Contributions to contribution analysis: structuring and extension of approaches to understanding contributions to impacts in Life Cycle Assessment

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Chapter 5

Recovering sand and gravel from End-of-Life concrete: The global potential

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Abstract

Concrete is a key material in our modern society and will remain an important material in the coming decades globally. Two main components of concrete, sand and gravel -together aggregates- could become scarce which may pose a significant problem the production of concrete. One option to mitigate scarcity is to recycle concrete. Two complementary technologies that have been in development for this are making this feasible; 'Advanced Dry Recovery' and 'Heating Air classification System'. Together they produce recycled sand and gravel. In this study we assess the recyclability of End of Life concrete up to 2050 in 26 regions for the production of new aggregates with a dynamic material flow analysis model and assess environmental impacts with Prospective Life Cycle Assessment. We find that recycling could reduce demand for conventional sand by 16% and gravel by 34% globally by 2050 without large increases in impacts, though impacts differ substantially per region.

5.1 Introduction

Concrete is a key material in our modern society and will remain an important material in the coming decades globally. It is an engineered material mainly made from sand, gravel, water, and cement. Production of concrete has quadrupled between 1990 and 2020 (Watari et al., 2023). Additionally, demand for concrete is expected to keep rising in most world regions up to 2050, either for new construction, maintenance and replacement of demolished buildings (Deetman et al., 2020; Harald U. Sverdrup et al., 2017). Two ingredients of concrete -sand and gravel (together aggregates)- made up 79% of all non-water resources extracted from nature in 2010 (Krausmann et al., 2017). The winning of aggregates causes land use change and hence may have biodiversity impacts. While the winning of aggregates is not carbon-intensive, the production of concrete is highly energy intensive and was responsible for 3.3 GT $CO_{2eq.}$ emissions in 2020 (Müller et al., 2024). Their large scale consumption makes it important to investigate how environmental challenges related to the use of aggregates could be limited (van der Meide et al., 2022).

Although sand and gravel seem to be abundantly available, the scarcity issue of conventionally produced aggregates has gained more scientific attention recently -though concern for sand scarcity is hardly new, see e.g. Giljum et al (2000)-. Torres et al. (2017) have shown that illegal sand mining is causing local problems in the global south. Peduzi (2014) highlights effects on biodiversity, land loss and erosion, water supply and potential damage to infrastructure. This poses a special concern to future concrete manufacturing, which demands not only a high quantity but also a high quality of aggregates, namely, construction grade sand and construction grade gravel. While construction sand is mostly discussed in the scarcity context, construction gravel can also be considered scarce, depending on the region and supply (Ioannidou et al., 2017), though the locality of scarceness is important for all aggregates. We can expect these problems to exacerbate significantly due to the growth in demand (Watari et al., 2023).

Several options have been proposed to mitigate the scarcity challenge for conventional aggregates, such as recycling secondary aggregates from end of life (EoL) concrete (Tukker et al., 2023; Zhang et al., 2022) and increasing efficiency in material use (Cao & Masanet, 2022). Zhong et al. (2022) show that to combat sand scarcity substitution is the single most effective strategy. The substantial flows of future EoL concrete projected by Deetman et al. (2020) indicate a potential worth to investigate for sand and gravel substitution by recycling secondary aggregates from the rising future EoL concrete flows.

While recycling concrete into construction grade aggregates has been an engineering and economic challenge (Ren et al., 2021; Zhang et al., 2019), two complementary technologies that have been in development in Europe over the past decade are making this feasible. They are 'Advanced Dry Recovery' (ADR) (Lotfi et al., 2017) and 'Heating Air classification System' (HAS) (Gebremariam et al., 2020). ADR works by separating concrete pieces into different sizes through a mechanical system. The output streams are recycled gravel and an intermediate. HAS works by separating the intermediate stream into two smaller streams through a thermal system. The output streams are recycled sand and a fine dust that can be used as a cement filler. The technologies could be deployed in tandem to recycle EoL concrete and reduce demand for conventional aggregates.

For ADR and HAS, some work has already been done to assess their environmental impacts with Life Cycle Assessment (LCA). Zhang et al. (2023) studied the environmental performance of the technologies, including a prospective study where the energy supply to the technologies was adjusted to future energy mixes with *Premise* (Sacchi et al., 2022). While this study provided deeper insight into material and fossil fuel footprints for EoL treatment, the potential of ADR and HAS as a technology to produce recycled sand and gravel and related environmental impacts has not been assessed.

Before the potential of recycling of EoL concrete and its environmental impacts can be assessed, we first need to better understand the relationship between availability of EoL concrete and demand for concrete. Additionally, it is not clear whether recycling concrete with ADR/HAS technologies may pose any trade-offs with environmental impacts or how these recycled aggregates compare against conventional aggregates in terms of their environmental impacts. In this study, we aim to address both of these gaps. We develop a dynamic material flow analysis model (MFA) for global aggregates and concrete to understand to what extent EoL concrete can provide secondary aggregates for future concrete production in 26 regions of the world from 2025 to 2050. We then model the potential for and environmental benefits of recycling concrete with ADR and HAS up to 2050. We do so by integrating these technologies into a prospective version of the ecoinvent Life Cycle Inventory (LCI) database (Wernet et al., 2016). We do this by linking the recycling processes to the sand and gravel markets, letting all processes in the database that consume aggregates make use of the recycled aggregates as well. We calculate potential environmental impacts using *Premise* to assess possible trade-offs from recycling. Our method is further elaborated in section 5.2. Section 5.3 provides results and finally Section 5.4 gives the discussion and conclusions.

5.2 Methods

We start by developing a dynamic MFA model to assess the global potential of concrete recycling to reduce the demand for conventional aggregates. Based on existing building material stock and flow data from Deetman et al. (2020) we build a 'recycling material flow analysis model' to show how much conventional aggregates could potentially be substituted by recycled aggregates in 26 global regions from 2025 to up to 2050.

Next, we describe the Life Cycle Assessment (LCA) goal and scope and the ADR/HAS inventories and how we integrate them with *Premise*. We do this by linking the recycling processes to the sand and gravel markets, letting all processes in the database that consume aggregates make use of the recycled aggregates as well. After this, we assess the environmental impacts of the recycling technologies compared to conventional production and assess what processes and products contribute to their impacts.

Finally, we combine both the stock model data and the calculated environmental impacts to assess any potential trade-offs at scale.

Our calculation of LCA results is done in Activity Browser 2.11.2 (Steubing et al., 2019) and the results analysis done is with Excel (available as Supplementary Information (SI) 1). The python scripts for our stock model and integration with ecoinvent data are provided as SI in van der Meide (2025).

5.2.1 Recycling material flow analysis model

To assess the availability of EoL concrete to recycle we make use of the outputs of Deetman et al. (2020), who calculate in-and-outflow of concrete in the building stock for a given year and region between 1970 and 2050. This is modeled with the IMAGE Integrated Assessment Model (IAM) (Stehfest et al., 2014) for the SSP2 scenario (O'Neill et al., 2014), which projects likely policy changes based on current and future policy plans. In this study, we only consider the recycling of concrete and use of aggregates again in concrete as data for other aggregate uses (e.g. road-fill) is lacking.

We use the stock model outflow from Deetman et al. (2020) as available material for recycling and use the inflow as demand for new concrete, we show this in Figure 5.1. We then split the EoL concrete outflow from the building stock into production shares that ADR/HAS can produce. Based on the amount of gravel/sand that can be produced from the outflow and the demand in a given year and region, we calculate a balance. The balance for sand/gravel is zero, positive or negative for every timestep and region. If the balance is zero, the demand can be satisfied exactly by the outflow of the concrete stock. If the balance is positive (more material is available than is demanded), the remainder is considered to be stored and available for future time steps in the same region. If the balance is negative (more material is demanded than is available), the remainder can be supplied from the storage, any remainder after that (e.g. when the storage is empty) must be produced as conventional concrete. Based on the balance, the market share between conventional and recycled concrete is determined.

The amount of outflow from the building stock can also be moderated as not all material can realistically be converted due to a recycled aggregates market that is still under-developed and other market/policy inefficiencies. We assess two explorative scenarios from a stock model perspective:

First, we assess a scenario where there would be no limit to market shares, i.e. everything that can be recycled will be recycled. We name this scenario *'Maximum'*. Secondly, we assess a scenario where the market share of recycling increases over time, from 0% in 2025 to a maximum of 50% in 2050. We name this scenario *'up-to 50%'*.

We stress that both scenarios are meant as an exploration of the potential for recycling aggregates, and do not reflect expectations with regards to market adoption of ADR and HAS. After assessing how much sand and gravel can come from recycled sources –the substitution rate- in both scenarios, we will only use the 'up-to 50%' scenario going further. We assess this scenario in more detail as it is the more realistic one of the two. We will show how much aggregates are produced from conventional and recycled sources in aggregated regions.

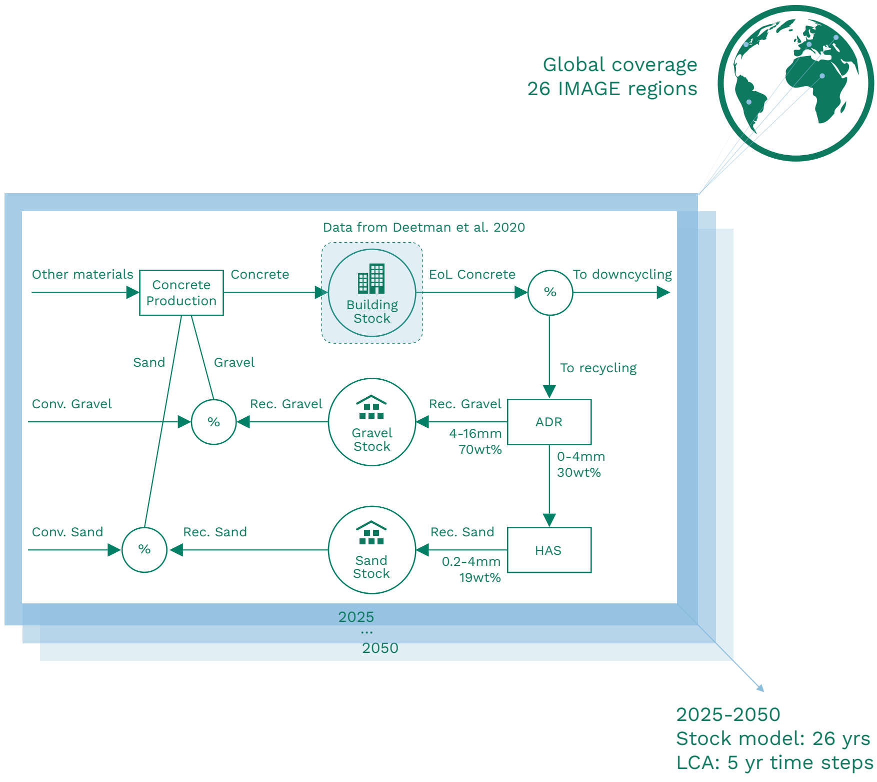


Figure 5.1 - Recycling material flow analysis model. Starting from the top-middle, EoL concrete is partially recycled (amount depending on the scenario) and converted to recycled gravel by ADR and recycled sand by HAS. Depending on the demand for concrete (top left), gravel and sand are supplied, first by recycled sources and supplemented by conventional sources. The model is calculated from 2025-2050 and the 26 IMAGE regions.

5.2.2 Life Cycle Assessment

Goal and Scope

Our goal with the LCA is twofold: First, we want to compare environmental impacts between conventional and recycled aggregate production, and what contributes to those impacts. For this, we will assess a 'cradle-to-gate' production of aggregates. For the recycled aggregates, this means production from recycled EoL concrete. Secondly, we want to assess whether a shift to recycled aggregate production would pose any trade-offs compared to conventional aggregate production, which is why we combine it with Prospective LCA and our stock model to assess potential impacts up to 2050.

The scope of our assessment is the production of aggregates as described above, which will be integrated into a prospective version of the ecoinvent database (Wernet et al., 2016) using *Premise* (Sacchi et al., 2022). This integration means that other processes that require sand and gravel (e.g. concrete production) make use of both the conventional and recycled aggregates, immediately affecting all processes in the database that would make use of sand or gravel somewhere in their supply chains. Other database changes like the changes in the generation of electricity, transport and steel sector as made by *Premise* are also included. We assess the regionalized production of aggregates in all 26 IMAGE regions, making use of the ecoinvent market mixes if multiple conventional production routes exist, to which we add the recycled shares from our stock model. The script to generate the prospective database is included as SI in van der Meide (2025).

For our assessment, we consider a functional unit of 'aggregates needed for 1 ton concrete', which is 373 kg sand and 461 kg gravel, based on ecoinvent inventory data. We compare conventional and recycled aggregates to each other and compare the process contributions, grouped by product names, we apply a cumulative cut-off of 80% to show the most important contributors, the full method is described by van der Meide et al. (2025).

To keep this assessment in the context of the most important use of aggregates, concrete production for this we use concrete production in Switzerland (in the IMAGE region Western Europe (WEU)). We show the product contributions of sand, gravel and cement as described in van der Meide et al. (2025). For this assessment, compare three alternatives:

100% conventional production in 2025, the market mix of 2050 with 20% recycled sand and 50% recycled gravel and a 100% recycled production. Finally, based on the original LCA model and market shares between conventional and recycled aggregates from our stock model we model, we assess how impacts change over time. We use the 'up-to 50%' scenario to assess impacts. We assess impact of aggregate production in five year time steps from 2025-2050 and show how the impacts change for the world average, highest and lowest regions on a per-unit basis. Lastly, we combine the demand from the stock model and the per-unit impacts to assess the potential total impact of aggregate production.

Advanced Dry Recovery (ADR) and Heated Air Classification System (HAS) Life Cycle Inventory
For the LCA of recycled aggregates, we use updated inventories from Lotfi et al. (2017) for ADR and Gebremariam et al. (2020) for HAS. We provide the exact inventories in the SI in van der Meide (2025) but do discuss the technologies here from a Life Cycle Inventory perspective. Advanced Dry Recovery (ADR) is meant to separate a stream of crushed end of life (EoL) concrete (0-16mm) into two streams. One stream can be used to replace gravel and is 4-16mm in size and the other is an intermediate of 0-4mm size that needs to be processed further. ADR works by physically separating particles based on density (see also Lotfi et al. (2017)). The machine can be installed locally on a deconstruction site, is filled and emptied by excavators and requires only electricity to run.

Heated Air Classification (HAS) is meant to separate the 0-4mm stream further into another two streams. One stream can be used to replace sand and is 0.125-4mm in size and the other is 0-0.125mm. In the future the latter stream may be used as a useful filler material in clinker, but we do not consider this stream further in this study. HAS works by rapidly heating and cooling the particles, fracturing them on weak points in their physical structure, splitting them into two stable fractions (as explained in more detail by Gebremariam et al. (2020)). The machine can be installed locally on a deconstruction site, is again filled and emptied by excavators and requires diesel to run. While Zhang et al. (2023) assessed the potential for biodiesel use in HAS, we use conventional diesel in our inventory to make for a fairer comparison to conventional aggregate production. We provide the ADR and HAS LCI in van der Meide (2025).

We consider both ADR and HAS multifunctional processes, producing two sizes of recycled aggregates. We apply mass-based allocation to the fractions, price-based allocation would not be possible as there is no openly available pricing on aggregates globally nor for the ADR and HAS products. The mass fractions of each stream are shown in Figure 5.1. We do not consider the processes as waste treatment processes, this happens at an earlier step of concrete crushing, which happens for all waste treatment options of EoL concrete, whether it is landfilled, used as road base or recycled with ADR and HAS. We consider the crushing step cut-off for two reasons, this is consistent with the cut-off model from ecoinvent (Wernet et al., 2016) and it is the same for all waste treatment options.

Conventional aggregates and concrete production Life Cycle Inventory
In our LCA we compare ADR and HAS to conventional production of aggregates, for this we use the inventories available in ecoinvent:

- 'Gravel and Sand quarry operation' for 'sand' and 'gravel, round'
- 'Sand quarry operation, extraction from river bed' for 'sand'
- 'Zinc mine operation' for 'sand'
- 'Gravel production, crushed' for 'gravel, crushed'

Some regions have multiple processes available, while others have only one source available, e.g. 'India', which –according to the ecoinvent data- only produces sand from riverbed mining. We make use of the market processes in ecoinvent so we use regional mixes for conventional production. For other regions, we use the market shares from the global market in ecoinvent. While market shares between these conventional routes could change, there currently is no information about these market shares and we assume no change. The integration into the LCI database through *Premise* (Sacchi et al., 2022) ensures that all consumers of aggregates in the database would consume from this modified market, making use of both conventional and recycled sand and gravel where applicable. The market shares between conventional and recycled aggregates differ per region and year based on our stock model.

Impact Assessment
We do a Life cycle impact assessment based on the Environmental Footprint (EF) 3.1 impact categories and characterization factors (EC, 2022). We focus on climate change, water use and land use, but provide the results for all 25 impact categories in SI 1.

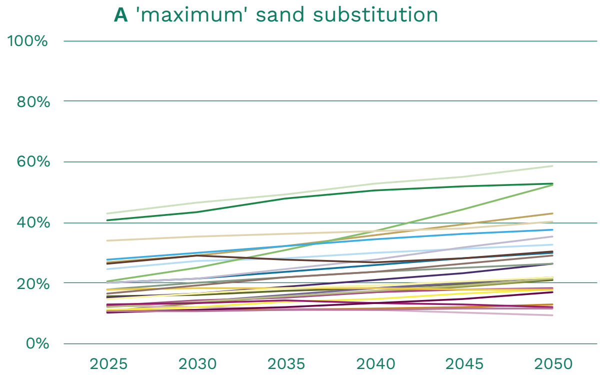
5.3 Results

5.3.1 Stock model

Our stock model shows how much sand and gravel can be substituted (indicated in percent relative to the total demand in Figure 5.2). We modeled this for both the *'maximum'* scenario without technological limits to recycling and the *'up-to 50%'* scenario where a maximum market share grows from 0% in 2025 to 50% in 2050.

In the maximum substitution scenario, we find that for sand the recycling depends mainly on the region and does not grow over 60% for the highest region (Figure 5.2 A). For gravel, we find substantially higher rates, even reaching a potential 100% substitution in some regions (Figure 5.2 B), suggesting that no further production of conventional gravel would be necessary in those regions to produce concrete.

In the 'up-to 50%' scenario, we find a maximum rate of 29% in 2050 and most regions not passing 20% (Figure 5.2 C). For gravel, we again find higher rates, though many regions still don't surpass the 40% substitution (Figure 5.2 D).



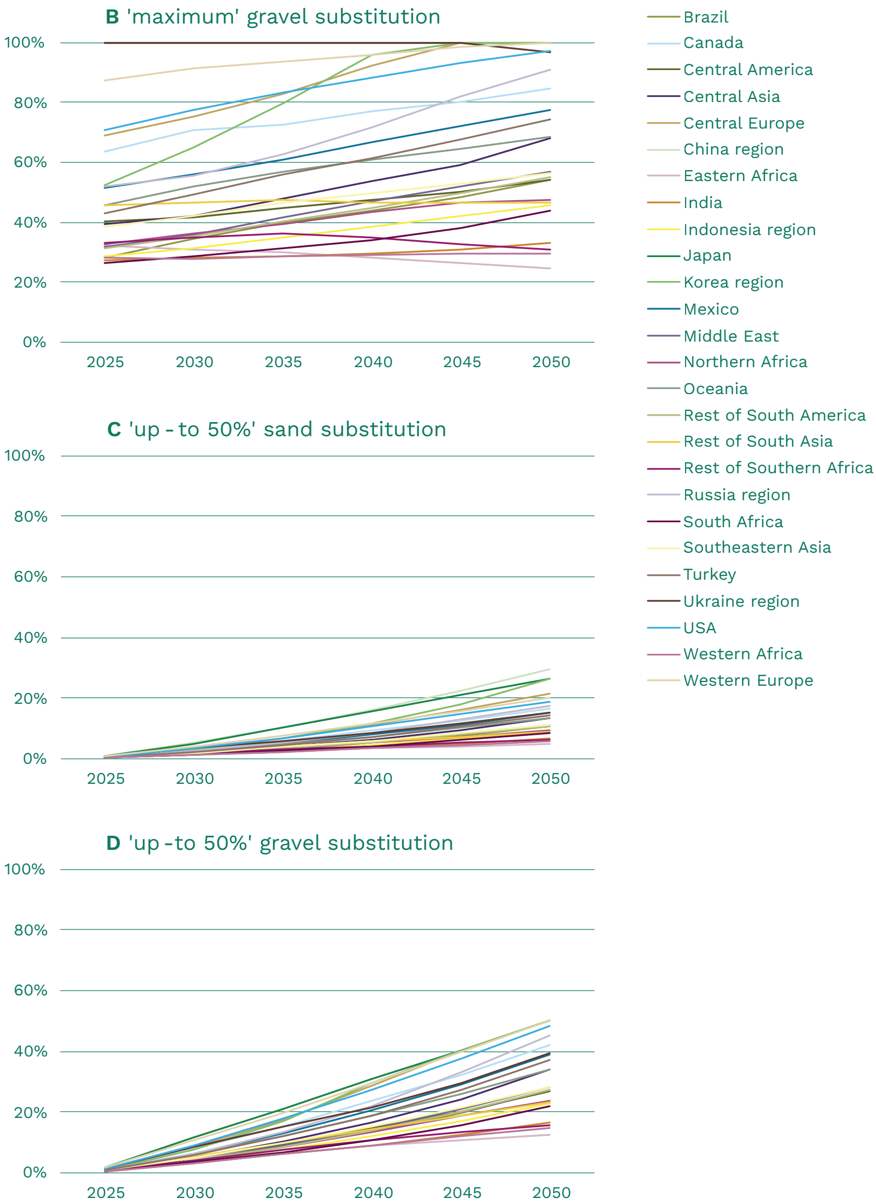


*Figure 5.2 - Substitution rate of recycled Aggregates over time. **A** 'maximum' scenario for sand, **B** 'maximum' scenario for gravel, **C** 'up-to 50%' scenario for sand, **D** 'up-to 50%' scenario for gravel*

For the ‘up-to 50%’ scenario we also show the aggregate demand for grouped regions (exact grouping presented in SI 1) in Figure 5.3. In the figure, we show the total demand for aggregates for concrete production in aggregated regions in five year steps and how much can be supplied from conventional and recycled sources in 2050. We find that in 2050, 26% of global aggregate demand could come from recycled sources, though about two thirds of this would be gravel.

Further, from Figure 5.3, we also find that demand in China is -and remains- the largest consumer of aggregates. While this is not surprising, we also see a strong growth in the availability of EoL concrete. In contrast, India also grows fast in total demand, but the end of life availability concrete remains relatively low. This is due to the fact that China has been developing its housing and infrastructure strongly for a longer period already, meaning that now already more stock reaches the end of life stage and needs to be replaced, providing significant amounts of EoL concrete.

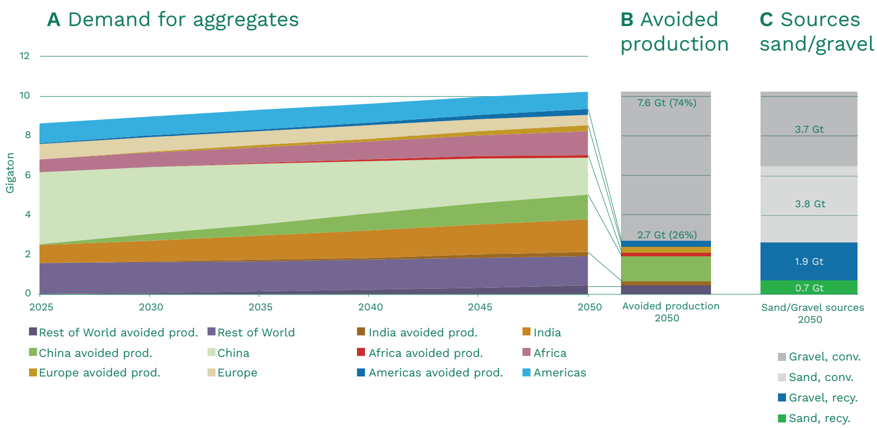


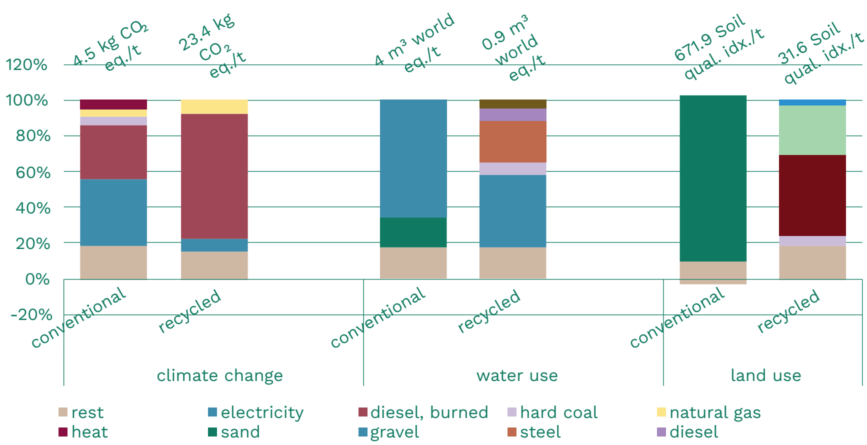
*Figure 5.3 - Demand for aggregates, **A** Demand in six aggregated regions between 2025-2050, **B** Avoided production of conventional aggregates in the same regions of **A** in 2050 based on 50% scenario, **C** Sources of sand and gravel in 2050 based on 50% scenario.*

5.3.2 LCA ADR/HAS

We assessed the environmental impacts for conventional and recycled aggregate production for 1 ton of concrete for the world average. We show comparative process contributions in Figure 5.4 A. We show the relative process contributions, grouped by product names for three important impact categories. The per-unit results for all 25 impact categories for sand, gravel and combined as aggregates are provided in SI 1. We find that for climate change impact, the 'diesel, burned' group results in a much higher impact for recycled aggregates, this is due to the HAS requiring substantial amounts of fuel. Furthermore, we find that for water use, over 80% of the impact can be explained directly by sand and gravel production for conventional production. While the per-unit impact for climate change is ~5x higher for recycled aggregates, the impacts in water use is ~4x lower and land use is ~20x lower.

To keep aggregates production in context of its main consumer, concrete production, we also assess the product contributions of sand, gravel and cement to concrete production in Switzerland based on the Central EU aggregates production, we do this for 100% conventional aggregates in 2025, the market mix of aggregates in 2050 (20% recycled sand, 50% recycled gravel, Figure 5.2)and 100% recycled aggregates in 2025. We show this in Figure 5.4 B. For the market mix of aggregates in 2050 compared to a 100% conventional production in 2025, we find that the contribution of aggregates to climate change increases from 2.8% to 5.3%. We find a < 1% decrease in water use impact and Land use contribution changes 3.7%. When assessing 100% recycled compared to re, the main changes are in the contribution of sand to climate change and reduction of the total land use of aggregates from 71.8% to only 14.2%.

A Relative process contributions to aggregate production



B Relative product contributions to concrete production

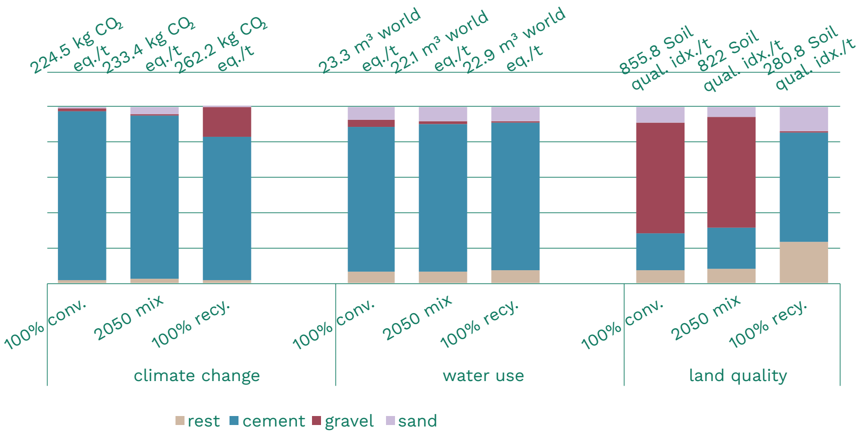
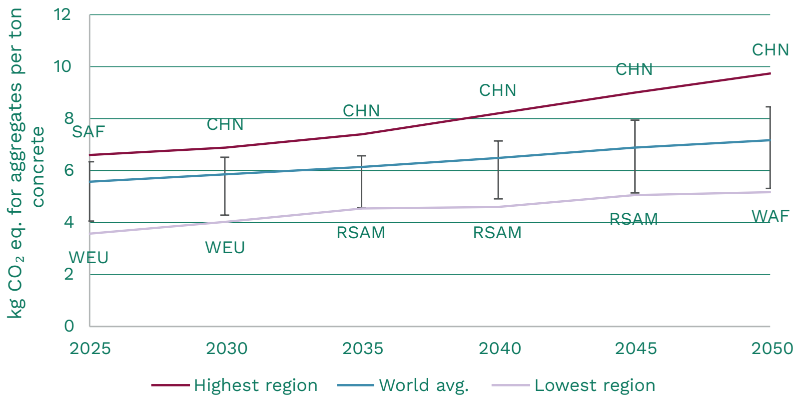


Figure 5.4 - Contributions to LCA results. A: Relative contributions of process groups to three major impact categories, cumulative to 80% of contributions. B: Product contributions to the production of 1m3 concrete with 100% conventional aggregates, the 2050 mix of conventional/ recycled aggregates and 100% recycled aggregates for 'sand', 'gravel', 'cement' and all other products.

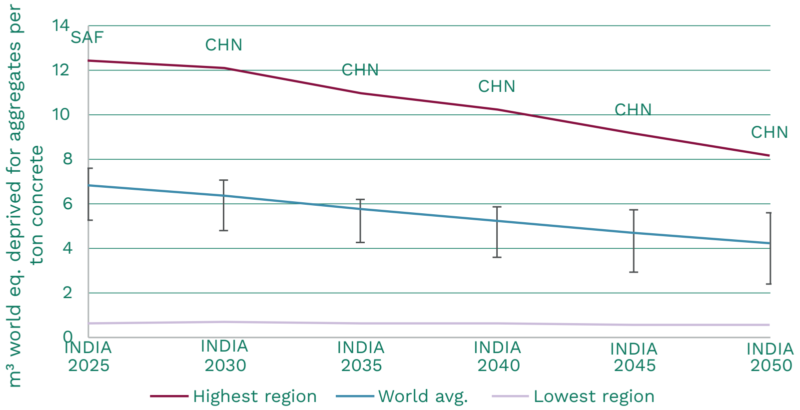
5.3.3. Prospective LCA

With market shares between conventional and recycled aggregates known, environmental impacts per-unit can be calculated up to 2050. We show this for the 'up-to 50%' scenario in Figure 5.5. From this figure, we find a slightly increasing climate change impact, coinciding with increased market share of recycled aggregates. For water use, we find that 'Rest of South America' (RSAM) and India are outliers compared to the majority of the regions –5th to 95th percentile, between the error bars-, with most of the data slowly declining from ~7m^3 to ~4m^3. For land use, we find that India is again a major outlier, with most regions having much lower results. These outliers can be explained by regionalized ecoinvent market datasets that use only material from a single source. Finally, we find that per-unit of aggregates, China shows the largest decline, due to its high recycling share. Overall, tradeoffs per unit of production for aggregates appear limited.

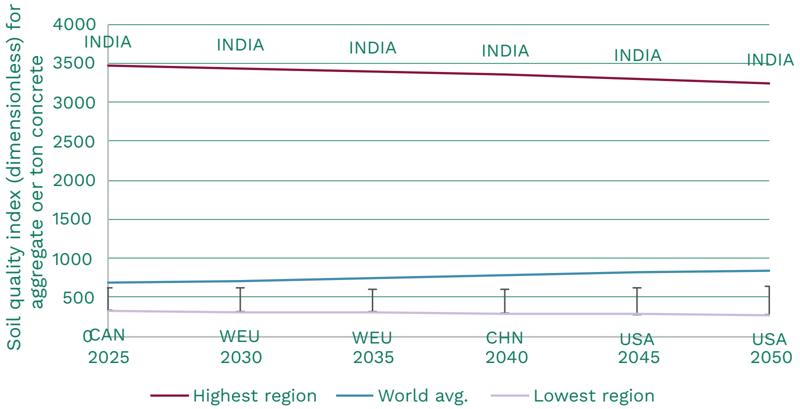
A Per - unit climate change impact



B Per - unit water use impact



C Per - unit land use



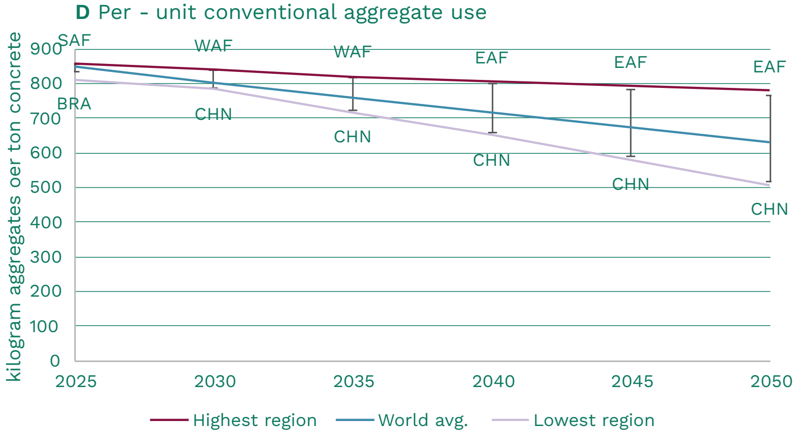
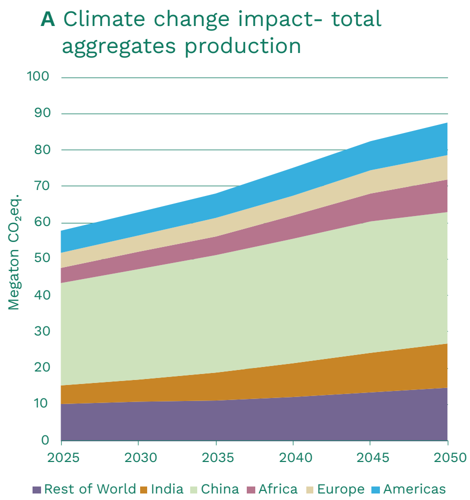
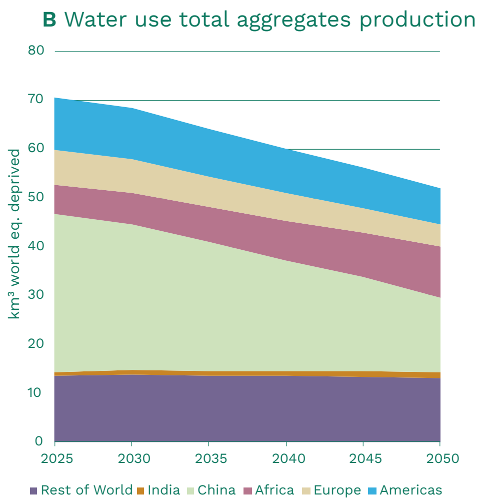


Figure 5.5 - Per-unit impact between 2025 and 2050 for aggregates, showing world average, the highest and lowest regions (labeled) and a 5th and 95th percentile as error bars. A: shows per-unit climate change impact, B: shows per-unit water use impact, C: shows per-unit land use impact, D: shows per-unit use of conventional aggregates.

Combining the per-unit impacts with the aggregate demand projected by the SSP2 scenario (as shown in Figure 5.3), we find that the total yearly climate change and land use impact from aggregates production would increase, while decreasing water use, as shown in Figure 5.6. Relating this back to concrete production, total land use could become a challenge, depending on the region.





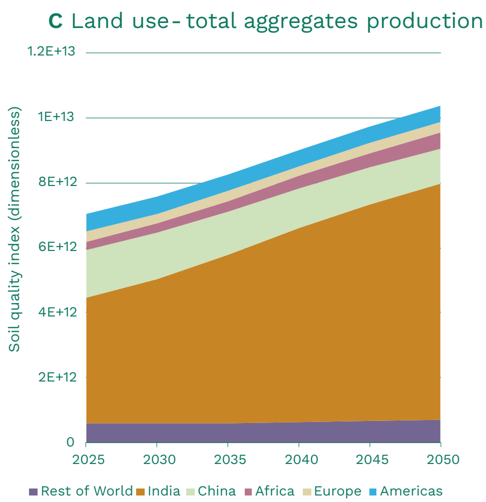


Figure 5.6 - Impact of aggregate demand between 2025 and 2050 for aggregated regions. ***A*** *shows climate change impact,* ***B*** *shows water use impact,* ***C*** *shows land use impact.*

5.4 Discussion

With our study, we have shown for the first time the potential of recycling aggregates from EoL concrete in a future scenario with a stock model and how this would affect environmental impacts with prospective LCA. We modeled the future potential of EoL concrete recycling to reduce sand and gravel scarcity with a dynamic stock model. We coupled this data to a prospective LCA to assess potential trade-offs of recycling with environmental impacts. From our assessment we found that up to 16% of sand demand and 34% of gravel demand for concrete production could be substituted with sand and gravel recycled from EoL concrete assuming a scenario where EoL concrete recycling reaches 50% market share.

These relatively low substitution rates –especially for sand- can be explained by a combination of two reasons: First, even if the ADR/HAS technologies would recycle all EoL concrete, the output is still only 19% recycled sand due to how ADR and HAS are currently used. This, combined with the fact that the concrete types we assessed require 37%wt sand, means that not all sand could be from recycled sources if the demand were the same as supply from EoL concrete. Secondly, many regions have a mismatch between their demand for concrete and supply of EoL concrete. If more material is required for new construction than becomes available for recycling, not all material can be recycled by definition –a circularity gap (Krausmann et al., 2017)-, we see this back in our comparison between the China and India regions in Figure 5.3.

While this circularity gap between demand for new concrete and supply from EoL concrete cannot be closed entirely, it can help significantly reduce demand for conventional sand and gravel. Recycling can especially help in regions where there is low growth, while regions like India and Africa would still need to supply a major share of their production from conventional sources.

In terms of environmental trade-offs with increases in supply from conventional sources, impacts can be expected to increase, though in the context of environmental impacts of concrete production, the increase would be rather limited. Specifically for climate change, the contribution of sand and gravel to concrete production would still only account for <5% if the total impact, with the majority of the impact still caused by clinker production. Despite this, ADR and HAS still have a high energy cost, making the cost-effectiveness of HAS largely dependent on the cost of energy. Technology developers should attempt to improve this in the future.

One major challenge for the production of sand and gravel is that the production is often limited to local production and consumption –though exceptions like Singapore exist, which imports significant amounts of sand (Peduzi, 2014)-. The low value of sand and gravel per unit weight makes it often uneconomical to transport over large distances, making scarcity of sand and gravel a local problem, requiring local solutions. We represented this in our model by only considering the balance between EoL concrete availability and consumption per region.

A main problem with recycling is that it can only partially help resolving current scarcity issues. It helps to reduce demand for conventional sand and gravel, but due to a still rising demand for concrete in many regions and imperfect collection and recycling, recycled aggregates can cover the needs for aggregates only for 26% (Figure 5.6). Recycling must be combined with other measures like reducing demand for aggregates e.g. like Zhong et al. (2022) modeled. Specifically for regions that have had strong growth in the past, this may be effective now, as there would still be a major amount of stock from the built environment, reducing the circularity gap in the future. For regions that do currently not have a large stock of materials in the built environment, this would not help reduce the circularity gap much as the ratio of demand and availability of EoL sand and gravel would not change much.

We identify one main limitation to our study: We modeled ADR and HAS while there are more technologies to recycled EoL concrete (Ren et al., 2021; Zhang et al., 2019). We used ADR and HAS due to availability of data and it's promising cost-effectiveness and market readiness. Our stock model can be adjusted with different recycling parameters and the Life Cycle Inventories could also be changed to apply our models to different technologies to assess their potential.

While we assess the potential to reduce sand and gravel demand and its associated environmental impacts, we do not know how these values relate to actual aggregate availability and scarcity problems, this would be a topic that needs to be investigated in the future. This needs to be studied both a level of local impact, but also globally.