissions¹⁶, because direct emissions in the year 2020 accounted for more than 90% of the total direct and indirect emissions of the global cement industry and therefore dominate the picture (own assessment based on GCCA, 2021). Furthermore, not considering emissions from the provision of secondary energy carriers (e.g. electricity) relieves the analysis from making assumptions on decarbonization pathways for the energy systems of analyzed countries. More specifically, and in accordance with the above-mentioned scope, no CO₂ emissions are accounted to the use of industrial by-products as supplementary cementitious materials (SCMs). But (fossil) CO₂ emissions caused by the utilization of waste as fuel in the cement plant are counted in. CO₂ captured through recarbonation of concrete buildings is not taken into account for the overall CO₂ balance in accordance with current IPPC rules, while negative emissions through the combined use of biogenic fuels and CCS (BECCS) are included, as these negative emissions are primarily generated at the cement plant.

With regards to mitigation levers, the analysis considers mitigation options up to the concrete level, reflecting the scope of the analyzed roadmaps which highlight that mitigation of emissions must happen across the whole value chain of the cement and concrete industries (Cembureau, 2020; GCCA, 2021; PCA, 2022). Large potentials for further reduction of concrete demand through using alternative building materials, urban planning and sufficiency may exist, but it is beyond the scope of this study to include these options.

The analysis focusses on the technical aspects of the cement sector transformation, taking systemic interdependencies into account where possible. It does not, however, include an analysis of the policies and regulatory changes required to make the described transformation happen – while fully acknowledging that the political and regulatory spheres are important fields for the future development of the cement sector (see Otto et al., 2023).

3.2.3 Model

The “WISEE-EDM Cement National” model developed and used for the analysis is a simplified representation of the cement production in a particular country at the national level for the time period of 2020 to 2050 in 5-year steps. The model covers 9 main parameters (resp. parameter sets), 8 of which mirror the mitigation options described in section 3.3. Besides these, the demand for concrete buildings is included as an exogenous driver.

For each time step, the variables for binder, cement, novel binder and clinker production are calculated from these input parameters and the resulting CO₂ generated, captured (including biogenic CO₂), CO₂ emitted and the net CO₂ balance are calculated from these production volumes and the parameters provided for thermal efficiency, fuel switch and carbon capture and storage (CCS).

Data for the parameters is primarily taken from the national roadmaps (see below) and supplemented with additional information from other sources and own assumptions, where information required for the modelling was not available from these roadmaps.

¹⁶ If not stated otherwise CO₂ numbers reported in this chapter always cover both, fuel-related and process-related CO₂.

3.3 Mitigation options

Direct CO₂ emissions of the cement industry are almost entirely related to the production of cement clinker (Schneider, 2019). Options to mitigate these Scope 1 emissions exist along the value chain of cement production and use. Broadly speaking these include three key strategies: 1) reducing the amount of clinker required to achieve the same performance of concrete structures, 2) reducing CO₂ generation during clinker production through thermal efficiency, fuel switch and use of decarbonated raw materials, 3) capture and storage of CO₂ generated during clinker production (CCS). An additional fourth strategy is the use of novel binders with reduced CO₂ footprints (typically compared to Portland cement). The potential for CO₂ emissions reduction through the use of novel binders is seen as limited by experts (Scrivener, John, et al., 2018). This strategy is thus not in the focus of the subsequent analysis. Moreover, alternative building materials such as wood could play a bigger role in the future and reduce demand (or limit the increase in demand) for concrete and cement. This latter strategy is, however, beyond the scope of this report.

Mitigation options for the cement industry have been extensively discussed by e.g. (ECRA, 2022; Griffiths et al., 2023; Olsson et al., 2023; Schneider, 2019; Scrivener, John, et al., 2018). The mitigation options that underlie the above presented model and which are specifically addressed in this report are briefly presented in the following.

3.3.1 Reduction of concrete intensity of structures

From a technical point of view, the efficient use of concrete can save approx. 10-30% of concrete by the year 2050 according to Cembureau (2020). A broad range of approaches in the concrete and construction industries may contribute to this, which are briefly outlined in the following.

The thickness of structural concrete elements is often not determined by the required compressive strength, but by the need to protect steel reinforcement from corrosion. In these cases, the thickness can be significantly reduced when using a material for reinforcement that is not susceptible to corrosion. Alternative reinforcements made of carbon, basalt, glass, stainless steel or coated steel therefore, in principle, offer a large potential for saving concrete. From a structural engineering point of view, there are no restrictions with regard to a far-reaching scaling of the approach. However, for the time being, the question of recyclability and the question of possible health risks due to carbon fiber abrasion are still unresolved issue with regards to carbon concrete, and scaling up the use of alternative reinforcements is currently hampered in some cases by significantly higher costs, among other things.

Further approaches include prestressed concrete, which is a proven, concrete-efficient technology, for whose application still untapped potentials are seen, e.g. in the area of prestressed prefabricated floors in multi-story construction. Ultra-high-performance concretes are concretes with a high compressive strength and a high durability, enabling leaner or more filigree structural elements than conventional concretes. Portland cement is generally used for their production, but cement clinker can be saved in total as the savings in concrete mass overcompensate the higher clinker content of cement. Hollow elements (e.g. plastic spheres) can be inserted into structural concrete elements (usually ceilings) at the points where the concrete is exposed to lower loads, which (according to a manufacturer) can save up to 35% of the concrete.¹⁷ A similar principle is followed by the approach of

¹⁷ www.cobiix.com

"gradient concrete", in which different concrete formulations are used or "filler material" (e.g. small plastic or expanded clay particles) is introduced in different layers of a component depending on the load.

In addition to the direct effects of these approaches on each single structural element, the weight load for the structural components below such lighter structural elements is reduced, allowing them to be planned thinner/slimmer. Structural planning that is drawing less on standardized designs of structural elements but more exactly tailored to the actual needs of the building is seen as a significant lever for the reduction of concrete demand.

3.3.2 Reduction of binder intensity of concrete

According to GCCA (2021), the binder content of concrete can be reduced by 14% until 2050, at global average. Requirements for the composition of the large variety of concretes that can be mixed according to industry standards and norms result from the required compressive strength, the requirements for durability and the ensuring of workability. Depending on the requirements of a specific concrete mixture, the required binder content can vary (significantly). Accordingly, a concrete composition adapted to the application purpose can lead to binder savings compared to the use of an "all-purpose concrete". Against this background, the transition from the production of concrete on small construction sites using bagged cement to industrialized processes offers considerable potential for savings, as the mix specifications can be better adhered to.

The (increased) use of concrete admixtures also offers potential for lowering the binder content in concretes in the future. Current scientific work shows that (in the laboratory) new types of concretes can be produced in which up to 70% mass of the clinker can be replaced by "fillers", such as unburnt limestone (John et al., 2018). This requires a separate grinding of different components into different, precisely adjusted grain sizes, a change in the water/cement ratio in concretes and the use of concrete admixtures.

3.3.3 Use of novel binders

"New binders" are binders that do not contain conventional Portland cement clinker. New binders come in many forms. They differ from cements commonly used today in terms of the raw materials used and, in some cases, the production processes. For a detailed description, we refer to the literature (Scrivener, John, et al., 2018). Compared to Portland cement, new binders make it possible to reduce specific CO₂ emissions per ton of binder from about 10% (Belite cements) to (theoretically) potentially CO₂-negative binders (magnesium silicate-based binders).¹⁸ However, in many cases their use is limited to certain applications due to their constructional properties. Additionally, the necessary raw materials are not available on a large scale or are significantly more expensive (e.g. bauxite). In the case of magnesium silicate-based binders, no manufacturing process has yet been developed on an industrial scale.

3.3.4 Reduction of clinker factor

In blended cements, a part of Portland cement clinker is replaced by "supplementary cementitious materials" (SCMs) such as ground granulated blast furnace slag (GGBS) and fly-ashes or by fillers

¹⁸ The CO₂ savings are lower or even negated when compared to cement with lower clinker factor.

(typically unburnt ground limestone) (ECRA, 2022). The clinker substitution rate has some influence on the technical properties of cements, therefore not all blended cements are suitable for all applications. Various types of cements with different compositions are described in national and regional norms, such as the European cement norm DIN EN 197-1. The use of SCMs in cements in total is today typically limited by their overall and local availability, with transport costs and transport related CO₂ emissions creating certain limits for trade. The use of some SCMs such as GGBS and fly-ashes is widely established.

Calcined clays are a promising option for a more wide-spread use as SCMs as they allow for comparably high levels of clinker substitution, are available in large amounts around the globe, and cements blended with calcined clays have similar properties to Portland cement (Scrivener, Martirena, et al., 2018). In so-called LC3 cements (combining clinker, calcined clays and limestone), the clinker content in the cement can be reduced to 50% in the most extensive case. Demonstration projects for some type of LC3-cement applications have been built in India and Latin America, while other applications (e.g. use of LC3 cements for reinforced concrete) are still subject of laboratory research. The TRL is thus estimated to be TRL 4-8, depending on the specific construction work. The future scaling depends primarily on the demand side, i.e.: norms and regulations, market acceptance and costs relative to other cements. The demonstration of the applicability of LC3 cements for different types of concrete structures and the durability of respective structures needs to be proven through demonstration projects and long-term monitoring, before wide-spread application may start. Thus, a step-wise diffusion into the market - from simpler to more complex construction works - can be expected. The specific costs of LC3 cements compared to Portland cement depend on various factors including the type of fuel used for clinker production, transport distance for clays, the type of cement plant (integrated / grinding station) and if existing equipment (rotary kiln) is used or new equipment is acquired (flash calciner) (Scrivener et al., 2019). Overall, costs are in the same order of magnitude compared to Portland cement. Scrivener et al. (2019) find that in many circumstances LC3 cements are even cheaper than Portland cement.

3.3.5 Use of decarbonated raw materials

The most important natural raw materials for clinker production are limestone or chalk and clay or marl, which are composed of limestone and clays. In addition, various alternative industrial by-products and wastes are also suitable as input material to clinker production, if used to a limited extent (Ruppert et al., 2020). The use is limited by clinker chemistry, which requires a careful balancing of calcium -, silicon - and ferrous / aluminum containing components, including consideration of natural raw material composition.

CO₂ savings can be achieved through the Calcium Oxide (CaO) content of alternative raw materials, that substitutes CaO from limestone and its associated process CO₂ emissions. The CaO content of alternative raw materials varies widely across different materials (Hoenig et al., 2022). For the subsequent calculations we assume an average CaO content of 10%¹⁹, which reflects CaO content of materials such as fly ash, waste bricks and tiles and waste concrete fines (Hoenig et al., 2022). Today, Austria is a world-leader in the use of decarbonated raw materials for clinker production. It achieved

¹⁹ For comparison: the CaO content of clinker is about 65% (Zementtaschenbuch 2002).

using 14% decarbonated raw materials for clinker production by 2018 and a corresponding reduction of process-based CO₂ emissions of about 2%²⁰.

Similar to SCMs and waste-based fuels, the potential for the use of alternative decarbonated raw materials also depends on their local availability. A pre-requisite is a well-functioning waste management system which assures the collection, sorting, and fractioning of industrial by-products and wastes.

3.3.6 Increasing thermal efficiency

Thermal energy is required in the clinker burning process for preheating the raw material, deacidification of the limestone at temperatures of 830 to 950 °C and sintering for the formation of stable cement clinker phases at temperatures of 1450 °C. The thermal energy requirement is influenced by the type of plant, the conditions of the plant, the operation of the plant, the composition, moisture and combustibility of the raw material, as well as the properties of the fuels used and their proportions of the energy input. For these reasons, the specific energy demand varies from cement plant to cement plant. The specific thermal energy demand of the rotary kilns also depends significantly on the kiln capacity. According to ECRA (2022), the thermal efficiency of state-of-the art short cement kilns with pre-heater and pre-calciner is already very high, today. A decrease of thermal energy demand per ton of clinker by 5% up to 2030 and 8% up to 2050 may be expected in the global average due to increasing average kiln capacity and a phase-out of less efficient wet, semi-wet, semi-dry or long dry kilns.

3.3.7 Fuel switch

Coal, petroleum coke, oil and natural gas are the main fuels used by the cement industry today, with significant regional differences, depending on availability (IEA/CSI, 2018). The use of fossil fuels accounts for approximately one third of the sector's direct CO₂ emissions today and therefore a switch to less CO₂-intensive or CO₂-neutral energy carriers is a main CO₂ reduction lever. Main options are discussed in the following.

3.3.7.1 Waste-based fuels

Different types of wastes such as used tires, waste oil, conditioned wastes from industry and municipal wastes and sewage sludge can be conditioned and then used to fuel the cement kiln. A reduction of direct CO₂ emissions is achieved through two effects: some waste fuels contain (a fraction of) biogenic carbon and most waste-based fuels have lower fossil CO₂ emissions factors related to their calorific value than the widely used fuels coal and pet coke. The specific emissions reduction depends on the substitution rate and the types of wastes used.

Moreover, only wastes that cannot be recycled should be used as sources for waste-based fuels. Hence, the alternative treatment for those wastes would be incineration (or landfilling), and – in case of waste incineration – an equivalent amount of CO₂ emissions would be released in that alternative treatment route as well. Given that, in a system wide perspective, the GHG mitigation potential of waste-based fuels equals that of the substituted fossil fuels.

²⁰ Own calculation based on 35 kt CO₂ avoided in 2018 (Hoenig et al. 2022) and process-based emissions of 1.827 kt in 2018 (Eurostat).

The use of waste-based fuels is widely established in the cement industry. In principle cement kilns can be fueled 100% with waste-based fuels (ECRA, 2022). The potential depends on the (interplay of) cement kiln technology and on the quality of wastes (e.g. the content of certain trace elements or chlorine). The application at the main firing of cement kilns fuels requires a minimum calorific value of about 20-22 GJ/t (ECRA, 2022). In the calciner of modern cement plants also fuels with lower calorific values may be used. The scaling potential depends in particular on the regional availability of suitable waste streams and the ability of the regional waste management system to condition wastes for use in cement kilns. No major modifications at the cement plant are needed for burning waste-based fuels, thus scaling does not depend on reinvestment cycles. Some minor investments may be required, however (e.g. additional storage and equipment for conditioning waste-based fuels on site).

The costs for the use of waste-based fuels depend strongly on the type and quality of waste used and the regional supply situation. Often, waste-based fuels are cheaper than their fossil fuel counterparts.

3.3.7.2 Biomass

Pure biomass fuels²¹ used in the cement industry today are mainly residuals such as wood waste, rice husks, saw dust, sewage sludge, and animal meal (ECRA, 2022). However, also biomass from energy-plants such as short-rotation forestry can in principle be used in cement ovens. Similar to waste-based fuels, biomass can be used as a fuel for clinker production, if quality criteria such as a sufficiently high calorific value are met in principle 100% of fossil fuels can be substituted. The use of biomass for thermal heat is highly beneficial for clinker production as it allows to provide high-temperature heat which is difficult to decarbonize otherwise and – in combination with CCS – can generate negative emissions which are required to balance residual emissions (IEA, 2021a). The scalability of the use of biomass fuels depends on their (local) availability and in the case of energy plants on land-use planning and competing uses in other sectors.

3.3.7.3 Hydrogen

From today's perspective, hydrogen can only partially replace carbon-based fuels in cement clinker production due to its deviating combustion properties. The maximum possible share of H₂ in the heat supply is the subject of research and development. In a study by (Mineral Products Association et al., 2019), for example, a share of 50% H₂ (based on the thermal energy input) was simulated in the main firing of the kiln of a cement plant with a five-stage cyclone preheater and calciner. This corresponds to 20% of the total heat input.²²

The availability of hydrogen at cement industry locations is dependent on the development of a future H₂ infrastructure, including to rural areas in which cement plants are often located, in close proximity to limestone quarries, as well as the availability of sufficient amounts of (renewable) electricity to operate an electrolyzer on site. Hydrogen is likely to remain more expensive in the medium and long term compared to waste-based fuels and biomass, and may therefore be interesting from an economic perspective at most as a booster fuel to compensate for low calorific values of other fuels.

²¹ Also some waste-based fuels contain biogenic carbon and waste-based fuels and biomass fuels are often discussed together as “alternative fuels”. Here we distinct both in the sense that biomass fuels contain only biogenic carbon. The distinction is useful to relate biomass use in the cement industry to biomass potentials.

²² In the simulated plant 40% of overall thermal energy is provided by the main firing and 60% at the calciner.

3.3.7.4 Direct electrification

From today's perspective, it may be possible to provide process heat for clinker production by electricity, but most technologies such as the use of plasma burners are at a conceptual or laboratory stage, only (ECRA, 2022). The LEILAC technology, a calciner with direct CO₂ separation (Project LEILAC, 2021) primarily designed for capturing process-based CO₂ emissions, processes the raw meal within a special steel vessel, which is heated from the outside and may also be heated through using electricity. An existing LEILAC calciner at a pilot plant in Lixhe is planned to be electrified in the course of a running EU project.²³ Other innovative technologies that are still at an early stage of research may also possibly play a role in the long term²⁴.

3.3.8 Carbon Capture

Since the generation of CO₂ during the production of binders cannot be completely avoided from today's point of view for process-related reasons, CO₂ capture and the subsequent use or storage of CO₂ is a central element in achieving climate neutrality in the cement sector.

Various different CO₂ capture technologies are under development that can be used on an industrial scale in the next years (post-combustion) or by about 2030 (oxyfuel, direct capture at the calciner) which have been described from technical and economic perspectives for example by (Gardarsdottir et al., 2019; Hills et al., 2017; Voldsund et al., 2019). The different capture technologies have various advantages and disadvantages that must be weighed against each other depending on the project. It can therefore be assumed that different processes will also be used in the long term.

In comparison, post-combustion processes (amine scrubbing) are the easiest to retrofit on a modular basis at an existing cement production plant. In addition, the separation rate can be scaled up over time. Post-combustion processes are therefore particularly suitable for the first phase of transformation. The maximum separation rate is > 90%. Compared to amine scrubbing, the oxyfuel process is much more energy-efficient: since in this process the air nitrogen is not passed through the combustion process, the CO₂ can be recovered relatively easily from the exhaust gases by condensation. The maximum capture rate is well above 90%. One disadvantage of the process is that it cannot be scaled up step by step on a furnace line, as the entire furnace must be designed or retrofitted accordingly in order to operate the burners with pure oxygen or an oxygen/CO₂ mixture and to minimize the ingress of false air as far as possible. From a technical point of view, retrofitting an existing plant is possible in principle but would require massive modifications. This, especially in the case of newer plants / kiln lines, does not usually appear to be advantageous from an economic point of view. Oxyfuel is therefore more the choice for new kilns. Direct separation at the calciner (LEILAC process) covers (only) the process-related emissions (approx. 66%), and of these, in turn, the proportion that arises at the calciner (approx. 90-95%), i.e. in total approx. 60% of the total emissions. Since an (almost) pure CO₂ stream is separated, it is very energy-efficient, and can be used both in new kiln construction and as a retrofit. Other processes, e.g. calcium looping, are also being developed or tested.

The captured CO₂ can then be used or stored permanently. The main potential uses are the production of synthetic base chemicals and fuels and the mineralization of CO₂ in the manufacture of products for the building materials industry. Geological storage of CO₂ is particularly suitable in depleted natural

²³ <https://www.leilac.com/project-leilac-2/>

²⁴ e.g. electric furnaces with temperatures up to 1,700°C, see at <https://coolbrook.com>

gas and oil fields and saline aquifers.

For the CO₂ quantities typically produced in a cement plant, there are three options for CO₂ transport: pipeline, (inland or deep-sea) ship and train. The options differ in terms of costs and other characteristics such as continuity of transport, expandability of capacity, changeability of transport routes, operational risks such as drought/flooding, required degree of purity of the CO₂. The specific costs in turn depend on various factors including distance, transport volumes, terrain. In the case of almost complete CO₂ capture, a CO₂ pipeline is the preferred transport option in most cases from a technical and economic point of view.

In the subsequent analysis CO₂ capture technologies are not differentiated but a capture rate of 90% (along the CCS value chain) is assumed. Similarly, whether captured CO₂ is used further or stored is not analyzed specifically, but geological storage is assumed to be the default case.

3.4 Sectoral pathways

The analysis of sectoral pathways starts from a brief description of the current ambition of the cement sector for the global level as well as for four major emitters (China, EU27, India, USA) and by assessing the CO₂ emissions implied in these roadmaps until 2050 (section 3.4.1). These *current ambition* pathways are subsequently assessed with regards to their compatibility with the Paris agreement (section 3.4.2). Levers for the increase of the ambition of the national-level roadmaps are identified by cross-comparison of the roadmaps and – based on this comparison – pathways with increased ambitions are suggested in section 3.4.3. In section 3.4.4 the increased ambition pathways are assessed.

3.4.1 Current ambition

3.4.1.1 Global level

The Global Cement and Concrete Association (GCCA) has provided a roadmap for the global cement sector in 2021 (GCCA, 2021). The roadmap proposes that CO₂ emissions of the global cement sector can be reduced from about 2.5 Gt CO₂ in 2020 to about 2 Gt CO₂ in 2030 and that net-zero emissions can be achieved by 2050, within the scope chosen for the roadmap (see below). This is achieved against the backdrop of increasing demand for concrete structures, which would lead to an increase of CO₂ emissions until 2050 to 150% of the 2020 level, if no action was taken. The mitigation levers that facilitate the CO₂ emissions reduction compared to this reference development are: efficiency in design and construction (22% CO₂ emissions reduction), efficiency in concrete production (11%), savings in cement and binders (9%), savings in clinker production (11%), carbon capture and utilization/storage (36%), decarbonization of electricity (5%) and recarbonation of concrete acting as a CO₂ sink (6%).

The cumulative CO₂ emissions implied by the GCCA roadmap have been extracted through visual scrutinization of the decarbonization pathway displayed in the roadmap. Corrections for CO₂ emissions related to electricity consumption (excluded), CO₂ binding through recarbonation (excluded) and emissions from the use of alternative fuels (added)²⁵ have been conducted to achieve similar system boundaries to the analysis conducted here (as well as to IPCC standards). The cumulative CO₂ emissions

²⁵ Fossil CO₂ emissions from waste-based fuels are not included in the calculations underlying the roadmap (GCCA, personal communication).

for the global cement sector implied by the net-zero pathway of the roadmap are found to be 51 Gt CO₂, according to this analysis.

3.4.1.2 China

In September 2022, RMI and the Chinese Cement Association (CCA) have published a decarbonization roadmap for China (RMI & CCA, 2022). This Roadmap is assumed to reflect the current ambition of main actors in the Chinese cement sector because of the involvement of CCA. The RMI/CCA-Roadmap includes in total 15 actions which are grouped to the levers of demand reduction, fuel substitution, energy efficiency, low-carbon cement composition and CCUS. For each action, the deployment over time until 2060 is displayed.²⁶

China currently produces about half of global cement (Andrew, 2019). Also per capita cement use has reached levels unprecedented by any other country before and even cumulative cement use per capita reached much higher levels (2-5 times) than developed countries (Xu et al., 2022). Against this background and considering the decreasing trend of Chinese population numbers and a slowdown of urbanization and infrastructure build-out, the roadmap predicts a significant decrease in cement demand for the next decades, leading to cement demand being only about one third of the 2020 level by 2050. Cumulative CO₂ emissions implied in the RMI/CCA-Roadmap amount to 11 Gt CO₂ from 2020 to 2030 and to 20,8 Gt CO₂ from 2020 to 2050 (own calculation based on RMI & CCA 2022).

3.4.1.3 EU

Cembureau, the association of European Cement producers has published a Roadmap for reaching climate neutrality along the value chain by 2050, which is assumed here to reflect the *current ambition* of the EU cement sector. Cembureau (2020) considers mitigation levers in 5 areas: clinker, cement, concrete, construction and recarbonation.

The roadmap includes targets for specific emissions of cement, but no absolute numbers for the CO₂ emissions of the EU cement industry. It names targets for specific mitigation levers for the years 2030 and 2050. No forecast for the future concrete demand is included and potential changes to the demand of concrete per structure are discussed, but not included in the quantification of the mitigation target.

Based on the information provided in the roadmap and assuming the concrete demand as well as the demand of concrete per structural element remaining constant on 2020 levels, own modelling of the CO₂ emissions implied by the roadmap have been done using the modelling framework described in section 3.2.3.²⁷ The calculation results show that the EU27 cement industry would reach almost net zero emissions by 2050 (0,3 Mt CO₂/year in 2050) and the cumulative CO₂ emissions in the period 2020 to 2050 would amount to 1,8 Gt CO₂.

3.4.1.4 India

To the authors' knowledge, the most recent roadmap for the Indian cement sector that reflects the ambitions of the sector's actors is the roadmap developed by the IEA and the Cement Sustainability Initiative (CSI) in collaboration with the Confederation of Indian Industry (CII) and the National Council for Cement and Building Materials (NCB) which was published in 2013 (IEA & wbcSD, 2013). The

²⁶ Quantitative information on the different mitigation levers for all national roadmaps is provided in table 3.1 in section 3.4.3.1.

²⁷ Table 3.1 in section 3.4.3 shows how mitigation levers have been quantified based on the information provided in Cembureau (2020). Development between 2020 and 2030 resp. 2030 and 2050 has been interpolated linearly.

roadmap distinguishes a “low demand” and a “high demand” case. The recent cement demand of India of 334 Mt/year in 2020 (GCCA India, 2022) is even below the cement demand projected for 2020 in the “low demand” case of the IEA/ WBCSD roadmap. We therefore focus on the “low demand” case for the further data collection and analysis as this case seems more credible than the “high demand”, according to which the cement demand increases to 598 Mt by 2030 and to 780 Mt by 2050.²⁸

The roadmap considers five mitigation levers: co-processing of alternative fuels and raw materials, thermal and electrical efficiency, clinker substitution, waste-heat recovery, and newer technologies. The most effective mitigation measures of the roadmap include an ambitious reduction of the clinker factor from 0.7 in 2020 to 0.58 by 2050 by using ground granulated blast-furnace slag (GGBS) and other blending material from non-ferrous industries. Furthermore, the use of 25% of alternative fuels by 2050 is envisioned. Among the “newer technologies” only CCS is considered to become commercially available over the timeframe analyzed and is highlighted as a potential key option to reduce CO₂ emissions through capturing and sequestering 86 Mt CO₂ in 2050. Energy efficiency plays a smaller role, according to the roadmap. Table 3.1 in section 3.4.3 shows the key mitigation levers for 2030 and 2050, expressed in the unified framework presented in section 3.3.2. The cumulative CO₂ emissions of the Indian cement sector in the period 2020 to 2050 calculated from annual emissions presented in the roadmap amount to 8.3 Gt CO₂.

3.4.1.5 USA

The PCA (Portland Cement Association) published a roadmap to carbon neutrality along the cement and concrete value chain in 2022 (PCA, 2022), which is assumed here to reflect the *current ambition* of the US cement sector. The roadmap addresses five steps along the value chain, very similar to the Cembureau roadmap for the EU (see above): clinker, cement, concrete, construction and carbonation. The roadmap assumes that the cement industry will still emit CO₂ by 2050, but that CO₂ neutrality can be achieved through offsetting. The amount of residual emissions by 2050, however, does not become clear from the roadmap. In the following analysis we assume that it equals the amount of CO₂ captured through recarbonation of concrete: 9.4 Mt CO₂ by 2050 – i.e. that CO₂ neutrality along the cement and concrete value chain is achieved if recarbonation is taken into account.

The roadmap features an encompassing list of mitigation levers which are translated into the unified framework used in this analysis in table 3.1 in section 3.4.3. Overall, the calculations behind the figures shown in the roadmap are not always fully transparent and it partly remains unclear which levers are included into which (intermediate) results. The values presented in table 3.1 therefore reflect our interpretation of the information given in the roadmap. The roadmap shows a comparably high ambition on the structural and concrete levels. Alternative binders are not considered and the use of SCMs is limited in quantity and in types of SCMs considered (e.g. no consideration of calcined clays). Consequently, the clinker factor remains comparably high over time, still being at the level of 0.75 by 2050.²⁹ The amount of carbon captured and stored is not quantified in the roadmap. We assume that the goal of CO₂ neutrality along the value chain is achieved when including CCS and recarbonation and adjust the amount of CCS for the year 2050 accordingly. For 2030 we assume a share of production

²⁸ In order to accommodate the difference of empirical cement demand and projected cement demand we take the empirical value of the cement demand for 2020, rather than the value given in the roadmap. This results in a strong increase of cement demand from 334Mt to 502 Mt between 2020 and 2025, which is, however, supported by expectations of strongly increasing cement demand in that period voiced by GCCA India (2022).

²⁹ See discussion below on interdependencies between concrete mix and clinker factor.

capacity using CCS of 5% given the current state of progress of CCS technologies. According to our interpretation and calculations, the cumulative CO₂ emissions of the US cement sector in the period 2020 to 2050 amount to 1.4 Gt CO₂.

3.4.2 Assessment of current ambition

3.4.2.1 A Paris-compatible CO₂ budgets for the global cement sector

The first step for assessing the current ambition pathways is deriving a Paris-compatible CO₂ budget for the global cement industry, which will be allocated to different countries / regions in the second step. The regional budgets will then be compared to the budgets implied by the *current ambition* pathways of the major emitter countries.

Deriving a Paris-compatible CO₂-budget for the global cement industry includes two sub-steps: 1) defining a global CO₂ budget that is in line with the goals of the Paris agreement; and 2) allocating a share of this budget to the cement industry. For the definition of a Paris-compatible global CO₂ budget we refer to IPCC (2021), which provides a relation between global CO₂-budgets and increases of the global average temperature. According to this, a CO₂-budget of 700 Gt CO₂ for the Energy and Industry sectors would allow to stay below 1.7 °C – i.e. “well below 2 °C” – with a probability of 67%. Based on these considerations, we use 700 Gt CO₂ as “Paris compatible” budget for the global Energy and Industry sectors.

There are no commonly agreed rules for allocating this budget to specific sectors. One simple approach could be a “sectoral grandfathering”; i.e. the budget is allocated to sectors according to their today’s share of emissions. Another approach is using global Integrated Assessment Models (IAMs) to identify an optimal allocation of a global CO₂ budget to sectors in Paris-compatible scenarios. Figure 3.1 compares the CO₂ budgets for the global cement industry from these two approaches to the cumulative CO₂ emissions implied by the roadmap of the Global Cement and Concrete Association (see section 3.4.1).

The sectoral grandfathering approach allocates 49 Gt CO₂ of the total budget to the cement industry, based on its today’s share of 7% of total CO₂ emissions from the Energy and Industry sectors (IPCC, 2022). The assessment of IAM’s CO₂ budget allocation to the cement sector is based on Paris-compatible scenarios from the AR6 scenario database that fulfill two conditions: the total CO₂ emissions from the Energy and Industry sectors stay below 700 Gt CO₂ in the period 2020 – 2050 and the emissions of the cement sector are made transparent (i.e. they are reported and the values are above zero).³⁰ The scenarios include budgets in a bandwidth of 19 to 119 Gt CO₂, with an average of 63 Gt CO₂.

The cumulative CO₂ emissions implied by the GCCA roadmap (51 Gt CO₂) are very close to the budget “allowed” by the “sectoral grandfathering” approach and well below the average of the budget suggested by the IPCC Paris-compatible IAM-Based scenarios. We conclude that staying below a budget of (about) 50 Gt CO₂ is an ambitious and Paris-compatible mitigation target for the global cement industry and that the GCCA roadmap hence can be considered being basically consistent with the Paris agreement.

³⁰ This results in 8 scenarios based on three models (IEA Energy Technology Perspectives Model; Mc Kinsey 1.0; REMIND-MAGPIE 2.1-4.) being taken into account.

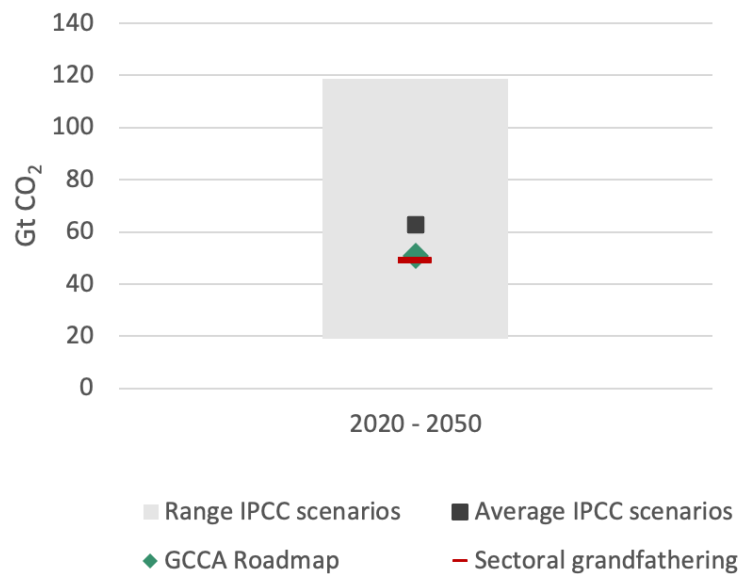


Figure 3.1: Comparison of cumulative CO₂ emissions of the GCCA Roadmap to CO₂ budgets allocated to the global cement industry by IPCC scenarios and through the sectoral grandfathering approach

3.4.2.2 Allocating CO₂ budgets to cement sectors of Tier-1 countries

Different approaches for allocating global CO₂ budgets to nations and world regions have been proposed (Höhne et al., 2014; Van den Berg et al., 2020). Although these have (to our knowledge) so far not been applied to the sectoral level we see no general barriers for doing so and are not aware of any other, more suitable approach for defining sectoral CO₂ budgets on a national level. We use the following approaches and their operationalization³¹ as suggested by (Van den Berg et al., 2020):

- › Grandfathering (GF2020): allocations of emission allowances to the cement sector of a specific region remain in proportion to current (2020) emission shares of this region on global emissions from the cement sector.
- › Immediate per capita convergence (IEPC): allocation of regional cement sectors' carbon budgets based entirely on average (projected) population shares of these regions in the period 2020-2050.
- › Equal cumulative per capita emissions (ECPC): allocation of regional cement sectors' carbon budgets based on cumulative emissions per capita in the period 1990-2050.³²

Historical process emissions of regional cement sectors have been taken from Andrew (2019) and historical energy related emissions have been approximated by us.³³ Population development has been assumed according to the UN Population Division Data Portal (UN, 2023, Median variant). The resulting regional CO₂ budgets are shown in figure 3.2 in the next section.

³¹ The reference year is updated to 2020 and the time period has been limited to 2050 (instead of 2100), compared to van den Bergh et al. (2020).

³² The discount factor d for historical emissions used in the formula for the calculation of ECPC has been set to $d=2$.

³³ Clinker production per year has been calculated from reported process related emissions and specific process related emissions. The thermal energy demand has been assumed to be constant on 2020-levels over the whole period 1990-2020. The use of alternative fuels has been from Cembureau (2021) for the EU, held constant on (low) 2020-levels for China and India and been assumed to have increased from low levels (1%) to today's levels in the U.S. and for the whole world. It has been assumed that the remainder of thermal energy has been provided by coal.

The Grandfathering approach allocates approximately half of the total budget to China, according to its currently high share of global cement related emissions (about 50%). The ECPC approach, on the other extreme, results in a negative value for China; i.e. following this approach, China has used up its total budget for the period 1990-2050 already well before 2020. This can be understood from the fact that China's per capita cement use has increased massively after 1990 and reached levels unprecedented by any other country before – 2-5 times higher than those of developed countries (Xu et al., 2022). For India, the picture is the opposite, i.e. the budget is smallest according to the sectoral grandfathering approach and biggest when taking historical emissions into account. This reflects India's current low per capita cement-related emissions, which have been even lower in the past. For all analyzed regions except China, the immediate convergence of per capita emissions would allow for bigger budgets than the sectoral grandfathering approach, which reflects their per capita emissions being below the global average (which is currently strongly influenced by China's dominant position regarding both, the share of global cement production as well as per capita emissions). The per capita emissions of both, the EU27 and the USA, historically were higher than those of the global average. This changed around 2007 for the USA and around 2010 for the EU27, with the rise of Chinese per capita emissions that massively influence the global average level. The overall lower per capita emissions of the USA compared to the EU27 and the earlier switch from above to below global average yield a CO₂ credit for the US cement industry but lead to a CO₂ debt for the EU industry in the period 1990 - 2020. As a consequence, the ECPC approach, which considers historical emissions, is most favorable for the USA but least favorable for the EU27 region.

3.4.2.3 Comparison of CO₂ emissions of current ambition pathways and available CO₂ budgets

Figure 3.2 compares the cumulative CO₂ emissions implied by the regional Roadmaps (section 3.4.1) to the allowances according to the three different approaches for allocating a global budget of the cement sector to regions. It can be observed that for all regions, the emissions implied by the roadmaps fall into the huge bandwidth of budgets spanned by the three allocation approaches which is caused by the very high level of current absolute and per-capita cement use (and emissions) of China. Hence, in all cases, there are perspectives according to which each roadmap is or is not compatible to the Paris agreement. None of the assessed regions fully exceeds the remaining budget in all cases. However, the cumulative emissions with the *current ambition* of China are above the budget for China according to both approaches which consider fairness aspects (IEPC and EPCP) and only stay below the budget allocated by the grandfathering approach, which is considered to be an extreme case among the suggested allocation approaches (Gignac & Matthews, 2015; Höhne et al., 2014). On the other hand, the roadmap for the USA is (almost) compatible to the Paris Agreement, according to all allocation methods applied.³⁴

³⁴ It should be noted, however, that the calculations of the cumulative emissions of the roadmap for the USA includes several crucial assumptions, as the information provided in the roadmap was not conclusive with regards to all mitigation levers, in particular CCS. See section 3.4.1

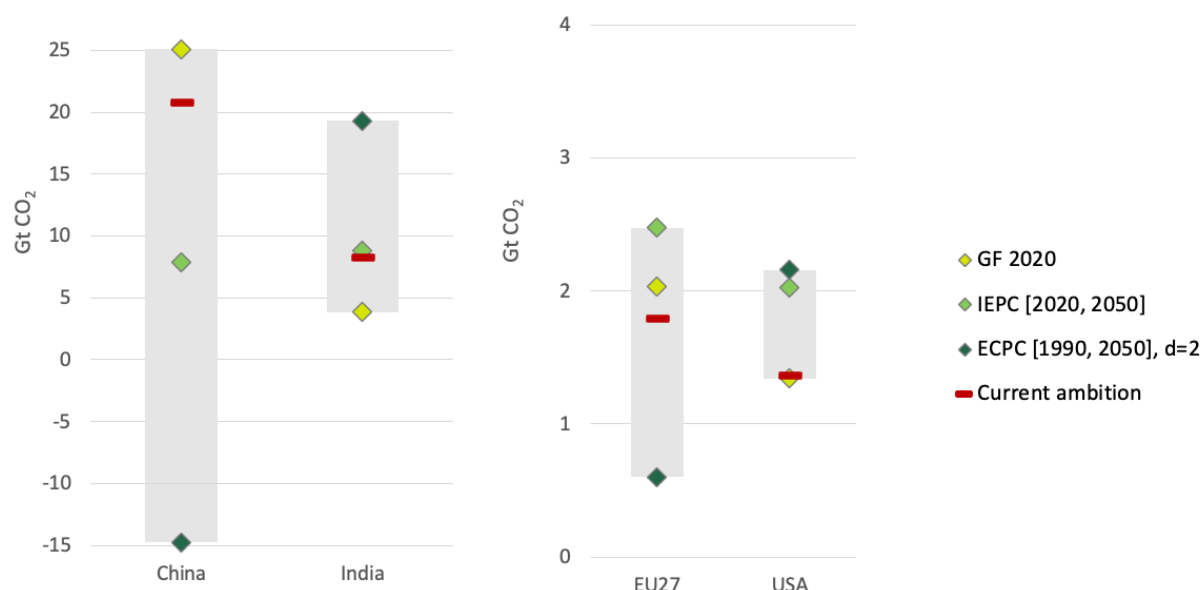


Figure 3.2: Carbon budgets allocated to cement sectors of world regions according to various approaches compared to cumulative CO₂ emissions implied by regional *current ambition* pathways.

Note: GF=“Grandfathering”; IEPC=“Immediate per capita convergence”; ECPC=“Equal cumulative per capita emissions”

3.4.3 Increased ambition

In order to address the second main objective of this report, we identify potential levers for acceleration of decarbonization compared to the *current ambition* pathways. We do so by comparing national pathways in a unified model structure (see section 3.2.3). According to our approach, a potential for increased ambition is assumed for country A, if the comparison of mitigation levers among all four analyzed countries indicates that some other country B has higher ambitions with regards to this lever. However, regional differences need to be taken into account and we thus conduct an additional plausibility check in each identified case, before considering it. The increased ambition for individual mitigation levers are then combined into a modelled *increased ambition* pathway, in order to assess their (joint) impacts on CO₂ emissions.

The use of novel binders is reported and compared across roadmaps, but not taken into account as potential lever for increased ambition because the mitigation potential of novel binders varies strongly between different binders while the different binders have different requirements in terms of raw materials and potentially other context factors. It is beyond the scope of this study to analyze a broad range of binders for each country. In total, the mitigation potential missed through leaving out novel binders from the analysis is assumed to be low, in line with the experts views (Scrivener, John, et al., 2018).

3.4.3.1 Levers for acceleration of decarbonization

Table 3.1 compares the individual mitigation levers of the *current ambition* pathways in our unified framework. The potential enhancements that become apparent from this comparison are discussed in the following subsections.

Table 3.1: Comparison of national pathways in a unified mitigation lever framework

	2030				2050			
	China	EU	India	USA	China	EU	India	USA
Concrete used per structural element (Index, 2020=100)	98	n.a. (90-95)*	n.a.	90	93	n.a. (70-90)*	n.a.	70
Binder intensity of concrete (Index, 2020=100)	n.a.	95	n.a.	90	n.a.	85	n.a.	74
Use of alternative binders (% of all binders)	2%	5%	n.a.	n.a.	6%	13%	n.a.	n.a.
Clinker factor (avg. clinker content of cement)	67%	74%	64%	85%	67%	65%	58%	75%
Use of decarbonated raw materials (% of all raw materials entering the cement oven)	5%	3,5% CO ₂ red. [§]	1%	7%	15%	8% CO ₂ red. [§]	1%	10%
Specific thermal energy demand (GJ / t clinker)	3,1	3,57	2,91	3,80	2,8	3,2	2,85	2,95
Waste-based fuels (% of thermal energy provided)	5%	60%	19%	22%	28%	90%	25%	45%
Biomass fuels, primary biomass (% of thermal energy provided)	2%	0%	0%	5%	5%	0%	0%	15%
Hydrogen (% of thermal energy provided)	1%	0%	0%	0%	5%	5%	0%	0%
Direct electrification of heat (% of thermal energy provided)	0%	0%	0%	0%	5%	5%	0%	0%
Production capacity with Carbon Capture (% of all clinker production capacity)	6%	0%	5%	5%	33%	92%	24%	70%

*range mentioned in roadmap but not considered in calculations, both in roadmap and current ambition; [§] value given and included in modelling as resulting CO₂ reduction (all other roadmaps: share of mass of decarbonated materials used); "n.a.": not mentioned in roadmap and hence not considered in current ambition

3.4.3.2 China

3.4.3.2.1 Assessment of levers in current ambition pathway

The most important mitigation lever in the RMI/CCA-Roadmap is demand reduction (see Fig 3.5). Cement demand falls from about 2400 Mt in 2020 to 750 Mt in 2050, i.e. demand is reduced to roughly 1/3 within 30 years. Although some decrease of future demand seems to be almost certain (see above), the decrease assumed by the RMI/CCA-Roadmap is much stronger than in other studies. For example, the per-capita development predicted by IEA and CSI (2018) would amount to a cement demand of about 1500 Mt in 2050³⁵, i.e., double the volume suggested by RMI/CCA (2022). The assumptions behind and the required measures to achieve such a strong cement demand decrease are outlined only very roughly in the RMI/CCA-Roadmap, but it can be assumed that substantial measures on the buildings and concrete levels are implied in these numbers (cf. also ETC & RMI (2019) who assume

³⁵ Own calculation using population numbers from UN (2023).

similar decrease in Chinese cement demand). Thus, it is assumed here that ambitions on the levels of structure and concrete composition are already very high and no further increase of ambition can be assumed for the *increased ambition* pathway.

The clinker factor does not decrease below today's levels (0.67), according to the roadmap and it is not made explicit which types of cements are assumed to be used in the future. The use of calcined clays for cement production is not mentioned in the roadmap, although LC3 cements allow clinker factors of no more than 0.5 and suitable clays seem to be abundant in China.³⁶ According to Liu et al. (2022), China's current installed capacity of coal-fired power plants will still be in operation in 2050 (but retrofitted with carbon capture) and thus the availability of fly ashes for cement and concrete production can be assumed to remain high. The prospects of GGBS are less clear, but some share of blast-furnace iron production will most likely be in operation in China in 2050 which will provide some amounts of GGBS – for example the Paris-compatible pathways described in Bilici et al. (submitted) include a strong decrease in the availability of GFBS from 287 Mio. t in 2020 to 20 Mio. t in 2050. In sum, there seems to be a comparably good availability of SCMs in China. An own assessment of a potential future cement portfolio suggests that the clinker factor could drop to 0.64 by 2030 and to 0.58 by 2050 if LC3 cements are used (at least) for mortar and concrete with the lowest strength class and fly ash cements are used approximately at today's share. It is thus suggested that the increased ambition pathway for China achieves the same clinker factor as the one for India.

The use of waste-based fuels increases in the RMI/CCA-Roadmap, but only to 28% in 2050. For comparison: the share of waste-based fuels in German cement production was increased from low levels (about 8%) to about 70% within 30 years (1990 – 2020). China's high per capita cement demand needs to be considered, though, which translates into lower availability of suitable wastes per ton of cement (Global Cement Magazine September 2023). The relation of waste and cement, however, will become more similar to other countries in the future, if cement demand per capita declines as projected by the roadmap. It is assumed that the amount of waste-based fuels can be increased to 45% until 2050, i.e. the target set by RMI/CCA for 2060 can already be achieved earlier. The share of biogenic carbon is assumed to increase from 20% to 30% until 2050, as other wastes beyond tires become more common for use in the cement sector.

The use of biomass is also limited in the RMI/CCA-Roadmap and increases from low levels to 5% in 2050. Considering the strong decrease of clinker demand assumed in the roadmap, the absolute level of biomass use in 2050 is 66 PJ (own calculation, including biomass use for calcination of clays), which amounts to about 1% of biomass used in China in 2019 (IEA Bioenergy, 2021a). Considering the benefits of using biomass for clinker production (see section 3.3.6) and the technical feasibility of biomass use in clinker ovens, it is suggested that an increase of biomass share to 30% of total thermal energy use by 2050 is doable (required biomass is then 6% of total biomass used in the country in 2019) and beneficial from a systemic point of view.

CCS is able to capture 30% of emissions in the cement sector by 2050, according to the RMI/CCA-Roadmap. It is then rapidly scaled-up to 90% by 2060. The scale-up of Carbon Capture needs to be understood in the context of rapidly falling production and required capacities, which potentially limits the lifetime of CCS-assets if the retrofitted capacity is not required anymore due to decreased clinker demand. However, own assessment of capacity demand (fig 3.3) suggests that – from a capture perspective – CCS could be scaled-up to 70% until 2050 while respecting that assets should

³⁶ <https://lc3.ch/the-material/>

have a life-time of at least 25 years and assuming a future decrease of clinker demand based on Chinese population decreasing to 1.1 billion in 2070 (Dai et al., 2022) and per capita cement demand decreasing to the level of Germany (400 kg / capita / year) until 2070.

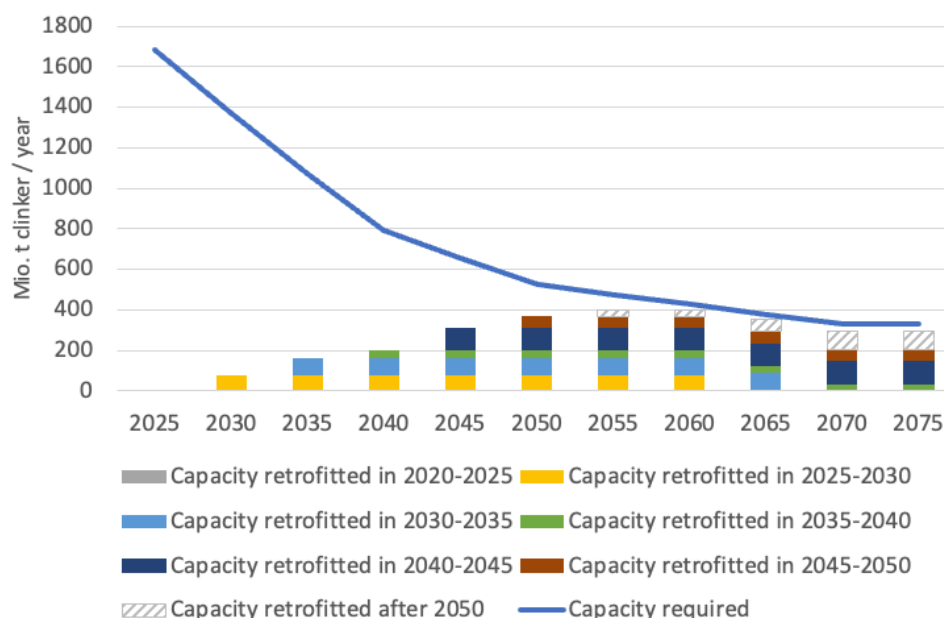


Figure 3.3: Possible Carbon Capture scale-up pathway in the context of decreasing clinker demand. The figure shows clinker production capacity which is retrofitted with CCS (columns) compared to the clinker production capacity required to meet clinker demand (line). The CCS upscaling pathway respects life-time of assets being at least 25 years. (source: own assessment)

3.4.3.2.2 Increased ambition pathway

An increased ambition pathway has been modelled by applying the above discussed enhanced ambition for the selected mitigation options using the model described in section 3.2.3.

Table 3.2: Overview of increased ambition for selected mitigation options

	2030 Current ambition	2030 Increased ambition	2050 Current ambition	2050 Increased ambition
Clinker factor	0.67	0.64	0.67	0.58
Waste-based fuels	6%	10%	28%	45%
Biomass fuels	2%	10%	5%	30%
CCS (% of capacity with CCS)	6%	6%	33%	70%

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The modelling shows that near-zero emissions of about 84 kg CO₂ / t binder are achieved in the *increased ambition* pathway by 2050, compared to 323 kg CO₂ / t binder in the *current ambition* pathway. Figure 3.4 shows that cumulative emissions can be reduced by about 2.6 Gt CO₂ to 18.2 Gt CO₂ in the period 2020-2050, i.e. by about 11%, compared to the current ambition.³⁷

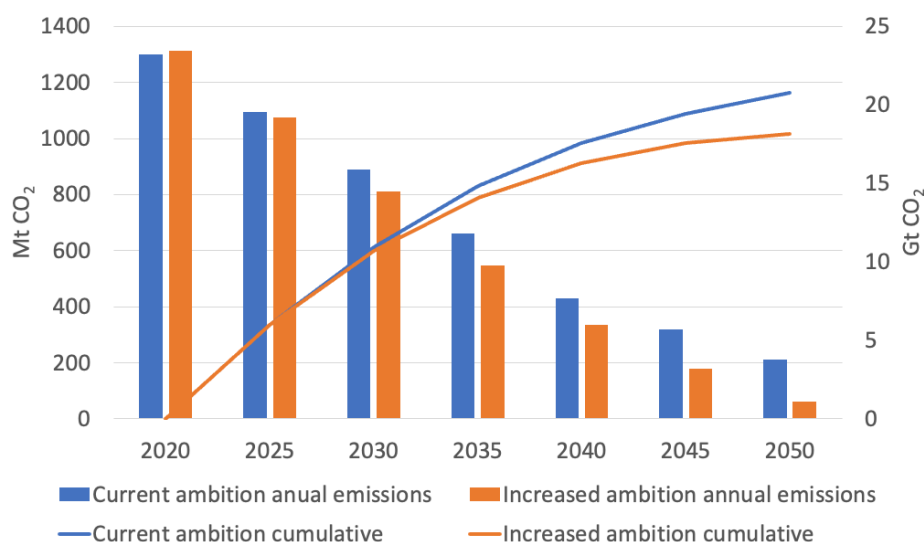


Figure 3.4: Annual emissions (columns, left axis) and cumulative emissions (lines, right axis) of the *current ambition* and *increased ambition* pathways for China.

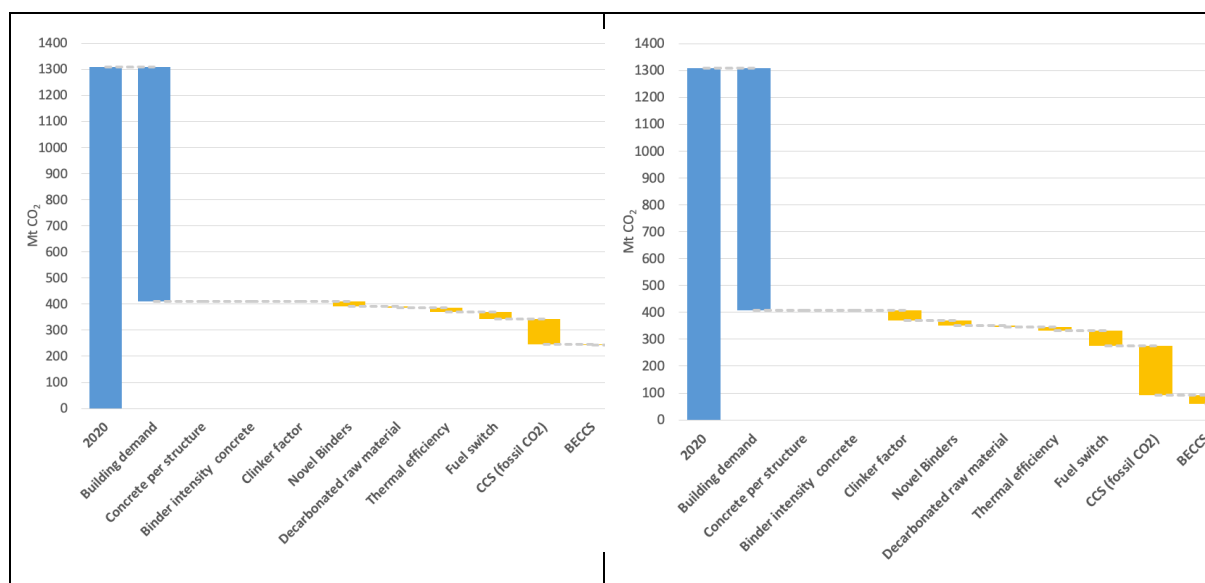


Figure 3.5: Contributions of various mitigation levers to overall CO₂ mitigation in the *current ambition* (left) and the *increased ambition* (right) pathways for China, respectively.

³⁷ The modelling of the current ambition pathway leads to annual emissions that are -3% to 8% higher than the numbers given in the roadmap of RMI/CCA. The origin of the delta is not clear as the roadmap does not disclose all parameter values required for our modelling. For the modelling, process-based emissions of clinker have been taken from Andrew (2019) and the emission factor of coal (being the most relevant fossil fuel) have been taken from Liu et al. (2015). Process based emissions and thermal energy demand of alternative binders have been reduced by 40%, compared to clinker (mirroring the savings associated e.g. with CSA cements). The unexplained delta in annual emissions sums up to 160 Mt CO₂ over the period 2020 – 2050. This delta is most likely also present in the *increased ambition* pathway and hence the mitigation that could be achieved by the *increased ambition* pathway is underestimated to some extent.

Figure 3.5 compares the contributions of the different mitigation levers to the overall mitigation between the current ambition and the increased ambition pathways for China. In both cases, the picture is dominated by the strong decrease of emissions related to a decreasing building demand (including the efficient use of concrete and binders). The ambition to reduce the clinker factor results in a clearly identifiable reduction of CO₂ emissions in the increased ambition pathway, while the larger share of additional mitigation results from the combination of a faster fuel switch and additional CCS (“Fuel switch”, “CCS” and “BECCS”).

3.4.3.3 EU

3.4.3.3.1 Assessment of levers in current ambition pathway

Factoring out concrete demand per structural element in the Cembureau Roadmap excludes this mitigation lever, which has potentially strong effects. We thus make it explicit in the increased ambition pathway below, based on the values discussed by Cembureau. However, then the future demand for concrete also needs to be made explicit. For doing so we build on Material Economics (2019) BAU scenario and assume an increase of demand for concrete structures of 9% until 2050.

The ambition for reducing binder intensity of concrete is higher in the USA Roadmap, compared to the EU (see table 3.1). However, this needs to be understood in the context of different traditions of using supplementary materials: while the EU has a stronger tradition in using materials such as fly ash and GGBS to reduce the clinker factor of cements, those materials are typically added at to the mix at the concrete level in the USA (U.S. Department of Energy, 2022). Clinker factor of cement and binder intensity of concrete can thus not be compared in isolation between the two regions. We thus do not alter the binder intensity of concrete in the EU *increased ambition* scenario, compared to the EU *current ambition* scenario.

The clinker factor envisioned for India is substantially lower than that envisioned in the Cembureau Roadmap. This needs to be understood against the background of an expected phase-out of blast-furnaces in the EU steel industry (see steel section of this report) in combination with a strong decline of coal-based power production in the EU. The EU cement and concrete industry which historically has strongly relied on GGBS and fly-ashes to reduce their clinker factor needs to shift the larger share of its cement production to innovative cement types based on new SCMs like calcined clays within a few decades. Further reducing the clinker factor at the same time to the level suggested in the Cembureau Roadmap is an ambitious goal in itself and thus no further reduction of the clinker factor is assumed for the *increased ambition* pathway.

The process CO₂ savings through the use of decarbonated raw materials envisioned in the Cembureau Roadmap are very ambitious, according to Hoenig et al. (2022) and would require to go far beyond best current practice in Europe. Hence, the ambition is not further increased in that regard for the *increased ambition* pathway.

The specific thermal energy demand is high for the EU Roadmap compared to other Roadmaps, in particular those for India and China. However, the EU uses a much higher share of alternative fuels, which comes at the penalty of additional thermal energy demand of clinker ovens. Furthermore, clinker ovens in the EU are typically smaller than those in India and China, which also affects efficiency. Considering these differences in context, we use the same assumptions for thermal energy use in both scenarios, *current ambition* and *increased ambition*.

Concerning the fuel use, we maintain the use of 90% alternative fuels with 50% biogenic shares by 2050 when moving from *current ambition* to *increased ambition*. But we assume that the residual 10% of thermal energy is provided by biomass fuels instead of electricity or hydrogen in order to increase the contribution of negative emissions based on the combination of biomass with CCS. Furthermore, the ambition for the use of waste-based fuels by 2030 is slightly increased based on recent progress reported by Cembureau (2023).

The Cembureau Roadmap does not explicitly name targets for carbon capture by 2030 and thus no carbon capture was included in the *current ambition* pathway. However, this is not in line with the pipeline of announced projects by the EU cement industry. Hence, we assume carbon capture at a scale of 7.5 Mt CO₂ / year for 2030, based on announced projects that should be operational before 2030 and provide information about the expected capture capacity (Leadit, 2023). This translates to 9% of capacity being retrofitted with carbon capture by 2030.

3.4.3.3.2 Increased ambition pathway (EU)

An increased ambition pathway has been modelled based on the previous assessment using the model described in section 3.2.3.

Table 3.3: Overview of increased ambition for selected mitigation options (EU)

	2030 Current ambition	2030 Increased ambition	2050 Current ambition	2050 Increased ambition
Concrete demand per structure (index)	100	95	100	80
Waste based fuels (%)	60	65	90	90
Biomass fuels	0%	0%	0%	10%
CCS (% of capacity with CCS)	0%	9%	92%	92%

Figure 3.6 shows that the *increased ambition* pathway derived through these modifications of the *current ambition* pathway achieves negative emissions of -2.1 Mt CO₂/year by 2050. The cumulated emissions in the period of 2020 to 2050 amount to 1.6 Gt CO₂, which is a reduction of about 190 Mt CO₂ or 11%, compared to the *current ambition* pathway.

Figure 3.7 compares the contributions of the different mitigation levers to the overall mitigation between the *current ambition* and the *increased ambition* pathways for the EU27. The contributions of mitigation levers appear to be quite similar in both pathways, reflecting the comparably small differences between both pathways in the EU27 case. The *increased ambition* pathway suggests, however, that concrete savings per structure may well overcompensate additional building demand. The use of biomass fuels instead of electricity or hydrogen for process heat facilitates a stronger contribution of negative emissions through BECCS.

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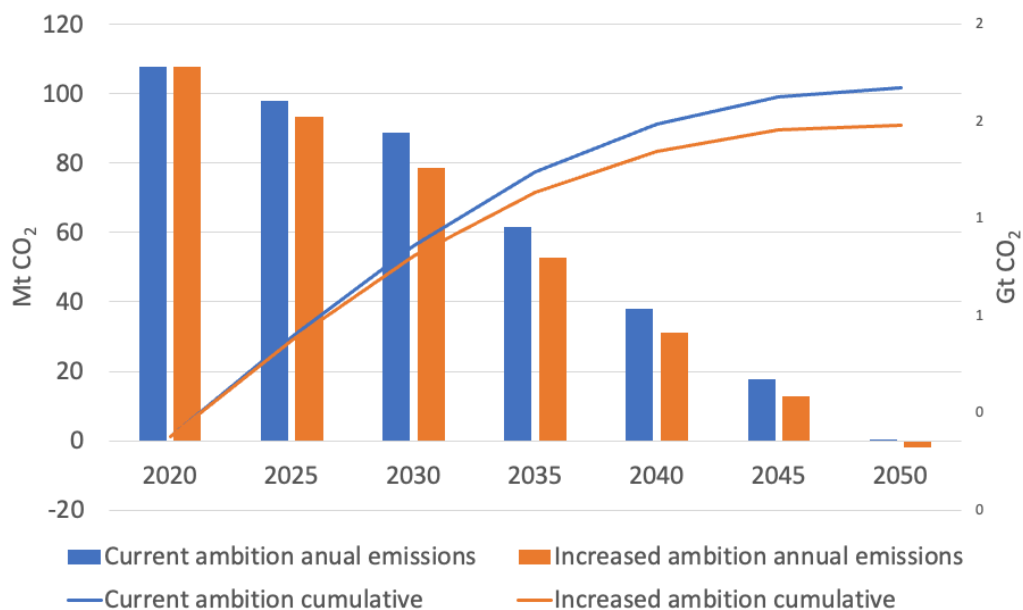


Figure 3.6: Annual emissions (columns, left axis) and cumulative emissions (lines, right axis) of the *current ambition* and *increased ambition* pathways for the EU27.

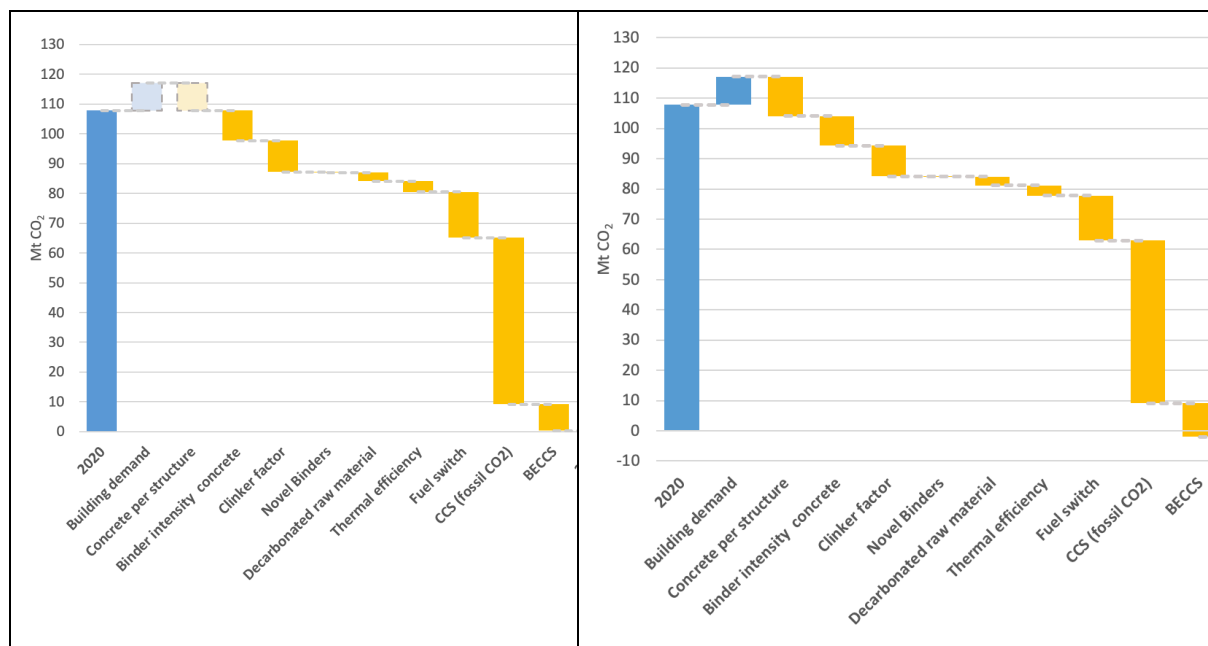


Figure 3.7: Contributions of various mitigation levers to overall CO₂ mitigation in the *current ambition* (left) and the *increased ambition* (right) pathways for the EU27, respectively.

3.4.3.4 India

3.4.3.4.1 Assessment of levers in current ambition pathway

The IEA/ WBCSD Roadmap is developed using a model of the IEA which considers GDP, population and per-capita income as drivers for cement demand per capita and eventually cement production. According to the information available, the model does not consider mitigation levers on the concrete level, namely concrete demand per structural element and cement intensity of concrete. According to GCCA (2021) the move from small project site batching of concrete using bagged cement to industrialized processes offers significant potential for reducing the binder content of concrete through adherence to mix specifications and quality control. In emerging economies such as India the vast majority of concrete production is currently on project sites (GCCA, 2021). The potential for reduced binder intensity of concrete is thus assumed to be high. We furthermore assume that similar effects hold on the structural level through improved planning in a more industrialized cement sector. Based on these considerations we propose that these mitigation levers on the structural and concrete levels can play a role in an increased ambition pathway to a degree that (at least) reflects ambitions in other world regions as well as the global averages proposed by GCCA (2021).

The clinker factor envisioned in the roadmap for India (0.58) is more ambitious than those for other regions, which is in line with expectedly higher availability of fly ash from coal-fired power plants and GGBS from blast furnaces in India, compared to the EU and USA. GCCA (2021) proposes even more ambitious targets for a global average clinker factor of 0.52 by 2050, which raises the question whether the ambition can be increased, despite of less ambitious targets of other regional roadmaps. According to Indian and EU³⁸ cement standards, cements which achieve a clinker factor below 0.5 need to include at least 20% of GGBS and today only few cements³⁹ that do not contain GGBS allow a clinker factor of 0.5. The availability of GGBS is limited to 3-6% of cement demand, when comparing the GGBS produced in the *domestic* and *DRI-trade* steel scenarios (see section 2.4) to the cement demand of the *increased ambition* cement scenario; i.e. cements with GGBS can play a small role, only, according to these numbers. New cements may still be developed with low clinker factors and without using GGBS in the future. However, their inclusion in standards and market uptake will take some time and thus we don't expect such new cements to play a significant role until 2050. Instead, Portland cement may still play a small role in 2050 for specific applications, as well as fly ash cements and other cements with limited use of SCMs. In sum, we consider the target of the IEA/ WBCSD Roadmap being ambitious and don't see a clear potential for further enhancing the ambition.

The use of decarbonated raw materials is not considered explicitly in the IEA/WBCSD Roadmap, but only implicitly included to a marginal extent through the use of alternative fuels (the ashes of which become part of the clinker). We are not aware of any specific reason why decarbonated raw materials should not play any role in the Indian cement sector. Hence, by comparison with other regional roadmaps and considering that waste management may be less developed in India compared to other regions, we assume a modest contribution of decarbonated raw materials of 2% in 2030 and 8% in 2050 in the *increased ambition* pathway.

³⁸ The EU cement standard EN-197-1 is widely adopted and used by 34 countries around the world (GCCA 2022) and is thus considered here as additional reference for possible cement compositions.

³⁹ CEM II/C-M cements listed in the European cement norm EN-197-1 may contain at minimum 50% clinker, up to 6-20% limestone and 16-44% of fly ash or pozzolanic materials such as calcined clays.

The use of waste-based fuels increases only slowly after 2030, from about 20% in 2030 to 25% in 2050, according to the IEA/WBCSD Roadmap. Considering that recent progress in regulatory boundary conditions supports the use of waste for fuels and several India's cement companies have gathered experience with waste-based fuels already (IEA & wbcscd, 2013), that at least one Indian cement company strives to replace fossil fuels entirely by alternatives already by 2035 (Dalmia Cement, 2020) and assuming that economic boundary conditions are designed in a way that supports a further strong increase of waste-based fuels use after 2030, we propose that India might be able to achieve waste-based fuels deployment rates that are similar to the global average proposed by GCCA (2021)

Primary biomass is not considered as fuel in the roadmap but we propose that energetic use of primary biomass has several advantages (see 3.3). Therefore, we propose a (modest) use of primary biomass in the increased ambition pathway. The suggested 25% of thermal energy provision as well as the use of 80% biomass for calcination of clays, both by 2050, would require about 300 PJ of (primary) biomass in 2050, which equals about 4% of total current bioenergy use (IEA Bioenergy, 2021b).

To the author's knowledge, there is currently limited practical knowledge about geological CO₂ storage sites in India that goes beyond simulations and feasibility studies (Shaw & Mukherjee, 2022). Considering lead times required for site exploration and development, onshore storage of CO₂ is not expected to play a role in the short term. However, CO₂ exports to other regions with large storage potential, e.g. the Arab region, may be feasible. For export of CO₂, transport infrastructure at ports and for inland transport to the ports is required, which today do yet not exist. Against this background, the scale-up of carbon capture envisioned in the IEA/WBCSD Roadmap appears to be (over-)optimistic in the short and medium term and thus the pathway is not further accelerated in the increased ambition pathway before 2040 in terms of mass of CO₂ captured. Assuming that the Indian cement industry may benefit from international experience with CCS afterwards and that favorable economic boundary conditions are created through regulation, the pace of CCS implementation is however increased after 2040 in the *increased ambition* pathway. It should be noted that the capacity with CCS in Mt clinker/year and the mass of CO₂ captured scale much less between the pathways than the percentage of capacity retrofitted with CCS shown in Table 3.4, as the amount of clinker produced (and thus capacity required) is significantly reduced through levers on the concrete and binder levels (see below).

3.4.3.4.2 Increased ambition pathway (India)

An increased ambition pathway has been modelled based on the previous assessment using the model described in section 3.2.3. As a consequence of the modified assumptions, the cement demand of India increases more modestly in the *increased ambition* pathway, compared to the current ambition pathway, due to (additional) efforts of the concrete industry: to 554 Mt instead of 598 Mt by 2030 and to 562 Mt instead of 780 Mt by 2050.

Figure 3.8 shows that the *increased ambition* pathway derived through these modifications of the *current ambition* pathway achieves a reduction of annual emissions in the year 2050 from 257 Mt CO₂/year (IEA/WBCSD Roadmap) to 83 Mt CO₂/year (*increased ambition* pathway). The cumulative emissions in the period of 2020 to 2050 amount to 5.9 Gt CO₂, which is a reduction of about 2.4⁴⁰ Gt CO₂ or 29%, compared to the *current ambition* pathway.

⁴⁰ This includes annual CO₂ emissions reported by IEA/WBCSD (2013) that could not be understood nor reproduced although the complete set of required parameters is provided in the study. Those emissions are thus not reflected in the modelled increased ambition pathway. The delta is 3-7% of annual emissions, which cumulate to 400 Mt CO₂ over the period 2020 – 2050.

Table 3.4: Overview of increased ambition for selected mitigation options (India)

	2030 Current ambition	2030 Increased ambition	2050 Current ambition	2050 Increased ambition
Concrete demand per structure (index)	100	95	100	80
Binder intensity of concrete (index)	100	95	100	85
Use of decarbonated raw materials	1%	2%	1%	8%
Waste-based fuels	20%	20%	25%	45%
Biomass fuels	0%	5%	0%	25%
CCS (% of capacity with CCS)	10%	11%	28%	56%

Figure 3.9 compares the contributions of the different mitigation levers to the overall mitigation between the *current ambition* and the *increased ambition* pathways for India. The increased ambition on the concrete level (concrete demand per structure, binder intensity of concrete) has a strong impact and facilitates the reduction of CO₂ emissions of about 85 Mt CO₂ /year by 2050. The stronger fuel switch decreases energy related fossil CO₂ emissions and facilitates a stronger contribution of BECCS. Although the ambition of CCS is doubled in relation to the share of capacity retrofitted with CCS, the amount of CO₂ captured increases significantly much less, by a factor of 1.5, approximately. The reason is that less CO₂ is generated in the first place, due to significantly reduced binder and clinker demand in the *increased ambition* pathway, compared to the *current ambition* pathway.

Technological Pathways towards Paris-compatible Steel, Cement and Petrochemicals

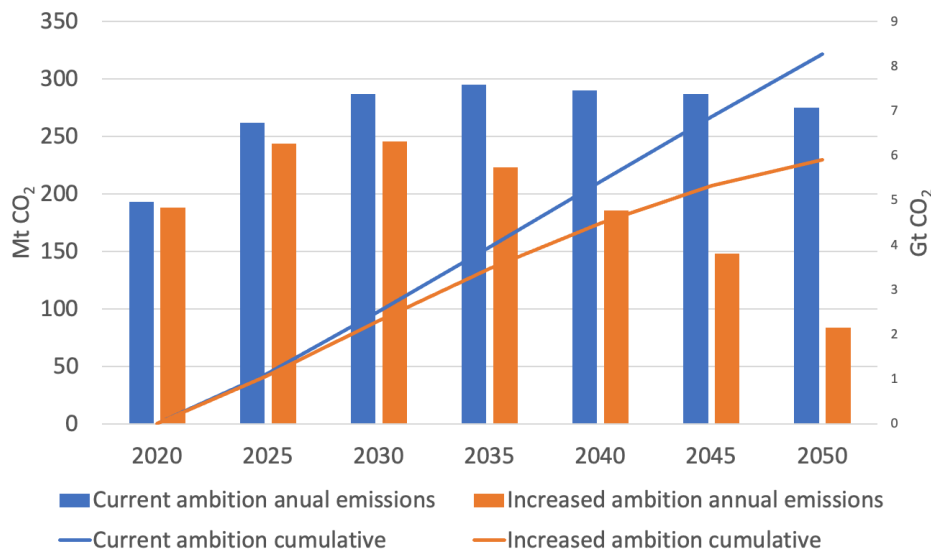


Figure 3.8: Annual emissions (columns, left axis) and cumulative emissions (lines, right axis) of the *current ambition* and *increased ambition* pathways for India.

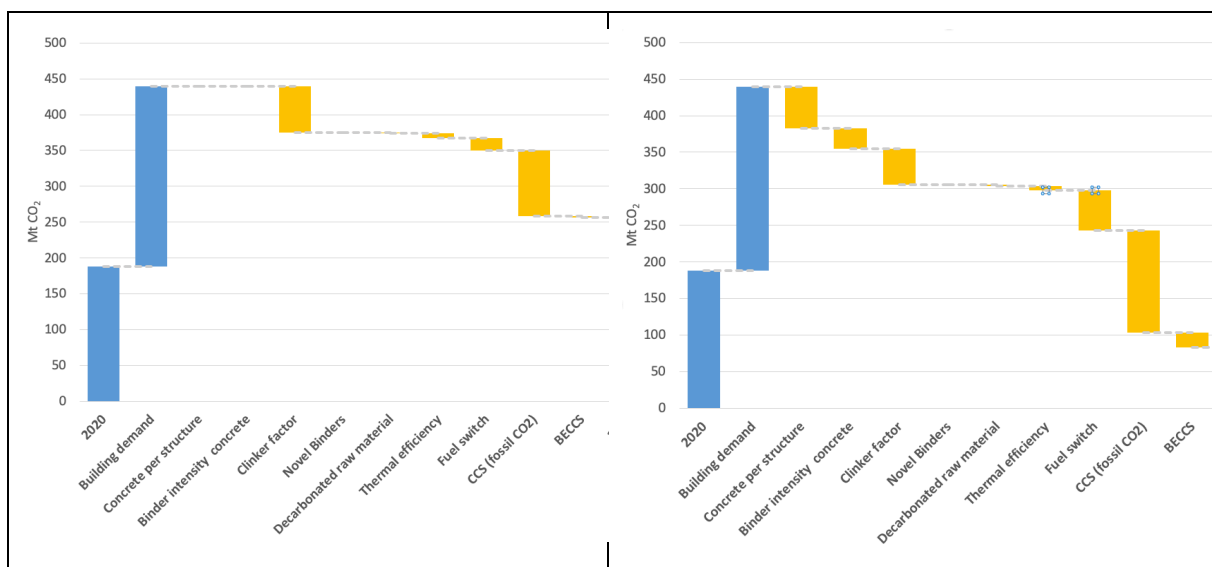


Figure 3.9: Contributions of various mitigation levers to overall CO₂ mitigation in the *current ambition* (left) and the *increased ambition* (right) pathways for India, respectively.

3.4.3.5 USA

3.4.3.5.1 Assessment of levers in current ambition pathway

The ambitions on the structural and concrete levels of the roadmap – i.e. optimization in the design and construction phase as well as optimizing concrete mixes – are highest among the compared regional roadmaps and thus a further acceleration of dynamics in these areas is not considered in the following.

The clinker factor remains on a comparably high level, which must be seen in the context of practices for using SCMs in the USA. The U.S. Department of Energy (2022) notes that, according to the PCA, “the common U.S. practice is adding less SCM during cement manufacturing and more SCM during the

concrete batching process, whereas other countries tend to incorporate the SCMs during the cement manufacturing process.” (p. 140). Acknowledging these interdependencies and considering that the binder intensity of concrete aimed at in the PCA roadmap is low compared to other roadmaps, we conclude that the overall clinker content in concrete is about the same level in the PCA roadmap as in the Cembureau roadmap for the EU.⁴¹ Further decreases in the clinker factor are thus not considered in the following.

The PCA roadmap aims at least at a doubling of the use of decarbonated raw materials. The target value of 10% is, however, low compared to the value aimed at in the roadmaps for China and the EU and compared to what is achieved in Austria already today. It is beyond the scope of this study to assess the availability of suitable raw materials in detail, but considering that the U.S. is an industrialized country with all the abilities and capacities required for handling materials and wastes, we propose that the ambition for the use of decarbonated raw materials can be increased (at least) to some extent in the long term.

The thermal efficiency is low in the U.S. compared to other world regions, today, but a considerable improvement is aimed at by the PCA roadmap, reaching thermal efficiency levels comparable to other world regions by 2050. The use of waste-based fuels is also low in the U.S., today, compared to the EU. The roadmap envisions an increase to 45% waste-based fuels by 2050. However, the German cement industry has achieved an increase from comparably low levels to about 70% waste-based fuels today within the last 25-30 years (Ruppert et al., 2020). Today, the knowledge base of the global cement industry has advanced and thus we propose that the U.S. cement and waste-management industries may be able to achieve a similar upscaling within the next 25-30 years, if regulations are revised accordingly. We propose that the remaining fuel demand can be satisfied by an increased use of biogenic fuels, compared to the PCA roadmap. The biomass demand from using 25% of biomass fuels in 2050 would amount to 45 PJ, which is about 1% of the energetic biomass in the U.S. today (IEA Bioenergy, 2021c). The remaining 5% of fuel demand could be satisfied by CO₂-neutral energy carriers such as hydrogen or electricity.

According to our interpretation of the PCA roadmap, CCS shall be deployed at 76% of all capacity (assuming 90% capture rate). This is high compared to the ambitions of the roadmaps for India and China, but lower than the target of Cembureau for the EU. The U.S. is a frontrunner for CCS today (Beck, 2020). Although the focus of current projects is not on cement but on other applications, we reckon that the experiences made with transport and storage put the U.S. in a pole position for a quick upscaling of CCS in the cement industry. We thus propose that CCS can be upscaled in the U.S. (at least) to the same level as in the EU by 2050. The LeadIT Green Cement Tracker (Leadit, 2023) includes four feasibility studies and one pilot project for CC(U)S in the U.S., which shows the increasing interest of the U.S. cement industry in CCS and which can be used to estimate the share of CCS by 2030.

3.4.3.5.2 Increased ambition pathway (USA)

An increased ambition pathway has been modelled based on the previous assessment using the model described in section 3.2.3.

⁴¹ It is beyond the scope of this study to analyze cement and concrete mixes in the U.S. compared to other regions at a greater level of detail. It should be noted, however, that the PCA roadmap does not consider the use of calcined clays for cement manufacturing, which might provide a lever to reduce clinker factor beyond the level aimed at by the PCA roadmap.

Table 3.5: Overview of increased ambition for selected mitigation options (U.S.)

	2030 Current ambition	2030 Increased ambition	2050 Current ambition	2050 Increased ambition
Use of decarbonated raw materials	7%	7%	10%	15%
Waste-based fuels	22%	22%	45%	70%
Biomass fuels	5%	10%	15%	25%
CCS (% of capacity with CCS)	5%	5%	76%	92%

Figure 3.10 shows that the *increased ambition* pathway derived through these modifications of the *current ambition* pathway achieves a reduction of annual emissions in the year 2050 from 9.4 Mt CO₂/year (*current ambition*) to -0.5 Mt CO₂/year (*increased ambition*). The cumulated emissions in the period of 2020 to 2050 amount to 1.25 Gt CO₂, which is a reduction of about 110 Mt CO₂ or 8%, compared to the *current ambition* pathway.

Figure 3.11 compares the contributions of the different mitigation levers to the overall mitigation between the *current ambition* and the *increased ambition* pathways. The increased ambition in the use of decarbonated raw materials plays a minor role, only. The additional CO₂ savings through a faster fuel switch and BECCS are somewhat increased, respectively, and additional CCS accounts for approximately half of the additional savings.

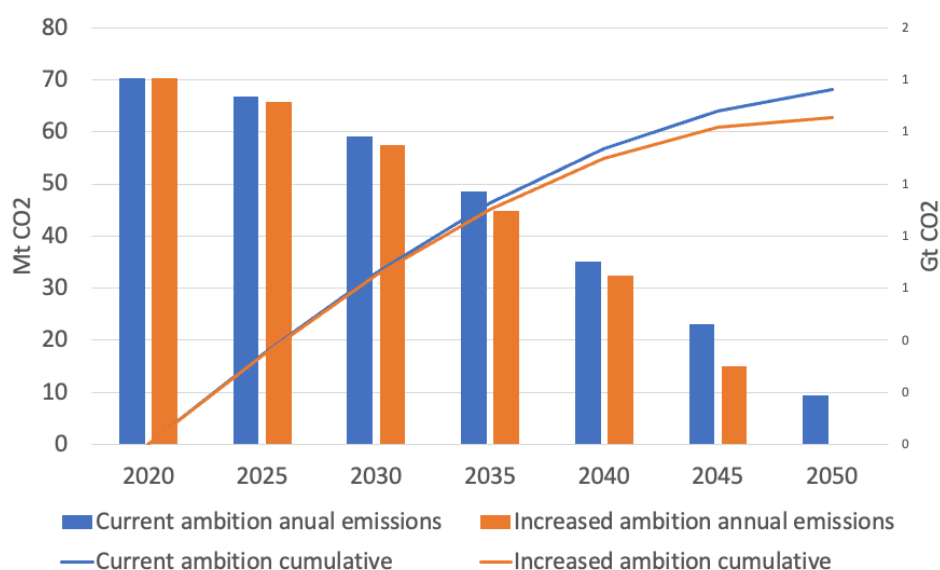


Figure 3.10: Annual emissions (columns, left axis) and cumulative emissions (lines, right axis) of the *current ambition* and *increased ambition* pathways for the USA.

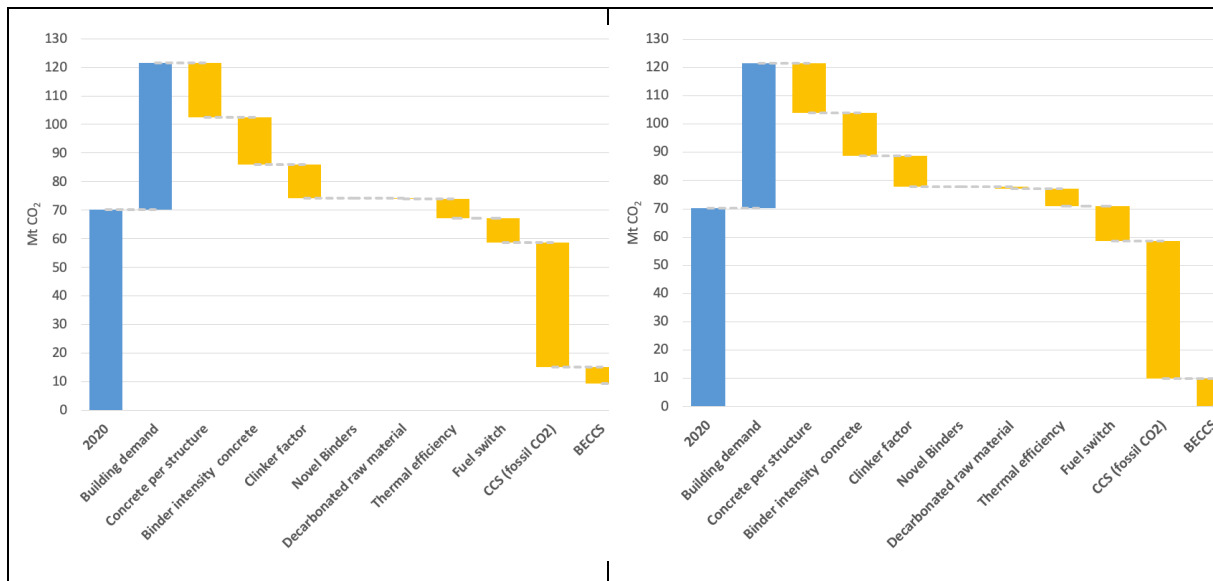


Figure 3.11: Contributions of various mitigation levers to overall CO₂ mitigation in the *current ambition* (left) and the *increased ambition* (right) pathways for the USA, respectively.

3.4.4 Assessment of increased ambition

The reduction of cumulative emissions between the *current ambition* and the *increased ambition* pathways appears to be modest in China (11%), EU27 (11%) and the USA (8%). In the case of China this is rooted in the fact that the (assumed) overall cement demand (and thus production) and associated emissions are envisioned to decrease strongly in the *current ambition* pathway. In the EU27 and the USA, emissions under the *current ambition* pathways are set to strong decreases as well, due to the envisioned mitigation strategies. In all these cases the decrease of emissions can be accelerated to some degree in the *increased ambition* pathways, but only gradually and to increasing extents over time as all mitigation levers require time for their (additional) upscaling. As a consequence, large shares of the cumulative emissions are already emitted before a massive (additional) scale-up of mitigation options can be achieved.

The case of India is different as cement demand increases strongly in both pathways – although to a smaller extent in the *increased ambition* pathway. Furthermore, the decarbonization pathway of India is somewhat delayed, compared to the other analyzed regions. As a consequence, annual emissions remain on a level above the emissions of 2020 for the whole analyzed period in the *current ambition* pathway. Hence, there are more opportunities for green investments and for acceleration of the cement transformation pathway and additional mitigation efforts that are scaled up massively after 2030 have higher emission impacts. The *increased ambition* pathway thus achieves a reduction of cumulative emissions by 29%, compared to the *current ambition* pathway, i.e. the impacts of the increased ambition are significantly stronger than in the other analyzed regions.

Figure 3.12 relates the cumulative CO₂ emissions implied by the *increased ambition* pathways to the CO₂ budgets according to different allocation approaches as well as to cumulative emissions of the *current ambition* pathways. The figure shows that the cumulative emissions of the *increased ambition* pathway rank similar to those of the *current ambition* pathway in all cases; i.e. the assessment of the Paris-compatibility does not change substantially between the pathways for any of the allocation approaches. For the USA, the *increased ambition* pathway becomes clearly compatible to the goals of

the Paris Agreement also for the grandfathering approach, while this was less clearly the case for the *current ambition* pathway.

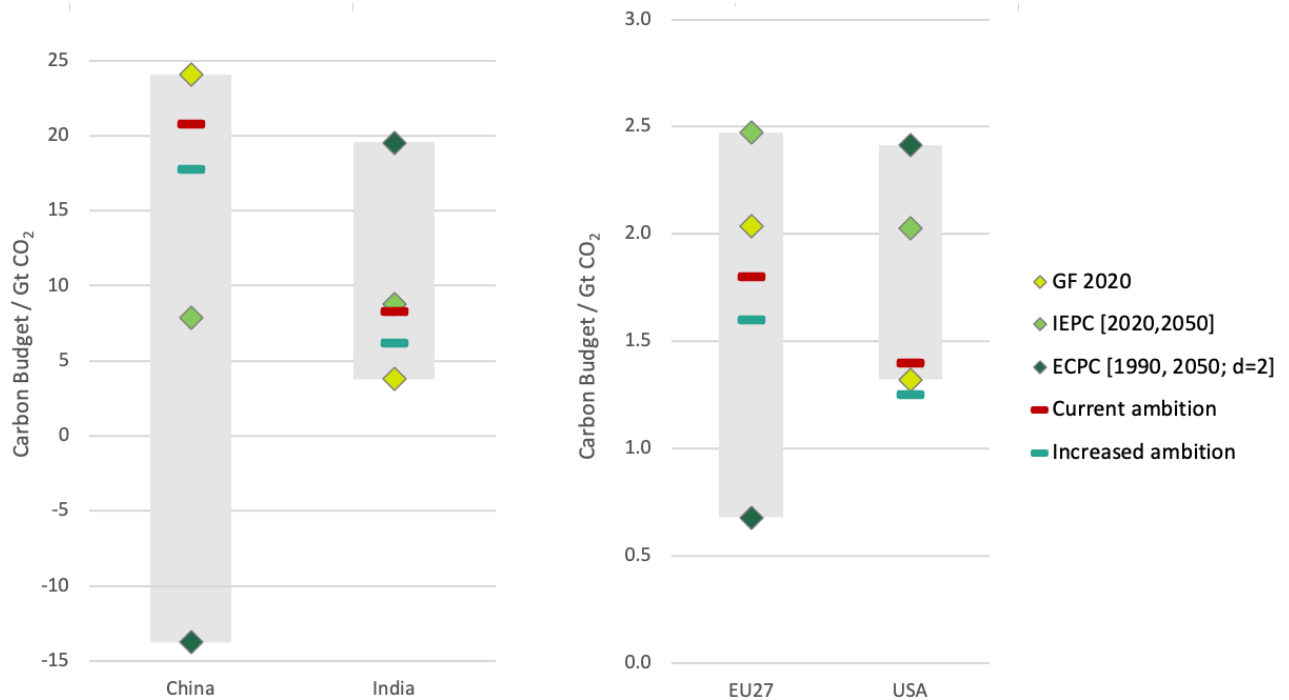


Figure 3.12: Carbon budgets allocated to cement sectors of world regions according to various approaches compared to cumulative CO₂ emissions implied by regional *current ambition* and *increased ambition* pathways. Note: GF=“Grandfathering”; IEPC=“Immediate per capita convergence”; ECPC=“Equal cumulative per capita emissions”

3.5 Assessment of mitigation options

Figure 3.13 shows the contributions of the analyzed mitigation levers related to overall CO₂ mitigation achieved in the *increased ambition* pathways of the analyzed cases.⁴² The figure shows that CCS contributes the most to mitigation across all cases. Fuel switch ranks second, while the reduction of the clinker factor plays a more modest role. The latter needs to be understood against the background that the clinker content of cements was already reduced to 67%, 77% and 70% in China, EU27 and India, in 2020 respectively. Therefore, potentials for further reduction in these countries are not negligible but limited. For the USA, future reductions of the clinker factor have been assumed to be limited due to a different tradition of using SCMs (on the concrete level instead of the cement level).

BECCS ranks slightly below the reduction potential of clinker, but the negative emissions provided by this lever are important for compensating residual emissions and for reaching close to net-zero emissions in China, EU27 and the USA. Furthermore, BECCS in the cement sector provides a low-effort option for negative emissions, if carbon capture plants and CO₂ infrastructures are build-up anyway to capture and store process-based emissions. The use of BECCS, however, requires a careful consideration of impacts on land-use emissions, biodiversity and food security. The amounts of (virgin) biomass proposed to be used in the *increased ambition* pathways appear to be small, compared to

⁴² A declining building demand in China was not included as mitigation lever. The contributions of the levers „concrete per structure” and „binder intensity of concrete” could not be assessed based on the used sources for the case of China. Those levers were thus not taken into consideration.

today's biomass use in the respective countries. Nevertheless, national scale cross-sectoral studies are required to assess the most beneficial use of limited biomass resources in each region.

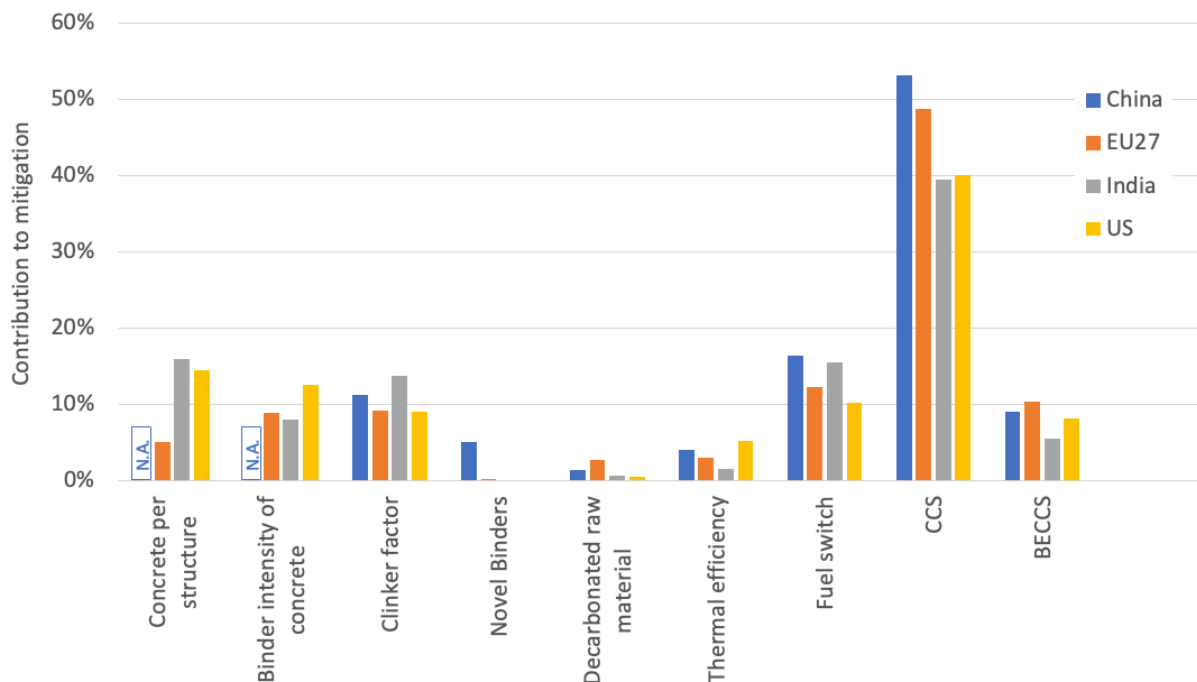


Figure 3.13: Contributions of the analyzed mitigation levers related to overall CO₂ mitigation achieved in the *increased ambition* pathways of the analyzed cases.

Thermal efficiency, decarbonated raw materials and novel binders have a smaller contribution to emission reductions, compared to the other levers.

The mitigation levers on the concrete level (concrete per structure, binder intensity of concrete) sum up to about 20-25% of all contribution and thus – if combined – rank second most important. This highlights the relevance of material efficiency strategies and the consideration of the whole value chain, including concrete.

Furthermore, it needs to be considered that the levers are not independent of each other, but strongly interact, as the modelling and the analysis have shown. Figure 3.14 illustrates these interdependencies in a simplified way and puts the most relevant levers into a hierarchy of influences:

- › Mitigation efforts and achievements on the concrete level influence the amount of cement required.
- › The amount of cement required strongly influences the amount of clinker produced. Most importantly, this is not a linear relationship determined by the clinker factor only. Instead, it needs to be considered that SCM's such as GGBS and fly ashes are (locally) scarce and their availability typically limits attempts to lower the clinker factor. If overall cement demand is reduced this provides the opportunity for a stronger reduction of the clinker factor of the remaining cement.

- › The amount of clinker produced strongly influences the thermal energy required and determines the amount of process CO₂ generated.
- › Similar to SCMs, suitable wastes and biomass for fuels are (locally) scarce. Hence a lower thermal energy demand allows to cover a larger share of it by these alternative fuels (waste-based fuels and biomass). Waste-based fuels typically have a lower emissions factor compared to the widely used fuels coal and pet coke. A stronger shift to alternative fuels thus reduces the amount of fuel-based fossil CO₂ emissions generated and released to the atmosphere (if not captured) beyond the mere linear reduction implied by reduced thermal energy demand.
- › The amount of clinker hence strongly influences the amount of CO₂ generated, both process-based and fuel-related CO₂. It furthermore influences the number of sites required to produce that clinker.⁴³ Less clinker production can thus lead to a reduced demand for CO₂ infrastructure, both in terms of sites to be connected as well as CO₂ to be transported and stored. It can thus be concluded that– given a fixed maximum up-scaling speed of CCS in absolute terms – a smaller amount of clinker produced allows a faster implementation of CCS, related to the share of CO₂ from overall clinker production that is captured.

In sum, the reduction of the clinker factor as well as increasing the shares of waste-based fuels and of CCS all depend on scarce “resources” (SCMs, alternative fuels, CCS infrastructure). Given that, the reduction of cement demand facilitates a faster up-scaling of these mitigation levers (related to their deployment share) and a stronger-than-linear CO₂ reduction.

Figure 3.15 displays the non-linear interdependencies across the mitigation lever hierarchy for some exemplary cases that represent different levels of availability of SCMs, suitable wastes for waste-based fuels and CCS infrastructure. In all cases, a reduction of cement demand by 50% leads to an over-proportional reduction of CO₂ emissions. In the *Low* case, the limited availability of SCMs/waste/CCS limits the non-linear effects. But a reduction of cement demand by 50% still leads to a reduction of CO₂ emissions by 60%. The effect becomes more prominent in the *Low-Med* case (CO₂ emissions down to 20% if cement demand is halved). In the *Medium* and more prominently in the *Med-High* case technical limits to SCM/waste-based fuel/CCS deployment start to affect the non-linear effects, leading to flatter curves towards the low cement demand end of the x-axis. The *High* case exemplifies a case in which near-zero emissions are achieved already with cement demand being at 100%. A reduction of cement demand in this case facilitates a switch from slightly positive to slightly negative emissions.⁴⁴

⁴³ Assuming that if clinker demand and thus capacity factors of plants drop, some of the plants in operation will be closed.

⁴⁴ Negative emissions arise in all cases through the joint use of waste-based fuels, which include about 30% of biogenic carbon, and CCS.

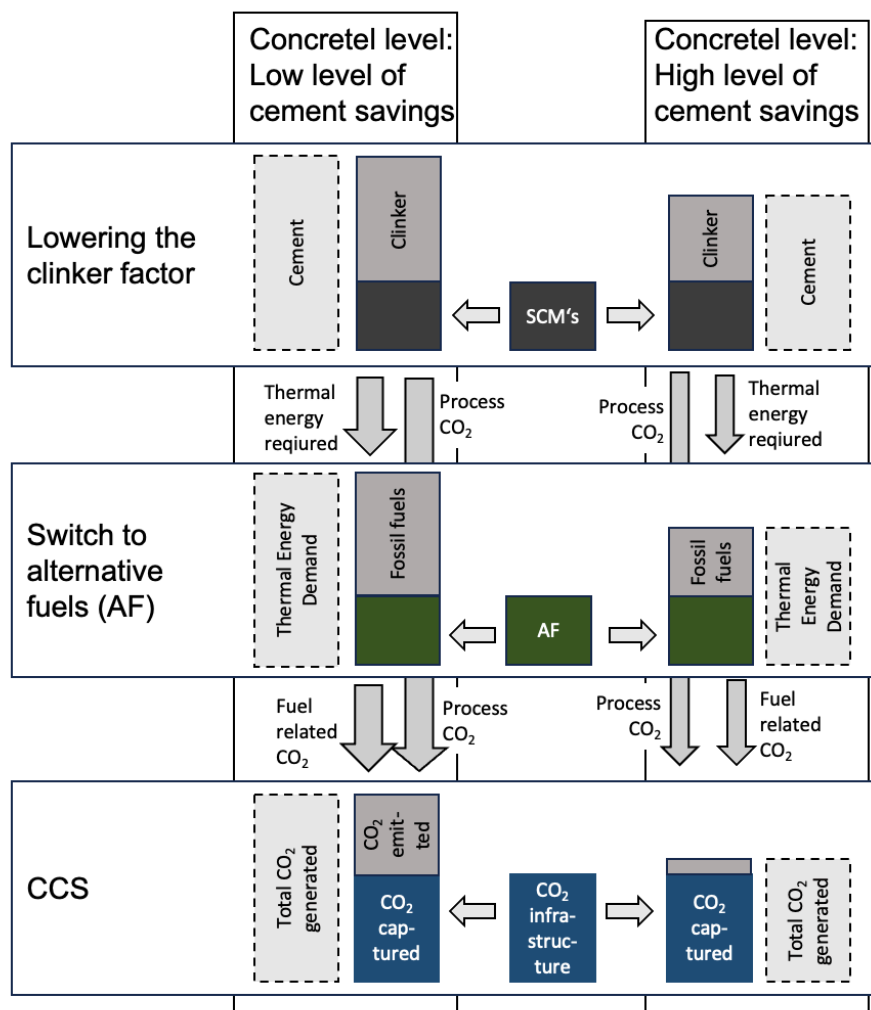


Figure 3.14: Hierarchy of mitigation lever influences (see text).

The calculations underlying Figure 3.15 assume that all SCMs, wastes and CO₂ infrastructure available can be put to use for a decreased amount of cement to be produced. They are hence simplified and do not account for spatial effects of SCM/waste/CCS availability. However, the calculations clearly illustrate that strategies for reducing concrete and cement demand have effects that go beyond a mere linear reduction of associated CO₂ emissions, in particular in cases of medium availability of SCMs/waste-based fuels/CCS. From that perspective, levers on the concrete level appear to be most influential in particular in emerging economies that still need to ramp-up their capacities for SCMs, waste-based fuels and CCS.

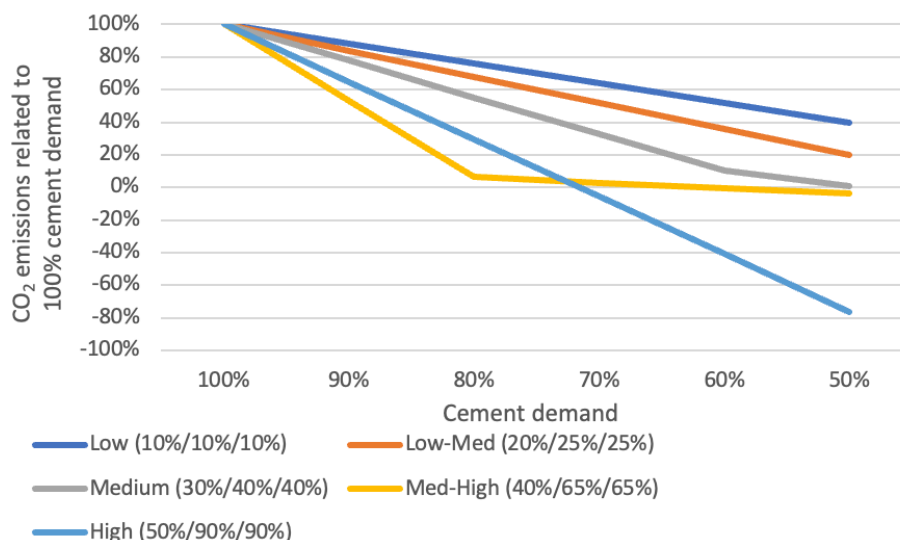


Figure 3.15: CO₂-emissions related to cement demand assuming limited availability of SCMs, waste-based fuels and CCS infrastructure. *Note: the numbers in parentheses indicated the assumed availability of 1) SCMs related to cement demand of 2) waste-based fuels related to thermal energy required in that case and 3) of CCS infrastructure related to total CO₂ generated in that case (including biogenic CO₂), in that order. Technical limits have been considered as follows: maximum use of SCMs is 50%, maximum use of waste-based fuels is 90% and maximum capture rate is 90% along the CCS value chain.*

3.6 Conclusions for cement

On the global level, the target and pathway envisioned by the GCCA for the global cement sector are basically compatible to the Paris goals, according to our analysis. The picture is less clear when it comes to the current ambition pathways of major emitters, as the uncertainty involved in defining allowances for single countries by far exceed any differences of mitigation ambitions. Debates about effort-sharing among countries' cement sectors for reaching the global target may thus be difficult. This highlights a strong need for further international cooperation on this matter (see Otto & Oberthür, 2022).

From a technical point of view, a further increase of the mitigation ambition beyond the *current ambition* of major emitters seems possible in all cases, according to our comparison of national roadmaps. Regional differences need to be respected for the development of increased ambition pathways, which was only possible to a limited degree in the scope of this study. The identified potential for increasing the ambition is however not essential for the assessment of the pathways' credibility in light of the Paris agreement. The main focus for policy makers and stakeholders should therefore be on implementation and realizing the existing pathways and the relevant enabling policies, while further discussions about targets appear to be of secondary importance.

The global south – here represented by the case of India – requires special attention due to its expected strongly rising demand for concrete buildings and production of cement. Additional CO₂ mitigation through an *increased ambition* appears to be highest in India, compared to the other major emitters analyzed, suggesting that any efforts beyond what is already planned would have the highest mitigation impact in the global south.

CCS is the mitigation option with the highest single emissions reduction impact, according to our analysis. The findings thus support the sector's current strong focus on this mitigation option.

However, the analysis furthermore reveals that material efficiency – saving concrete and binders – is beneficial in multiple ways: on the one hand it has the potential to directly reduce clinker demand and associated CO₂ emissions considerably. On the other hand, reducing the cement demand makes it easier to swiftly reduce the clinker factor and to increase the shares of alternative fuels and CCS at the remaining cement production plants as fixed amounts of limited resources (SCMs, suitable waste, CO₂ infrastructure) can still be used even if the overall cement demand is reduced.

The analysis suggests that recent mitigation pathways proposed for the cement industry are close to limits beyond which an even faster CO₂ reduction seems infeasible from a technical point of view. If even faster CO₂ reductions are deemed to be required in order to keep cumulative CO₂ emissions at even lower levels, the baseline building demand (with concrete) needs to be addressed - i.e. mitigation options such as alternative building materials (e.g. wood) and lifestyle changes in housing that are out of scope of the cement and concrete industry need to be taken into account.

4 Petrochemicals

4.1 Introduction

4.1.1 Background

The petrochemical sector produces a broad range of intermediary and final chemical products from mineral oil and natural gas. It was once built up in strong synergy with the fossil fuel industry as a way to make money of its waste streams, and now has become an increasingly important and profitable part of fossil feedstock value streams (Bauer et al., 2022). The materials produced by the petrochemical industry, including plastics, rubbers and fertilizers have become pervasive in our societies and everyday lives and include a large variety of consumer goods used in a wide range of applications, from plastic packaging to cars and building elements. However, while the total portfolio of final products is large, these are produced from a much smaller number of key primary chemicals –ethylene, propylene, benzene, toluene, xylenes, methanol and ammonia (IEA, 2018).

According to the IPCC (2022) the direct⁴⁵ energy- and process-related CO₂ emissions from the global chemicals and petrochemicals sector made up approximately 9.9% of the total global direct industrial CO₂ emissions in 2019, with 977 Mt CO₂ being energy-related emissions and 720 Mt being process-related.⁴⁶ While the chemicals and petrochemicals sector itself emits significant amounts of CO₂, its role in mitigating climate change becomes most apparent when considering Scope 3 emissions, i.e., the upstream emissions related to feedstock provision and the downstream fate of its products.

Concerning the upstream, the petrochemicals sector is highly integrated with refineries which on the one hand provide naphtha as a main feedstock for the petrochemicals sector and on the other hand generate propylene, benzene, toluene and xylenes as by-products of refining processes. With regards to the downstream, the carbon contained in the products made from HVCs and methanol is eventually released into the atmosphere through waste incineration or degradation at the product's end-of-life.⁴⁷ The Scope 3 CO₂ emissions of the petrochemical sector are therefore significantly larger than its Scope 1 emissions. For example, in Europe and according to Agora Energiewende and Wuppertal Institute (2021), for every ton of plastic produced, 1.2 tons of CO₂ will be emitted in the chemical sector, while an additional 0.8 tons of CO₂ will be emitted in the refining sector and 3.1 tons of CO₂ will be emitted through the incineration of plastic waste. A main challenge is thus the reduction of CO₂ emissions along the petrochemicals value chain, including feedstock provision, production, and fate of the products.

⁴⁵ i.e., the Scope 1 CO₂ emissions

⁴⁶ Quantifying the emissions from the chemical and petrochemical industry is notoriously difficult due to the large number of products and processes included in this sector, and varying estimations are often found due to the different methodologies used (Cullen et al., 2022). The mentioned figures for the chemical and petrochemical sector are given by IPCC, but another quantification from IEA presents that the direct CO₂ emissions from the production of primary chemicals (ethylene, propylene, benzene, toluene, xylenes, methanol and ammonia) was about 935 Mt in 2022 (IEA, 2023a).

⁴⁷ Ammonia (NH₃), derived from natural gas through steam reforming does not contain carbon and hence no CO₂ emissions are associated with its use. However the use of ammonia as fertilizer leads to significant GHG emissions in the form of NO₂.

4.1.2 Scope of this study

The scope of this study covers the most important material flows and processes to produce five key primary chemicals also referred to as high value chemicals (HVCs): ethylene, propylene, benzene, toluene and xylene. The value chains related to these HVCs are strongly interrelated as these are today co-produced in steam crackers, with naphtha and ethane being the main feedstocks, globally (IEA, 2018). While ethylene is almost exclusively produced in steam crackers, significant shares of propylene and BTX aromatics (benzene, toluene, xylenes) are generated as by-products of refinery processes as well (IEA, 2018).

Furthermore, this study focuses on the petrochemical industry and its opportunities for decarbonization during the production of HVCs. The global chemicals demand shows no sign of reaching saturation in the coming decades. Rather, according to the IEA (2018, 2021b) the demand is expected to be constantly increasing, driven mostly by developing countries. An important CO₂ emissions mitigation strategy therefore is the reduction of future demand and production growth rates. This holistic strategy has been receiving increased attention in research as well as in policy discussions around plastic pollution (IPCC, 2022; Meng et al., 2023; UNEP, n.d., 2023). However, such approaches on the level of the wider production and consumption system are beyond the scope of this study.

4.2 Objectives and approach

The widespread use of the petrochemical industry's large variety of products and the seemingly strong increase in future demand ask for strategies for significantly reducing the CO₂ emissions associated with the production and use of HVCs along the value chain. At the same time, given the fossil nature of the HVC production in its use of fossil resources for feedstock and energy, the challenge of reducing these emissions to net-zero also becomes evident. The complexity of the HVC production system – being closely intertwined with the fossil fuel sector and its products being partly substitutable – offers a very wide range of possible future pathways towards net-zero.

To the perception of the authors, the discussion of pathways towards a net-zero HVC production has only gained traction in the most recent years (Bauer et al., 2022; Gabrielli et al., 2023; Meng et al., 2023; Rootzén et al., 2023), and later compared to the steel and cement sectors. Mitigation technologies covering specific parts and aspects of the production value chain have been described before (e.g., Agora Energiewende & Wuppertal Institute, 2021), but this type of exercise is only able to address the complexity of the sector to a limited extent. Furthermore, scenario studies have been conducted based on energy system and industrial modelling (Bazzanella & Ausfelder, 2017; Deloitte, 2021; Geres et al., 2019; IEA, 2018; Stork et al., 2018) which typically integrate a considerable range of mitigation options. How the results of these scenario studies are generated remains (necessarily) opaque to the reader to some extent, due to the complexity of the models used.

Against this background and in order to better understand the structural changes required for a defossilized HVC production, this study approaches the topic of emission reduction in the HVC value chain by describing and qualitatively characterizing three main defossilized archetypical process routes:

- › Synthetic fuel integrated production route
- › Green methanol-based production route

› Carbon looping production route

These defossilized archetypical production routes highlight different approaches that can contribute to an overall defossilized petrochemical production system for HVCs. The routes are thus not to be understood as stand-alone systems, rather, they carve out different core elements of an encompassing defossilized petrochemicals production system as a means to analytically decompose its complexity. The defossilized archetypical process routes, in addition to the current fossil system, are illustrated and characterized in terms of necessary mitigation technologies, feedstock and energy use, carbon efficiency, their interaction with other sectors along the value chain, as well as geographical aspects. Each archetypical process route has its own limitations and shortcomings, which are also presented.

The archetypical process routes have been derived based on the process characteristics of petrochemical production processes as defined in the WISEE EDM-I model.⁴⁸ Relations of processes with educts and (by-) products have been extracted from the model database and possible connections of processes via products and educts were mapped in one large flow diagram in a first step.⁴⁹ Subsequently, simplifications have been made through aggregation where appropriate (e.g. aggregation of multiple process steps without branching points into one process) and the scope of the analysis has been limited to cover processes and (by-products) up to HVCs, only. Finally, the archetypical process routes have been carved out through visual scrutinization and group discussions. Characteristics of the archetypical process routes have been derived from the carbon balance as well as energy and resource demands of mitigation options according to the model database and from own expertise.

The archetypical production routes would in reality likely be implemented at specific sites simultaneously, but to different extents, depending on the context of the site. In order to illustrate this, the different ways in which the defossilized archetypical process routes may interact, how a defossilized petrochemical industry could take form and how it could fit into the larger industrial and energy systems, two qualitative scenarios are presented in the form of narratives about the development of two fictional cases:

- › Transformation of an existing cluster
- › Emergence of a new cluster

The narratives of fictional cases follow a tradition of qualitative scenarios whose primary objective is to illustrate possible futures and stimulating the imagination of the reader. The narratives have been developed through internal group discussions.

4.3 Mitigation options

As a background information and basis for the subsequent analysis key mitigation options included in the archetypical pathways derived in section 4.4 are briefly described in this subsection, including their energy demand, CO₂ mitigation potential and technology readiness level (TRL).

⁴⁸ See https://www.i2am-paris.eu/detailed_model_doc/wisee-edm

⁴⁹ The initial diagram is not shown in this report.

4.3.1 Electrification of Steamcrackers

Steamcrackers decompose feedstock (naphtha and ethane) into high-value chemicals (HVC), i.e., olefins and aromatics, which are subsequently used to synthesize a large range of polymers and other chemical products. Today, the high-temperature heat (600-900°C) required for the cracking process is provided by thermal use of by-products of HVC production. Efficient steamcrackers are (mostly) fired with these by-products and further thermal energy demand of steam crackers is satisfied by fossil fuels or gases, if required. In the electrified steamcracker the heat is provided (completely) by electricity, instead.

The electricity demand is (about) 2.5 MWh/t HVC (Agora Energiewende & Wuppertal Institute, 2021). Electrification of steamcrackers thus would add a significant load to the electricity system. For example: in the EU27 40,2 Mt HVC were produced in 2017 (Agora Energiewende & Wuppertal Institute, 2021). Electrifying this production would require about 100 TWh electricity, equal to one sixth of current German electricity demand.⁵⁰ Moreover, assuming a continuous monovalent operation of crackers, that makes full use of existing production capacities, the load would be a base load. The high electricity load would most likely require the retrofitting and expansion of electricity grids (distribution and possibly also transmission) next to a massive scale up of clean energy production capacity.

The CO₂ mitigation potential of electrified steamcrackers is up to 90% of direct emissions on the plant level (BASF, 2021). The wider, Scope 3 mitigation potential depends on the alternative treatment of by-products from HVC production. Only if an emissions free (material) use of by-products is developed, a significant CO₂ mitigation can be achieved on the Scope 3 level.

The TRL of steam cracker electrification is at 5, according to the IEA (2023b). A pilot plant is planned to be completed by the end of 2023.⁵¹

4.3.2 Methanol-to-olefins/aromatics (MtO/MtA)

High value chemicals (HVC) including olefins (ethylene, propylene) and aromatics (benzene, toluene and xylene) can be produced from renewable methanol in two different production routes, one dedicated to olefins (MtO) and one dedicated to aromatics (MtA). Various specific procedures exist in both cases (Bazzanella & Ausfelder, 2017; Li et al., 2021).

The energy demand is dominated by the production of methanol, for which two basic routes exist: via biomass and via methanol synthesis from H₂ and CO₂ (Hobson, 2018; IRENA, 2021), while the electricity demand for the rest of the process is relatively small. The provision of methanol from biomass or via methanol synthesis is outside the system boundaries chosen for the subsequent analysis and a detailed description and analysis of the provision of methanol is thus out of scope of this report, but the interested reader is referred to the literature (Hobson, 2018; IRENA, 2021).

No CO₂ is emitted in the step from methanol to olefins/aromatic and hence the mitigation impact of MtO/MtA depends on the emission or utilization of CO₂ related to the production of methanol. For the production of 1 t of olefins (ethylene or propylene), about 2.8 t of methanol are required. For the production of this methanol from H₂ and CO₂, 3.8 t of CO₂ are used and (temporarily) bound in the

⁵⁰ The electricity demand of Germany today is about 600 TWh.

⁵¹<https://www.sabic.com/en/news/41898-basf-sabic-and-linde-reach-final-steps-in-the-construction-of-the-demonstration-plant-for-electrically-heated-steam-crackers>

chemicals/products. For aromatics it amounts to about 5.9 t CO₂/t (own calculation based on Geres et al., 2019). The technology hence has the potential to switch the production of HVC from a CO₂ source to a CO₂ sink, but the overall GHG mitigation potential strongly depends on the embedding in the wider system, in particular the source of the CO₂ (fossil, biomass or Direct Air Capture) and the duration of use and the end-of-life treatment of the products made from HVCs.

The technology is at TRL 8 (MtO) respectively TRL 7 (MtA). The technology for MtO is developed far enough to be applied on industrial scale. Several pilot- and demonstration plants exist (Geres et al., 2019), but (to the authors' knowledge) up to now no full-scale plant has been built due to economic considerations. For the MtA process some demonstration plants exist, but the process requires some further refinement before commercialization is feasible (Li et al., 2021).

4.3.3 Fischer-Tropsch synthesis

In Fischer-Tropsch synthesis, synthesis gas is converted to long-chain hydrocarbons. The synthesis gas can be obtained from H₂ and CO₂ or from other carbon-containing sources such as biomass and carbon-containing waste (Geres et al., 2019). Fischer-Tropsch synthesis does not produce pure end products, but a type of synthetic crude oil. It is often referred to as "syncrude". Like crude oil, the product of Fischer-Tropsch synthesis must be refined to produce marketable end products. This requires a number of processing steps, such as hydrocracking or hydrotreating. The target end products include synthetic fuels such as kerosene and diesel, with some amounts of Fischer-Tropsch naphtha (FT-naphtha) resulting as a by-product.

By far the largest part of the energy requirement is for the provision of the synthesis gas and depends on the resource used and similar to the methanol-based routes, the GHG mitigation potential strongly depends on the embedding in the wider system, in particular the source of the carbon and the duration of use and the end-of-life treatment of the products made from HVCs.

The provision of FT-naphtha via Fischer-Tropsch synthesis is outside the system boundaries chosen for the subsequent analysis and a detailed description and analysis of the provision of FT-naphtha is thus out of scope of this report.

4.3.4 Chemical recycling: pyrolysis / gasification of used plastics

Chemical recycling decomposes (mixed) plastic wastes into products that can, with additional treatment, be used as petrochemical feedstocks. The process of pyrolysis of plastic waste takes place at high temperatures (300-700 °C) in the absence of oxygen. Gaseous, liquid and solid hydrocarbon mixtures are formed. The gasification process happens at temperatures of 700-1200°C and converts the plastic waste to a synthesis gas containing CO₂, CO, H₂, CH₄ and other light hydrocarbons. A broad range of specific procedures exist, both for pyrolysis and for gasification (Solis & Silveira, 2020).

Geres et al. (2019) assess the thermal energy demand to be 11.2 GJ/t plastic. This can be covered either by burning parts of the plastic waste (which reduces carbon efficiency) or needs to be provided via power-to-heat. The electricity demand (without power-to-heat) is 0.13 MWh/t plastic (Geres et al. 2019).

Within the sectoral boundaries of the petrochemicals sector chemical recycling has no CO₂ mitigation potential. Instead, CO₂ emissions increase due to additional conversion steps with less than perfect carbon efficiency and associated CO₂ emissions as well as due to increased energy demand. The CO₂

mitigation potential must be assessed in the wider scope, including the refinery process and HVC production process, as well as waste treatment. The CO₂ mitigation potential arises from the replacement of fossil feedstock by recycled hydrocarbons and through avoiding the incineration of plastic waste. The incineration of 1 t of plastic leads to emissions of about 3bt CO₂ (own calculation, assuming carbon content of plastics being about 80% of weight). Hence, recycling (parts of) the carbon contained in plastics in principle avoids these end-of-life emissions. According to Geres et al. (2019) the efficiency (related to carbon recycling) of pyrolysis and gasification is about 45%, assuming the thermal use of parts of the material to generate the heat required for the process. By using power-to-heat, the efficiency may increase to about 75% (Geres et al. 2019). The potential to replace virgin fossil feedstock with products from chemical recycling depends on a range of factors, including the availability of (suitable) waste and the required yield shares of different olefins and aromatics during HVC production. For an overall assessment of GHG mitigation potential it must also be considered whether avoided plastic wastes would have been put to thermal use (e.g., in cement plants) and how the heat of those processes can be provided in an alternative way.

The technology is at TRL 4-9, depending on the specific process. Conventional pyrolysis and gasification are at TRL 9 while some innovative procedures (such as plasma pyrolysis and plasma gasification) have lower TRL.

4.4 Description and characterization of production routes

In the following, four production routes are described and characterized:

- › Current fossil fuel integrated production route
- › Synthetic fuel integrated production route
- › Green methanol-based production route
- › Carbon looping production route

The *Current fossil fuel integrated route* is described for setting the scene and as a reference point for the portfolio of primary chemicals which is required in the subsequent petrochemicals value chain and which should therefore be provided (to similar shares) by a future defossilized system. The *Synthetic fuel integrated production route* shares a strong resemblance to the current fossil system in that it presumes a retained strong connection to the fuel industry. But the fuel industry is assumed to have been transformed, now producing renewable Fischer-Tropsch fuels, and the chemical industry can make use of its by-products. Also similar to the current system is the use of these fuel by-products in steam crackers. The *Green methanol-based production route* instead is a new type of petrochemical production route, no longer strongly linked to the production of fuels. In this system, naphtha is no longer the central input commodity for the production of petrochemicals. The new platform chemical is methanol, produced from renewable CO₂ and H₂. Finally, the *Carbon looping production route* highlights how the carbon can remain in-loop, avoiding losses and thus reducing the need for new input feedstock. Steam crackers are used as well as methanol-based processes, interacting in a way that makes use of the processes by-products.

4.4.1 Current fossil fuel integrated production route

The petrochemical industry today builds upon the by-products from fossil fuel extraction and processing, where the key HVCs are obtained from steam cracking of naphtha or ethane. An overview

is displayed in Figure 4.1, illustrating the processing path from raw materials to olefins and aromatics, as well as the by-products produced.

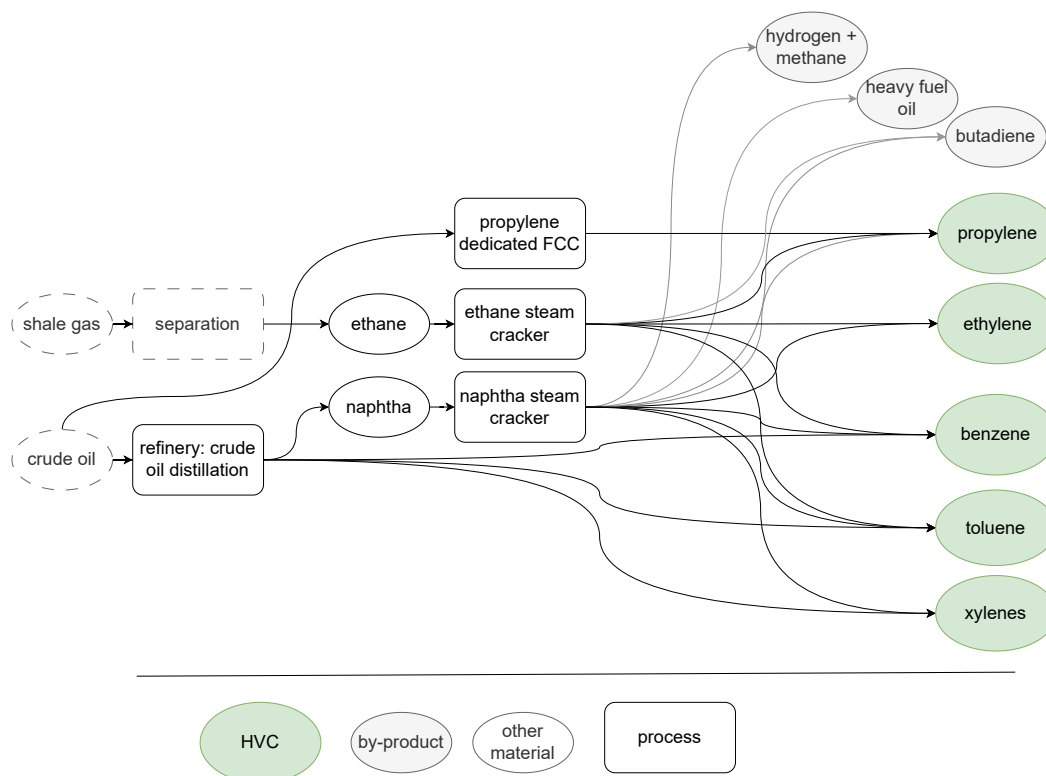


Figure 4.1: Current fossil fuel integrated production route

The most common cracker feedstocks used are naphtha and ethane. Naphtha is obtained as a fraction of the products in refining of crude oil, and naphtha crackers are thus often co-located with refineries and the production of transport fuels. When naphtha is cracked, a range of products are produced, about half of which are olefins (34% ethylene and 16% propylene) and about 12% aromatics (Dehandschutter, 2006). In addition to the main HVCs produced, about 5% becomes butadiene, which is used to produce rubber materials and a smaller volumes of polymers (like ABS). The cracking process also produces a light fraction of mixed methane and hydrogen, as well as a heavy fraction. These by-products are in the first place used to provide heat to the steamcrackers themselves and furthermore used for steam production at chemical sites. This use of (fossil) by-products also constitutes a major source of carbon losses and CO₂ emissions of the petrochemicals sector.

Ethane is obtained as a by-product in methane extraction from shale gas, something that is mainly done in the USA and from “natural gas liquids” coming from the Middle East. From an ethane steam cracker, ethylene represents approximately 80% of the output products (Dehandschutter, 2006) and – similar to the naphtha crackers – the light and heavy by-products are burned within the cracker to provide energy. Own calculations suggest that in contrast to naphtha crackers, all byproducts from ethane steam crackers are consumed for providing heat to the crackers themselves.

Another option to produce propylene from heavy crude oil fractions is by fluid catalytic cracking (FCC), which yields up to 20% propylene. This is also displayed in the figure as an FCC unit optimized for propylene production, as a complement to the ethylene-dominated ethane crackers. Finally, propane dehydrogenation units are an option for dedicated propylene production.

4.4.2 Synthetic fuel production integrated production route

This route highlights that a future renewable-based chemical production route, similarly to the current fossils-based one, could be partly integrated with the fuel production system, which has then been transformed to be renewable-based. This route is illustrated in Figure 4.2, where renewable naphtha produced via Fischer-Tropsch (FT) processes has taken the place of fossil naphtha.

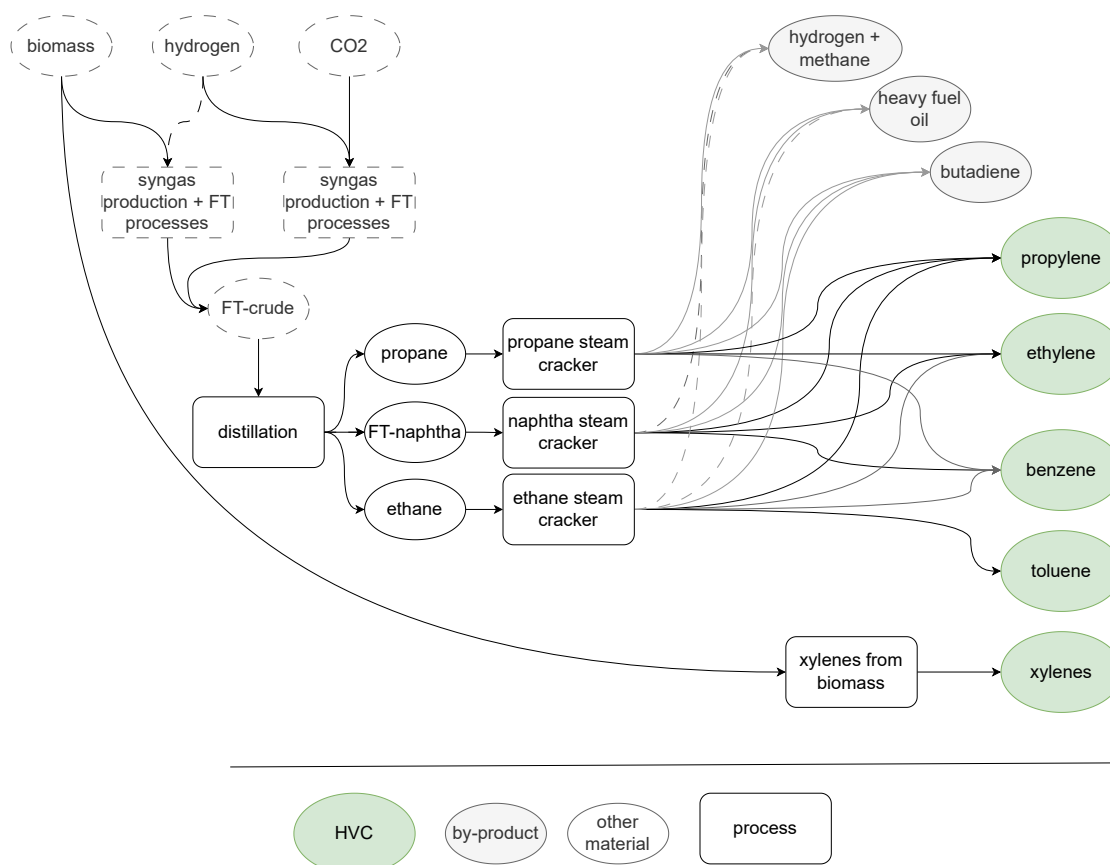


Figure 4.2: Synthetic fuel integrated production route

FT-naphtha has a different product structure than fossil naphtha, with a higher yield of ethylene and a lower yield of aromatics (Wang et al., 2010). Therefore, in the illustrated system, some of the aromatics production needs to be complemented by processes producing aromatics from sustainable sources in order to achieve the same balance of output products as the fossil naphtha cracker route. This is illustrated in the figure with a process that produces xylenes from biomass.

Central new technologies in this route mainly concern the upstream production of green FT naphtha. The FT naphtha could either have been produced from biogenic wastes and sustainable virgin biomass sources or alternatively be based on CO₂ and H₂ as feedstocks. As the Fischer-Tropsch reactor has to be operated with carbon monoxide and hydrogen, CO₂ is not an ideal carbon source. To feed a Fischer-Tropsch reactor, CO₂ has to be converted with additional hydrogen to CO and the CO₂ based alternative is thus less developed than the biobased alternative.

In the chemical industry, less major changes are necessary if FT naphtha is used as feedstock, although minor adaptations might be made to better accommodate the different feedstock. Complementary processes for aromatics production may also need to be developed. Compared to the fossil route, the

crackers in this route generate a marginally higher yield of total HVCs, but also a lower net by-products output to be used as fuel in other parts of the cluster (i.e., hydrogen, methane and heavy fuel oil).

The production of FT-naphtha in this route is assumed to be a by-product of a larger production of renewable hydrocarbons via Fischer-Tropsch processes somewhere in the world. Any system not dependent on fossil resources must provide the required energy some other way. In the described route, vast amounts of renewable energy are required to produce the synthetic naphtha, either in the form of biomass feedstock, or in the form of electricity. These upstream processes are therefore likely located where such resources are abundant. This upstream part of the system could also be co-located with for example pulp and paper or agricultural industries if biomass is used as the feedstock, or with industrial point sources for (renewable) CO₂ or a CO₂ grid. In any case, the location needs not necessarily be close to the chemical cluster, as the FT-naphtha can be relatively easily transported around the world.

Just like the chemical industry today uses a by-product from the fuel refineries, the main product of the Fischer-Tropsch production would rather be renewable fuels. However, the future use of synthetic fuels in the transport sector is expected to be much lower compared to today's production level of fossil fuels, as large parts of the transport sector are expected to be electrified and hydrogen may also play a role in some transport segments. Consequently, the global production level of FT naphtha is expected to be low compared to the production level of naphtha today. Kerosine for aviation would likely be the main target product, since the aviation sector is difficult to decarbonize in other ways. Kerosene would thus represent the major volumes and economic output of the upstream Fischer-Tropsch production system.

While the production of feedstock in this route is located at a place in the world where renewable energy is most abundant, the location of chemical cluster is partly independent from this and depends on other factors as well, such as access to transport infrastructure and connections to other industries to benefit from cluster advantages. Hence, the chemical processing itself basically can interact with surrounding industries and infrastructures overall similarly to the fossil case.

The route described here has limitations in terms of energy efficiency as well as product output balance. As mentioned, the production of hydrocarbons from renewable CO₂ and H₂ requires vast amounts of electricity, and entails large energetic losses in the process. It is estimated that of the initial electric energy for the electrolysis, only 44% remain in the hydrocarbon (Transport & Environment, 2017). This will reflect on the cost of the hydrocarbons produced. Furthermore, the FT-naphtha route illustrated does not by itself produce aromatics to the same extent as the current fossil system does, indicating that the route may need to be complemented with processes focused on aromatics.

A risk for this route is the way in which it is fully dependent on the transformation processes of fuel production systems. If a renewable naphtha-like by-product from aviation fuel production turns out to not be available in the future as assumed, the option described in this route becomes unavailable to the petrochemical industry.

4.4.3 Green methanol-based production route

This route highlights a different approach for producing the HVCs, focusing on methanol rather than naphtha as the main input to the chemical industry. In this way, the route is significantly different from the current system and is also potentially independent from the fuel system.

Compared to the *synthetic fuel integrated production route*, processes to produce aromatics are integrated in the main structure, also being produced from methanol. Figure 4.3 illustrates the main process structure of this route, showing methanol as the central feedstock.

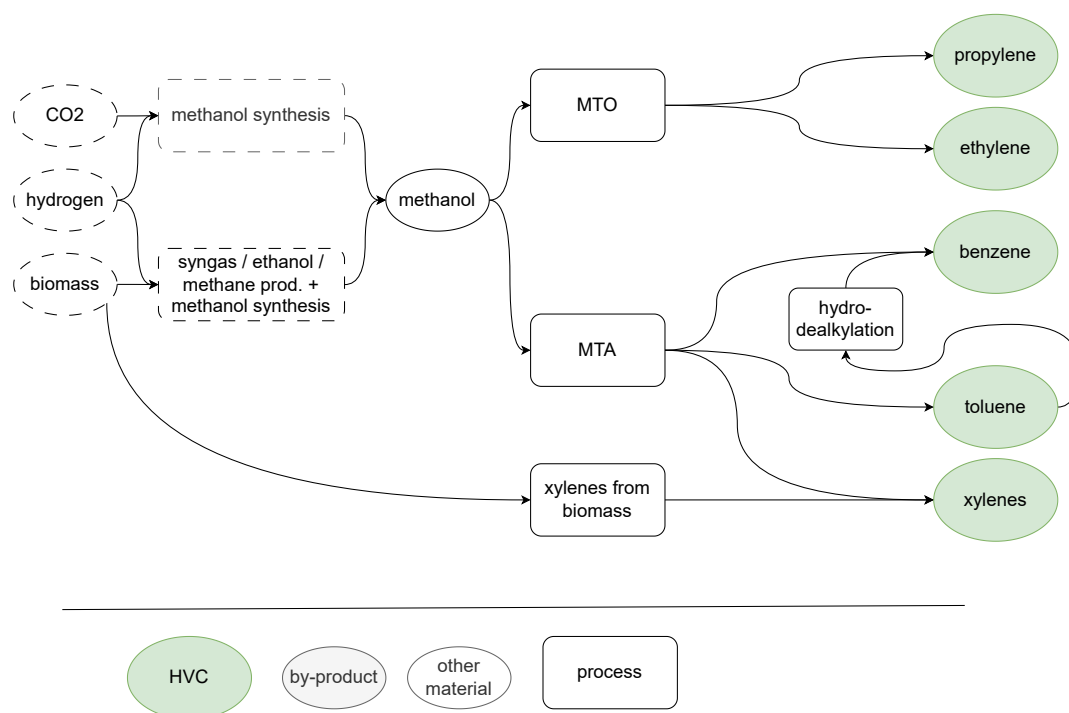


Figure 4.3: Green methanol-based production route

The processing of methanol into the target HVCs happens via the two main processes methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) described in the previous section. Additional processes might be necessary to adjust the product structure, as indicated by the process “hydrodealkylation” in figure 4.3, which produces benzene from toluene.

The resource base options are generally similar to the *synthetic fuel integrated production route* described above. The methanol can have been produced as a synthetic feedstock, or from biomass. The structure of the simple methanol molecule lends itself well to synthetic production from syngas (a mixture of CO and H₂) or directly from CO₂ and hydrogen, which is a major benefit compared to the Fischer-Tropsch process. CO₂ could be taken from a (non-fossil) point source or captured via direct air capture (DAC), with electrolysis to provide hydrogen. Production of methanol from biomass could for example be derived from gasification of biomass and subsequent methanol production from syngas (Geres et al. 2019).

In this route, carbon is lost through the production of methanol from the carbon source and in the Mto and Mta processes. For Mto, the carbon conversion rate from methanol to ethylene and propylene is about 86% (Tian et al., 2015), while for the production of aromatics via Mta, the conversion rate is significantly lower, about 54% (Z. Chen et al., 2019). A range of other products are included in the output of the Mta process, mainly alkanes (C1-C4) and C9+ hydrocarbons (Chen et al 2019). With regards to energy, the largest amount is required for the production of methanol, in the form of renewable electricity or biomass. The Mto and Mta processes on the other hand are overall exothermic and thus require no addition of energy.

Methanol could also have taken an important role in as a renewable fuel or as a platform product to produce hydrocarbon (aviation) fuels, in which case interaction with the fuel system remains. In this case, methanol could turn out as the new standard hydrocarbon carrier in liquid world markets.

Just like the *synthetic fuel integrated production route*, if the carbon should be sourced from CO₂, this route requires production of renewable electricity for hydrogen production in sufficient volumes and at a sufficiently low price. The conversion from electricity to methanol entails energetic losses and, as noted, especially the MtA process suffers from carbon losses towards the target products, further reducing the carbon and energy efficiency of the process. This can be an issue when the carbon sources are restricted (e.g., biomass, sustainable point sources) or energy intensive to obtain (e.g., DAC). Another potential issue in this system is that it no longer produces butadiene as a by-product. Butadiene is mainly used in the production of synthetic rubbers, which are a main input for the tire industry.

Since methanol can easily be transported and stored, the MtO and MtA processes do not necessarily need to be in the vicinity of the methanol production. But, if the by-products of the MtO and MtA processes should not be wasted, some complementary processes are required. The large use of hydrogen in case of CO₂-based methanol synthesis creates a strong link to hydrogen production and the electricity system while methanol from biomass sources could be co-produced with other biobased products and fuels, for example in connection to a biogas plant or a pulp and paper biorefinery. Since the methanol-based route is not based on the conventional steam cracker route, the geographical location is less dependent on such previous infrastructures. While it may still be beneficial to be close to existing downstream processing of HVCs into polymers, the MtO and MtA processes may likewise benefit from co-location with the upstream hydrogen and methanol production and (in the case of MtA) from existing installations to separate the aromatics from other streams. In sum, the geographical placement may be less bound to existing structures, and an upscaling of the green methanol-based production route could entail bigger changes to the geography of the global chemical industry.

4.4.4 Carbon looping production route

This final route highlights the integration of flows of waste and by-products in a chemical system, which would help increase the carbon efficiency of the system. This is an important objective in a sustainable chemical production system, as sustainable carbon sources are restricted (biomass) or available only with high energy costs (CO₂ from the atmosphere). The general structure of the route's production flows is illustrated in Figure 5.4. The carbon looping route lends structures both from the *synthetic fuel integrated production route* in the form of steam crackers, and from the *green methanol-based production route* through the use of MtO and MtA, but particularly includes recycling of by-product flows, as highlighted in turquoise in figure 4.4.

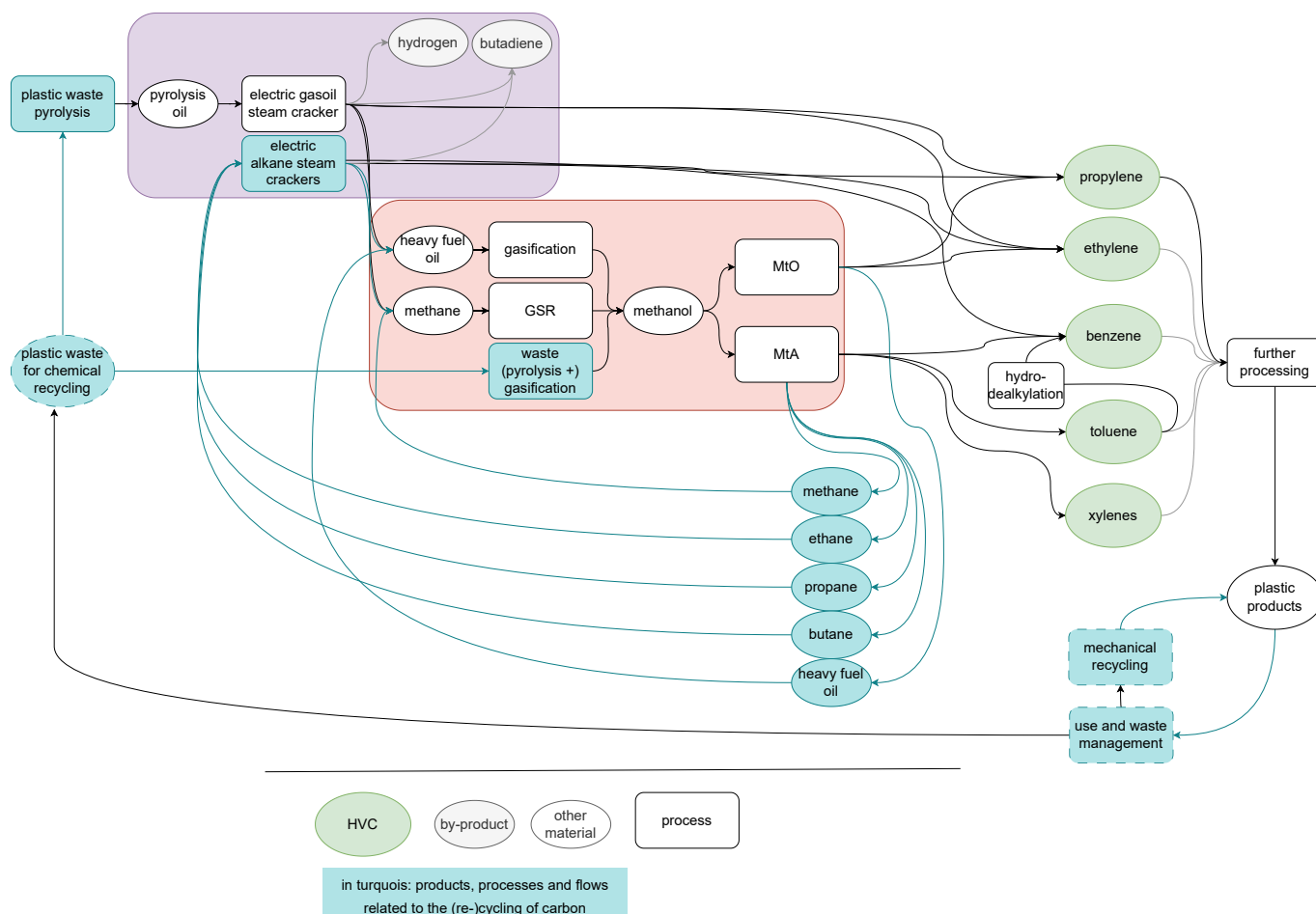


Figure 4.4: Carbon looping production route

Central processes and technologies to this route are in particular pyrolysis, gasification, and methanol synthesis from syngas or methane. As in the methanol route, MtO and MtA are important here as well. The crackers in this route are converted to electric crackers.

The focus of this route is the reuse of feedstock already in the product value chain, where an inner and an outer loop exists. The inner loop takes the by-products from the electric steam cracking, MtO and MtA and returns these to the crackers and methanol processes either directly or via gasification, depending on the product. The electrification of the steam crackers in this route facilitates the material use of the by-products, rather than an energetic use. One major flow is a by-product of a mix of heavier hydrocarbons (simplified as heavy fuel oil (HFO) in the figure) which are produced from both crackers, MtO and MtA. This is returned to the methanol path via gasification and methanol synthesis. Methane, produced from crackers and MtA is returned in a similar way, in the illustration via gas switching reforming (GSR). Some of the products from MtA, namely ethane, propane and butane, can be used as feedstock in steam crackers.

The outer loop shows the chemical recycling of plastic waste which is taken from the end of the processing chain, returning the carbon to the very beginning. The plastic waste recycled this way is the fraction not suitable for mechanical recycling.⁵² Suitable plastic waste is pyrolyzed into a pyrolysis oil to be used in steam crackers while the remaining waste is gasified and synthesized into methanol. The

⁵² Outside the chemical production system considered here, mechanical recycling is assumed to be used to the highest extent possible to recycle appropriate waste fractions as efficiently as possible.

syngas produced in gasification is adjusted to a suitable composition by addition of hydrogen in order to maximize carbon efficiency.⁵³ Since as much carbon as possible is returned to the cycle, the carbon efficiency of this route is much higher than in the other two routes.

Through this route, the requirement for new input material is reduced, and thereby the need for energy input in upstream feedstock production. However, the processes necessary to maintain the carbon in cycle, i.e., pyrolysis, gasification and additional hydrogen in methanol synthesis from syngas, are all energy-intensive as well. In other words, part of the required energy input is moved downstream from feedstock production into the chemical industry. Consequently, the necessity is higher for the chemical industry to be close to renewable energy and hydrogen production. The use of electric crackers also necessitates availability of renewable electricity. Overall, however, carbon looping considerably reduces the energy demand.⁵⁴

This route most clearly requires a strong interaction between different parts of the chemical processes and the product value chains. Many of the processes are co-located, and the route benefits from existing structures such as steam crackers and connected processes like separation and heat production. It requires integration of crackers with methanol-based paths and both with chemical recycling and gasification processes. The route also interacts with other sectors to some extent. The energy intensive processes – electric crackers and potential addition of hydrogen – suggest a strong dependence on the energy, electricity and hydrogen system and the interaction with these energy systems becomes important. If the energy demanding processes can be operated flexibly depending on electricity production and price, it could become an opportunity for the electric system.

This route focuses on making use of the resources available locally (waste, by-products) rather than relying on good connections to a global hydrocarbon system. For achieving that, the route relies on a well-functioning waste management system where a significantly higher share of the plastic waste reaches recycling streams than is the case today. It also benefits from availability of waste resources, for example being close to highly populated areas or possibly with good transport connections for waste trade. Additionally, as more energy must be added in the integrated processes of the chemical cluster, the local access to renewable energy and electricity must be sufficiently high.

4.4.5 Complementarity of defossilized production routes

The three defossilized production routes are described as distinct, but have strong complementarities concerning their role in a future petrochemicals system. The *carbon looping production route* attempts to re-use carbon already in the techno-sphere to a large extent in order to limit CO₂ emissions, save renewable resources (biomass) and reduce the renewable energy demand of the future petrochemicals system. However, some carbon losses will still occur. Additionally, the future global demand for polymers is assumed to increase (see above), if no major trend-breaks occur. Virgin feedstock must hence be supplemented.

On the one hand, the additional carbon required can be provided by the *synthetic fuel integrated production route* through making high-value use of by-products from renewable fuel production. To

⁵³ To produce methanol from syngas, the H₂/CO-ratio in the syngas should be 2, whereas the H₂/CO-ratio in syngas obtained from HFO or plastic waste is lower. To achieve a ratio of 2, either addition of H₂ or removal of CO as CO₂ is necessary

⁵⁴ Although exact numbers depend on the specific configuration chosen, the energy demand of alternative production routes reported by Agora Energiewende and Wuppertal Institute (2019) clearly indicate this: For the CO₂-based MtO and MtA routes an electricity demand of 22.7 MWh/t Olefins and 36.5 MWh / t aromatics are reported. This compares to 6.8 MWh/t HVC for pyrolysis and 2.5 MWh/t HVC for electric steam crackers.

the extent that this carbon source is not sufficient, the *green methanol-based production route* is a comparably energy-efficient route to provide HVCs from renewable sources.

The defossilized production routes differ with regards to the yield shares of the various HVCs as well as further target products such as butadiene. They are hence also to be seen as complementary with regards to the provision of the portfolio of intermediary chemicals required in down-stream processes of a particular chemicals site.

4.5 Scenarios for two fictional defossilized chemicals cluster

To illustrate how the routes could be combined in the transformation of specific sites towards a future defossilized chemical industry, this section describes two future scenarios of two different fictional chemical clusters. The narrative style of the qualitative scenarios is used to illustrate ways in which different contexts could shape the industry in practice. The first fictional cluster described represents an existing cluster that manages to undergo a transition from a conventional fossil system to a fully decarbonized system, whereas the second cluster is a greenfield development within the new renewable resource economy that has formed. These two scenarios are imaginative and exploratory, and the reader is invited to imagine alternative scenarios and possibilities.

4.5.1 Transformation of an existing cluster

This cluster, originally built over 30 years ago, was even before its transformation well equipped with crackers, boilers for heat, situated adjacent to a refinery and is well connected to both pipelines and waterways. However, much of the older equipment still in use was in need of retrofits, but new investment into fossil-dependent processes was starting to look less attractive to the context of net-zero emission goals and policies and innovation races towards a sustainable industrial landscape. The cluster is located in close proximity from a few larger cities and well connected via high-speed road and train connections to the biggest cities in the region. Except for the cities, the surrounding land mainly consists of agriculture land.

After it was decided that the future of the cluster did not lie in retrofits with incremental efficiency improvements to fundamentally fossil processes, the cluster began its long journey towards defossilization. In a first stage, trials were made feeding the crackers with different mixes with hydrogenated vegetable oil (HVO) imported from biorefineries, eventually replacing more and more of the fossil naphtha feedstock. Operation with smaller volumes of plastic waste-based pyrolysis oil from a pilot plant was also tested. Meanwhile, renewable electricity production was continuously expanded in the area. Later, demonstration plants for pyrolysis and gasification units were constructed in the cluster for the chemical recycling of plastic waste. Units for methanol synthesis and a smaller MTO unit were then also installed, the latter processing increasing amounts from the gasification processes which is occasionally complemented with smaller volumes of imported bio-based methanol.

Eventually, electrolysis units were built to produce hydrogen from the ever-increasing renewable electricity production in the area, and adding green hydrogen to the gasification and methanol synthesis process allowed for higher methanol yields. The processes and global markets for e-fuels, renewable FT-naphtha and methanol also grew successively. Just like the fossil naphtha before it, the HVO was eventually mostly replaced by imported CO₂-based naphtha produced in renewable electricity sweet-spots around the globe during the production of synthetic kerosene. With more renewable methanol available on the market, an MtA unit was constructed as well to increase the

production of aromatics. The cracker capacity was decreased and adapted to use the alkane by-products from the MtA process.

In the end, the cluster operates by resting mainly on two pillars: provision of virgin feedstock in the form of green naphtha, and careful recycling of waste and by-products. The opportunity to shift between global market commodities and more local commodities is seen as an advantage making the cluster operation both resilient and flexible. Green naphtha represents the main source of new feedstock provided to the cluster. Green hydrocarbon fuels are produced and imported from various sources on the world market and reach the cluster mainly via waterway. The nearby refinery has been adapted to focus on jet fuel production, but has a sufficient by-product flow of naphtha suitable for use in the chemical cluster.

The renewable electricity production in the region has been significantly expanded and the cluster has developed to also be a hub for plastic waste recycling. The chemical recycling units have been greatly expanded since the initial pilot- and demonstration plants. Due to its advantageous placement with good connections to surrounding cities and waterways, even the import of waste from other surrounding regions is feasible. Mechanical recycling facilities have been built nearby the cluster, so that the fractions that could not be mechanically recycled, can easily continue to chemical recycling. The waste is sorted into a fraction suitable for pyrolysis and a fraction suited for gasification, through which pyrolysis oil and syngas is produced respectively.

The crackers have been electrified and have an overcapacity, allowing it to shift between different oven lines to be able to process different kinds of inputs, where the main inputs are green naphtha and pyrolysis oil from pyrolysis of plastic waste. The syngas produced from gasification of waste and by-products from HVC production is converted into methanol. Hydrogen is produced nearby from the newly built renewable energy park and is added to the syngas to reach a high enough H_2/CH_4 ratio for a carbon efficient methanol production. While the naphtha route and the carbon looping route represent the major volumes processed in the cluster, they do not provide aromatics to the extent the previous fossil-based processes did. The aromatics production is thus complemented with some imports of green methanol, particularly processed via MtA. The by-products are recycled back into the crackers and gasification processes. The cluster now requires significantly more electricity, for cracking, for steam and for hydrogen production. The region has seen a build-out of low-carbon electricity production (including the nearby energy park), maintaining a competitive electricity price most of the time. However, the cluster is also able to adapt its production during periods of low electricity availability and higher prices by planning for example methanol production from hydrogen to avoid higher prices. The methanol can be stored in the existing storage facilities of the integrated cluster.

4.5.2 Emergence of a new cluster

This cluster is built on new ground, in an area previously considered void of any substantially valuable natural resources. It had already previously been noted that the area had great potential for renewable energy production, mainly in the form of solar but also wind power. However, the plans to construct a low-carbon energy park had received a low priority and been delayed because, except for some medium sized industries in the area, it had been considered too poorly connected to any major power consumers or cities that could benefit from such an energy park. The interest however changed as discussions on chemically stored energy –hydrogen and e-fuels – grew that provide an opportunity to store, transport and sell the abundant renewable resources available in the region.

Once built, the new energy park was connected to the electricity grid, although most of the produced electricity was directly used to produce renewable hydrogen. Already when the energy park and electrolyzers were being built, the plan was to produce methanol, which could begin once a source of CO₂ was obtained. As a start, CO₂ was imported from a larger waste incineration plant in the region, which had recently installed a carbon capture unit. With that, a methanol synthesis plant was built and the e-methanol was sold as a fuel on the global market. As the cluster grew, it accepted CO₂ from a near-by cement plant, and MtO and MtA units to produce HVCs were constructed to eventually be able to produce polymers on site. A gasification and methanol synthesis unit were also built to return the by-products from these processes to the cycle, using hydrogen to avoid carbon losses. The CO₂ from industrial point sources would eventually not be enough and markets increasingly demanded methanol and polymers from renewable carbon sources. As reaction to that, a pilot plant for direct capture of CO₂ from air was increased to a demonstration plant and finally a large-scale unit was built, which from then on provided the main source of CO₂ for the cluster. With the practically unlimited sources for sustainable CO₂ and energy secured, the cluster could grow to produce an ever-wider range of chemical products. The cluster also experiments with various catalysts and process variations to increase the yield of the target HVCs as well as to steer the conversion towards different products depending on preferences.

In its final state, the core of the production in the cluster focuses on renewable methanol, with internal carbon looping of by-products into methanol via gasification or more dedicated processes such as GSR for methane to increase the carbon efficiency. While most of the produced methanol is further processed to HVCs on-site, the cluster also produces methanol to be directly sold to the world market, and alters its production depending on market prices.

4.6 Conclusions for chemicals

The transformation of the HVC production towards a defossilized system is a complex endeavor due to the high relevance of its carbon-based feedstock for CO₂ emissions along the value chain and the intertwinement with other sectors that arise from this. Furthermore, the complexity of the interrelation of the chemical compounds themselves and of mitigation technologies add to the overall complexity of the issue.

This report chapter aimed to provide an analytical lens for understanding the transformation of the petrochemicals sector on an intermediary ground in-between single mitigation technologies and full-fledged scenarios. For this purpose, three defossilized archetypical production routes for five most important intermediary products – ethylene, propylene, benzene, toluene and xylene – jointly referred to as high value chemicals (HVCs) have been proposed.

Technological Pathways towards Paris-compatible Steel, Cement and Petrochemicals

These production routes feature different key mitigation technologies and take complementary roles in a future petrochemicals production system: the *synthetic fuel integrated production route* makes high-value use of green naphtha, a by-product from renewable fuel production, with steam crackers being at the core of the route, similar to the currently dominant route. The *green methanol-based production route* is a comparably energy-efficient route to provide additional carbon from renewable sources and to convert it into HVCs. Methanol is the central feedstock and the MtO and MtA technologies are used to produce HVCs out of it. The *carbon looping production route*, finally, aims at re-using carbon already in the techno-sphere to a large extent in order to limit CO₂ emissions, save renewable resources and reduce the renewable energy demand of the petrochemicals system. Technologies for chemical recycling of by-products and plastic wastes are the characterizing elements of this route.

The development and characterization of the production routes revealed that these are also different with regards to yield shares of the different HVCs, as well as with regards to the production of other by-products such as butadiene. If major disruptions of the downstream polymer industry are to be avoided, the design of future petrochemicals systems – if practically implemented or if simulated – need to take these differences of yields into account to achieve a balanced portfolio, overall.

It became furthermore apparent, that the routes differ with regards to their overall energy demand, the possibility to make use of existing capacity stock and infrastructure as well as requirements for nearby facilities such as waste-management. Furthermore, the routes also differ with regards to the energy demands that arise at different steps in the production chain (feedstock provision, HVC production, recycling) and therefore which production steps are particularly sensitive to energy costs. The transformation will hence in all likelihood play out differently across different geographies, while regional developments will interact on a global market for feedstock and HVCs. The two narratives for fictional chemical clusters provided in this chapter – one for the transformation of an existing cluster and one for the emergence of a new cluster – illustrate this. Consequently, an interplay of regionalized “deep dive” studies and global analyses is required in the future for fostering the understanding of the transformation of the petrochemicals sector towards net-zero.

5 Gender

The author of the following chapter on gender aspects of industrial decarbonization is a white middle-class cis woman in Central Europe. This background of experience is disclosed following the concept of ‘situated knowledges’ (cf. Haraway, 1988).

Out of the four sectors analyzed in NDC ASPECTS – industry, buildings, transport and AFOLU (agriculture, forestry and other land use) – gender aspects in relation to the decarbonization of energy-intensive industry are arguably the most elusive. The transformation of our homes and workplaces, the way we travel and the food we grow and eat all directly impact our day-to-day lives. The gendered breakdown of who spends time in and takes care of the home the most, who runs most (care work-related) errands such as school pick-ups, doctors’ appointments or trips to the grocery store, and who chooses and prepares the majority of meals is both anecdotally apparent and fairly well-researched. However, gender implications of producing steel with hydrogen rather than coking coal or electrifying chemical production processes are less obvious – beyond the fact that these industries predominantly employ men.

Previous research specifically looking into gender impacts of decarbonizing heavy industry is scarce, and generating any significant amount of primary data on this topic is beyond the scope of this work package. There is, however, some literature around gender aspects of labor and just transition, as well as some work from feminist scholars around femininity and masculinity of relevant industrial and economic concepts, which have informed this chapter.

5.1 Employment

Energy-intensive industries such as steel or cement have traditionally employed men, and their workforces are, to this day, overwhelmingly male. This is true both for countries that industrialized early (such as the United States or Sweden) and countries that built up their industrial base more recently (e.g., India). Although there is some variation between different countries and different industrial sub-sectors, women make up considerably less than half of the workforce across the board.

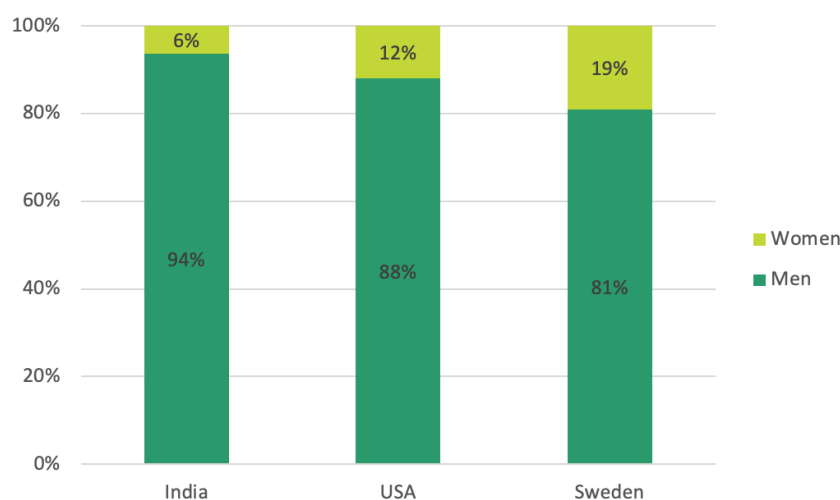


Figure 5.1 Distribution of men and women employed in the steel industry in India, the USA and Sweden (sources: Ministry of Steel, n.d.; Salminen-Karlsson, 2020; U.S. Bureau of Labor Statistics, 2023)

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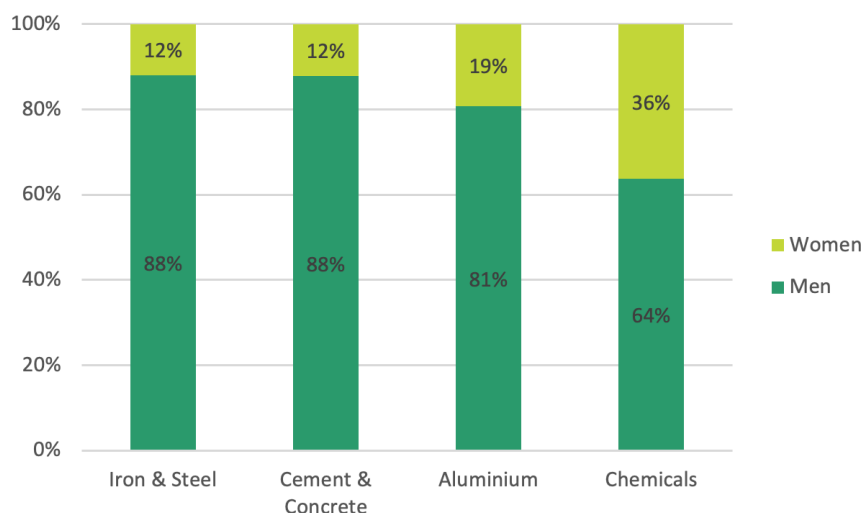


Figure 5.2 Distribution of men and women employed in energy-intensive industries in the USA
(source: U.S. Bureau of Labor Statistics, 2023)

Historically, this large gender gap can be partially explained with the physically demanding nature of the work. Today, automation and increasing digitization have contributed to lowering barriers rooted in sex-based differences in physical ability. However, if not appropriately addressed, the gender imbalance in these industries becomes self-perpetuating. Barriers to equal participation of women are “grounded in often unconscious gender bias and societal ideas about what kind of work is suitable or desirable for women and for men” (Giner-Reichl & Veldhuizen, 2023). In predominantly male industries, hiring decisions are also often made by men, who tend to hire male applicants, unless a practice of gender-sensitive recruitment has been implemented. In addition, companies in male-dominated sectors are overall less attractive to female applicants, as they are less likely to facilitate a work-life balance (because male employees traditionally did not have to also perform significant amounts of care work) and often have workplace cultures that are hostile to women, with many women reporting harassment and gender-based discrimination. Another issue is that there often are fewer qualified female applicants because the corresponding technical study programs fail to attract as many women as men. In order to increase female participation in energy-intensive industries, support of women needs to start earlier, during key stages of education (ibid.).

Attracting more women to jobs in energy-intensive industries not only opens up more opportunities for women, but also for the companies operating within these sectors, especially as they pursue climate- and sustainability-related goals. Studies have found that “companies that explicitly place value on gender diversity perform better in general, and perform better than their peers on the multiple dimensions of corporate sustainability” (McElhaney & Mobasseri, 2012).

Furthermore, many places where industry clusters are located are now characterized not by lack of employment opportunities but by lack of (skilled) labor. Retraining existing employees is only one half of the story. The other half will involve finding new employees to do the work necessary to transform the industry sector and operate it in a climate-friendly way. A key opportunity lies in tapping into the female labor market, which has been historically underexploited by heavy industry. Industry needs to actively seek to become more attractive to the full breadth of the potential workforce in order to harness the skills necessary to successfully decarbonize (Giner-Reichl & Veldhuizen, 2023).

Decarbonization will mean change in companies' activities, which will involve quantitative as well as qualitative changes to work. Companies, trade unions and governments alike need to shift away from a singular focus on existing (predominantly) male jobs within the industry and pay attention also to the types of new jobs that will be created, as well as affected jobs beyond directly affected "frontline" labor. It is important to "consider indirect (jobs in supporting processes) and induced (as a result of overall changes in economic activity flowing from energy investments) jobs created and lost" (Eadson et al., 2023) as a result of industrial decarbonization. Women often work in lower paid, less secure and less unionized jobs that do not enjoy the same amount of political recognition, protection and support if industrial decarbonization and structural change lead to job losses in the area (Walk et al., 2021).

5.2 Just transition beyond paid work

Concerns around a just transition originated in trade unions, which explains why just transition programs are often focused on the effects of decarbonization on waged jobs. In discussing industrial decarbonization processes and how they may affect work, what counts as work and what does not is rarely put into question. However, when analyzing industrial decarbonization through a gender-sensitive lens, it is imperative to look beyond paid work (Eadson et al., 2023).

As established, formal jobs in energy-intensive industries are predominantly performed by men, gendered divisions of labor often mean that women take on the majority of unpaid work, including care work and community organizing. The value of care work, though essential for any functioning society, is "barely recognized, neither in economic terms nor as a high-skilled and energy-intensive activity" (Walk et al., 2021). As community organizers, women are important agents of change in their local communities but often lack access to formal decision-making (Mohr, 2021).

When decarbonizing energy-intensive industries, a just transition must take into account not just the companies and their employees but the impact on local economies and communities, including the role of unpaid work in maintaining stable, functioning and cohesive communities. Eadson et al. (2023) emphasize the "need to consider the wide variety of informal, unpaid and unrecognized forms of work involved in maintaining (industrial) communities and shaping lived experiences of change. Such unpaid work often is critical to supporting cultural heritage, memory and commemoration in places affected by industrial change."

5.3 Environmental protection

A focus on maintaining local industry and associated (male) jobs may lead to the under-valuation and under-representation of other ecological concerns such as local pollution, resource depletion, biodiversity loss and environmental degradation. In fact, trade unions' "primary concern for workers' welfare can lead to opposition to environmental action" (Eadson et al., 2023).

While productive industry is associated with masculinity, environmental conservation is often considered "women's work". Women are socialized to be caretakers, and this extends to the natural environment as well. Green behavior is thus generally associated with femininity (Brough et al., 2016). In the realm of sustainable consumption, this phenomenon presents itself as an "eco gender gap" in commitment to good environmental habits (Capecchi, 2018). In cases of climate denial, climate action is even seen as a "threat to the masculinity of industrial modernity" (Anshelm & Hultman, 2014). In decarbonizing male-dominated energy-intensive industry, focus on paid jobs and

“carbon tunnel vision” may result in adverse effects on environmental (and social) causes – often represented by (local) women – being overlooked.

5.4 Gender imbalance down the value chain

Just as energy-intensive production is largely controlled by men, it could be argued that decision-making around the consumption of many basic materials produced within these industries is also often in male hands. One example is the building industry. In the European Union, as many as 97% of builders are male (Eurostat, 2018). According to analysis from the career portal Zippia, 96% of tradespeople and 55.7% of landlords in the USA are men (Zippia, 2023b, 2023a). Land and property ownership in the global South is especially uneven (Our world in data, n.d.). Women account for just 11% of employees in architecture and engineering (Moosajee, 2017). According to Harmonised European Time Use Survey statistics, men spend more time than women on construction activities in the home. However, women spend more time overall working in the home (performing household and care work) (Eurostat, 2023). One could thus hypothesize that while women spend more time in the home, decisions around the use of building materials for construction and repairs are predominantly made by men. The lack of gender balance in energy-intensive industries may thus continue further down the value chain and decisions around the use of “alternative” low-carbon strategies such as material substitution, material efficiency and sufficiency may be disproportionately made by men.

5.5 “Masculinist” technological solutions and economic organization

Building on the previous point, the focus on technological mitigation options such as electrification, chemical recycling or CCS over the aforementioned “alternative” strategies that would reduce the overall use of basic materials also has gender implications. Drawing from Massey (1994), Eadson et al. (2023) describe the connection between technology, masculinity and industrial policy as follows: “the construction of ‘industry’ as a male, productive domain was also linked to regional policy solutions which reinforced a masculinist approach to managing industrial change. Arguably we can see similar visions in productivist policy prescriptions that valorise hi-tech growth-orientated solutions to industrial decarbonization.” With decision-making throughout the value chain – from mining to R&D to car manufacturers and construction companies – being overwhelmingly male, the “masculinist” technology-forward approach dominates.

In focusing on technological solutions, the overall growth-centered industrial paradigm is not questioned and more radical socio-economic change in response to the climate and ecological crises are not considered. A feminist perspective can help open up this hierarchical, “masculinist” understanding of economic organization and envision more diverse economic futures “including, within and beyond market or capitalist logics” (ibid.).

5.6 Gender dimensions

In lieu of a full gender impact assessment (GIA), the findings from this chapter are summarized along the seven gender dimensions (Spitzner et al., 2020).

Table 5.1 Overview of gender impacts of industrial decarbonization along the seven gender dimensions

Gender dimension	
Symbolic order: Hierarchization of the “masculine” (industrial production, technological solutions, hierarchical growth-centered economic organization, paid male “productive” labor) over the “feminine” (unpaid (care) work, jobs in supporting (service) industries, environmental conservation, non-technical solutions & more diverse economies)	Care economy/care work: - care work largely performed by women - lack of political significance attributed to care work in industrial communities
	Market driven/labor economy: - industrial jobs largely performed by men - women mostly work in less well compensated, more precarious jobs outside main industry
	Public resources/infrastructures: public resources for just transition mostly focused on directly affected (male) industrial jobs
	Institutionalized androcentrism/power of definition: - dominance of “masculinist” model of high-tech industrial productivity & growth-oriented economic organization - importance of maintaining & decarbonizing industry (masculine) over environmental protection (feminine)
	Shaping power at actor’s level: - women under-represented along industrial value chain & lack access to formal decision-making processes (e.g., in their roles as community organizers/leaders) - gender equality & gender expertise not sufficiently (or not at all) considered in discussions around industrial decarbonization
	Body/health/safety/privacy (intimacy): work environments in male-dominated industries are often hostile to women, including harassment

5.7 Conclusions on gender

In discussions around industrial decarbonization, the issue of gender impacts is a marginalized, if not entirely absent, topic. This does not, however, reflect reality. The industry sector is by no means a gender-free space, as this chapter has outlined. A gender-sensitive analysis of industrial decarbonization will need to look beyond directly affected paid jobs, beyond reducing carbon emissions, beyond purely technological solutions, and beyond existing forms of economic organization.

Bringing gender expertise and a feminist sensibility into the transformation of energy-intensive industries will mean expanding on the sparse existing analysis in several ways. It requires both a more holistic examination of green industrial transformation and a closer look at gender impacts of the transformation of industrial sub-sectors and specific mitigation options. The role of women, men and of other genders beyond the binary – the latter being entirely unrepresented in existing analysis – in alternative decarbonized industrial futures needs to be strengthened in order to ensure that everyone who is affected by the problem stands to benefit equally from the solution.

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Appendix

WISEE-EDM Cement National model

The model includes 9 parameters (resp. parameter sets) which each have to be provided manually for each case (country) and year of the analysis:⁵⁵

- › **Demand for concrete buildings:** this parameter covers the building demand taking into account a potentially increasing use of alternative building materials. This parameter is not considered being a mitigation option, but reflects external boundary conditions such as population growth and urbanization. It is given as index value (2020=100)
- › **Concrete used per structural element:** can be used to reflect changes to the concrete intensity of structures. It is given as index value (2020=100)
- › **Binder intensity of concrete:** can be used to reflect changes to the binder intensity of concrete. It is given as index value (2020=100).
- › **Use of novel binders:** Percentage of novel binders used related to the overall binder use in this country and year.
- › **Clinker factor:** the average clinker content of cements (excluding novel binders) in that country and year. Given as percentage.
- › **Use of decarbonated raw materials:** Percentage of all raw materials entering the cement oven which is provided through alternative raw materials.
- › **Specific thermal energy demand:** Average thermal energy demand of clinker ovens in that country and year, in GJ / ton clinker.
- › **Fuel shares:** Percentage of thermal energy provided by a specific fuel in the particular country and year. The model distinguishes between coal, lignite, waste-based fuels, natural gas, pet coke, biomass, hydrogen, electricity and other fossils. (The main focus of the analysis rests on waste-based fuels and biomass).
- › **Production capacity with carbon capture:** Percentage of all clinker production capacity in the particular country and year. It is assumed that clinker production is distributed equally across the existing capacity, i.e., the parameter also reflects the percentage of clinker production to which CCS is applied. The capture rate is assumed to be 90% in all cases.

The variables for binder, cement, novel binder and clinker production in the year t are represented in Mt and calculated as:

- (1) $Binder_production(t) = Demand\ for\ concrete\ buildings(t)/100 \times Concrete\ used\ per\ structural\ element(t)/100 \times Binder\ intensity\ of\ concrete(t)/100 \times Binder_production(2020)$
- (2) $Novel_binders(t) = Binder_production(t) \times Use\ of\ novel\ binders(t)$
- (3) $Cement_production(t) = Binder_production(t) - Novel_binders(t)$
- (4) $Clinker_production(t) = Cement_production(t) \times Clinker\ factor(t)$

⁵⁵ See section 4.3 for explanation of mitigation options.

For some pathways in addition a production of calcined clays (*Calcined clay production (t)*) is assumed based on a rough assessment of the cement production, the clinker factor and possible uses of calcined clays.

Process-based CO₂ (Mt CO₂) is calculated as:

$$(5) \text{ Process_CO}_2(t) = \text{Clinker_production}(t) * EF_c + \text{Novel_binders}(t) * EF_c * 0.6$$

with EF_c being a emissions factor for process-based emissions (t CO₂ / t clinker) that is specified per country. The process-based emissions of novel binders are assumed to be 40% lower, compared to clinker (e.g. CSA cements).

Fossil and biogenic fuel related CO₂ amounts are calculated per fuel as follows:

$$(6) \text{ Fuel_CO}_2\text{_clinker_fossil}(t) = \text{Clinker_production}(t) \times \text{Specific thermal energy demand}(t) \times \text{Fuel share}(t) \times EF_{ff} / 10^3$$

$$(7) \text{ Fuel_CO}_2\text{_novel_binders_fossil}(t) = \text{Fuel_CO}_2\text{_clinker_fossil}(t) \times \text{Novel_binders}(t) / \text{Clinker_production}(t) * 0.6$$

$$(8) \text{ Fuel_CO}_2\text{_clays_fossil}(t) = \text{Calcined_clay_production}(t) \times 2 \text{ GJ/t} \times EF_{cf} / 10^3$$

$$(9) \text{ Fuel_CO}_2\text{_total_fossil}(t) = \text{Fuel_CO}_2\text{_clinker_fossil}(t) + \text{Fuel_CO}_2\text{_novel_binders_fossil}(t) + \text{Fuel_CO}_2\text{_clays_fossil}(t)$$

$$(10) \text{ Fuel_CO}_2\text{_clinker_bio}(t) = \text{Clinker_production}(t) \times \text{Specific thermal energy demand}(t) \times \text{Fuel share}(t) \times EF_{fb} / 10^3$$

$$(11) \text{ Fuel_CO}_2\text{_novel_binders_bio}(t) = \text{Fuel_CO}_2\text{_clinker_bio}(t) \times \text{Novel_binders}(t) / \text{Clinker_production}(t) * 0.6$$

$$(12) \text{ Fuel_CO}_2\text{_clays_bio}(t) = \text{Calcined_clay_production}(t) \times 2 \text{ GJ/t} \times EF_{cb} / 10^3$$

$$(13) \text{ Fuel_CO}_2\text{_total_bio}(t) = \text{Fuel_CO}_2\text{_clinker_bio}(t) + \text{Fuel_CO}_2\text{_novel_binders_bio}(t) + \text{Fuel_CO}_2\text{_clays_bio}(t)$$

with EF_{ff} being an emission factor for fossil CO₂ emissions of fuel f (t CO₂ / TJ) and EF_{fb} being the corresponding emissions factor for biogenic CO₂. For the calcination of clays slightly different emission factors are assumed that reflect a mix of production of calcined clays in cement kilns (same fuel mix as clinker) and specific flash calciners (renewables only). Thermal energy demand of novel binders is assumed to be 40% below that of clinker, but the same fuel mix is assumed for their production. For calcined clays a thermal energy demand of about 2 GJ/t is assumed.

The CO₂ captured is calculated from the emissions and the production capacity with carbon capture, assuming a capture rate of 90%:

$$(14) \text{ Captured_CO}_2\text{_fossil}(t) = [\text{Process_emissions}(t) + \text{Fuel_CO}_2\text{_total_fossil}(t)] \times \text{Production capacity with carbon capture}(t) \times 0.9$$

$$(15) \text{ Captured_CO}_2\text{_bio}(t) = \text{Fuel_CO}_2\text{_total_bio}(t) \times \text{Production capacity with carbon capture}(t) \times 0.9$$

Finally the net emissions are calculated as:

$$(16) \text{ Net_emissions}(t) = \text{Process_CO}_2(t) + \text{Fuel_CO}_2\text{_total_fossil}(t) - \text{Captured_CO}_2\text{_fossil}(t) - \text{Captured_CO}_2\text{_bio}(t)$$

PARTICIPANTS



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