newTRENDs

Modeling circular economy along the EU building value chain: Impact on steel and concrete demand until 2050

Deliverable 6.1 - Focus study report on decarbonization and circular economy in industry

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Datasets and parts of the energy demand models, which are newly developed within this project, will be made open access latest at the end of the project and can then be found at https://github.com/H2020-newTRENDs. All previously existing datasets and model parts are explicitly excluded from this open access strategy.

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Executive Summary

The 2015 Paris Agreement has as the central aim to strengthen the global response to the threat of climate change by keeping global temperature rise in this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (United Nations 2015). To reach this ambitious goal, two central strategies have to be implemented in all countries: (i) enhancing energy efficiency (EE) and (ii) decarbonizing remaining energy supply and demand, in particular by large penetration of renewable energy sources (RES). Scenarios with different focuses and assumptions have been developed to map the European energy transition until 2050 (European Commission 2021b). While these scenarios present important tools to support decision makers, much more progress is necessary to quantify the impact of New Societal Trends on future energy demand and greenhouse gas (GHG) emissions.

Industry is responsible for about 22% of Europe's GHG emissions making the sector critical for the achievement of European climate goals (EEA 2021). It is expected that the circular economy (CE) can contribute significantly to the achievement of these goals while enabling further economic growth (European Commission 2018b, 2019). Considering the challenging decarbonization of the industrial sector and especially the basic material industry, the umbrella concept CE can have great impact on industry transition by reducing virgin material demand and consequently industrial emissions. The concept includes strategies as recycling, material efficiency, material substitution and sufficiency. An ambitious increase in energy and material efficiency in all applications and sectors is a prerequisite for carbon neutral industrial production, as it reduces the final energy demand and thus lowers the costs for the expansion of renewable energies, grid expansion and the import of secondary energy sources.

The following report addresses the aforementioned research needs and describes an improved modeling approach to assess the role of CE as contributor to industry decarbonization. The study focuses on buildings - a typical end-use good - and the associated basic materials steel and concrete. The building value chain was chosen, as it is the main source of demand for two of the highest-emitting materials and has high CE potentials.

The bottom-up industry demand model FORECAST (FORecasting Energy Consumption Analysis and Simulation Tool) is a tool designed to support strategic decision. It calculates scenarios on future energy demand and GHG emissions (all sources incl. process emissions) and the assessment of different technology pathways (Fleiter et al. 2018). However, the model in its current form does not directly consider material flows or the effects of CE endogenously. The suggested method aims to consider cross-sectoral impact via a stock-driven material flow analysis (MFA) linking FORECAST with the building model Invert/EE-Lab (TU Wien et al. 2021). The chosen methodology enables the explicit consideration of CE actions at the relevant stages of the building value chain. In this study, the eight following actions were selected to represent the 9R framework (Kirchherr et al. 2017):

- Using timber instead of (reinforced) concrete in residential buildings;
- Reducing floor space demand in residential buildings and offices;
- Reducing the over-specification of elements by volume;
- Protection of cultural heritage buildings;
- Renovation of existing buildings;
- Reuse of building elements;
- Reuse of building materials;
- Recycling of cement.

The model results showed that the reference demand for steel and concrete until 2050 in the building sector of the European Union (EU) is still increasing. This is driven by the increasing floor space demand provided by Invert/EE-Lab in line with the EU reference scenario (European Commission 2021a). When looking at individual actions, the reduced over-specification and the renovation of existing buildings had the largest impact on material demand reduction. The lowest impact was allocated to the material-specific actions for reusing structural steel and cement recycling. In addition, three sets of CE actions were modeled:

- The first set included actions addressing changing lifestyles ("Lifestyle");
- The second set addresses construction methods ("Construction");
- The third set was a combination of the previous sets where a lower ambition level for the individual actions was considered ("Mix").

Overall, the "Lifestyle"-set had a larger impact on material demand than the "Construction"-set due to the greater specific impact. Nevertheless, the changing construction methods reduced the steel inflow more than the action set addressing lifestyle due to the respective CE actions. The steel inflow of the "Mix"-set was lower than in the "Lifestyle"-set but higher than in the "Construction"-set, and the reverse for concrete. This indicates that a well-balanced set of actions which addresses both lifestyle and construction methods makes a relevant contribution without having to go to extremes in the implementation of actions. The reference results imply that without further efforts the material demand and consequently the energy demand and GHG emissions related to material production for the EU building sector will increase. Hence, the reduction of material demand through the analyzed circularity actions can contribute to the decarbonization of the industry sector.

By explicitly modeling the material flows along the entire value chain, the developed model enables a consistent endogenous assessment, both of individual CE actions and of different CE sets. This allows the evaluation of their contribution for industry decarbonization, which were previously only considered by exogenous scenario assumptions in FORECAST. Furthermore, the developed approach allows for the first time an integrated view on the development of the building sector through a soft linkage between the building and the industry sector models, which are normally run and analyzed separately. Nevertheless, some uncertainties remain. Both the framework assumptions as well as the mode parametrization could be validated by further literature reviews, in comparison with statistics and expert interviews.

Overall, the described work leads to an improved consideration of CE in bottom-up energy modeling. Consequently, scenario analyses considering CE for industry decarbonization can support the political debate and decision making.

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1. Introduction

Industry is responsible for about 22% of Europe's GHG emissions making the sector critical for the achievement of European climate goals. This high share of final energy demand is mainly due to energy-intensive basic material industries. Within these industries, specific products and processes are particularly relevant for achieving European climate targets(EEA 2021). Previous analyses have shown that for the industry sector available technologies are not sufficient for deep decarbonization. The remaining energy efficiency potentials are limited and fuel switching is often not possible. In addition, process emissions pose a special challenge for the sector, as they are difficult or even impossible to mitigate with today's productions processes and products (Fleiter et al. 2019). Therefore, the relevance of material based strategies for the reduction of GHG emissions is increasing. Especially, strategies grouped under the umbrella concept of CE are considered promising for the GHG emission reduction while maintaining economic growth (Ghisellini et al. 2016). Thus, the CE could substantially contribute to the objective of a carbon-neutral economy as set out in the long-term vision of the European Commission (European Commission 2018b).

As the concept of CE gains momentum in the political debate across all stakeholders, synergies exist between the decarbonization and the CE policy agendas. Scenario analyses that investigate potential impacts of CE on GHG emissions can support decision making e.g. via the assessment of individual CE actions or whole sectors. In addition, CE and its connection to the energy system through material and energy flows have to be considered in energy demand modeling and the analysis of ambitious GHG mitigation pathways (Kullmann et al. 2021). Currently the effects of CE as well as material efficiency and substitution are only roughly considered in these studies from a modeling point of view (European Commission 2018b).

The following report addresses the aforementioned research needs and describes an improved modeling approach to assess the role of CE as contributor to industry decarbonization. The study focuses on a typical end-use good - buildings - and the associated basic materials steel and concrete. The building value chain was chosen as it is the main source of demand for two of the highest-emitting materials and has high CE potentials. After a theoretical framing of the CE in chapter 2 and a summary of the current state of research in chapter 3, the method and data generated are summarized in chapter 4. Consequently, this is the main part of this report. Subsequently, exemplary results are presented in chapter 5 and their implications as well as limitations are discussed in chapter 6. Parts of this report are based on a unpublished publication (Lotz et al. NYP). The report answers two research questions:

1. How to quantify and model circular economy actions, their impact on energy demand and emissions for typical basic material use sectors?
2. How does the circular economy (in the broader sense) in the building value chain contribute to decarbonizing the industrial sector?

2. Theoretical background

2.1 Circular economy and industry transformation

CE is not a new concept for material based strategies but "offers a new framing of these strategies by drawing attention to their capacity of prolonging resource use as well as to the relationship between these strategies" (Blomsma et al. 2017). The fundamental idea of an economy which is characterized by limited material resources and hence necessary to be circular was formulated by Boulding (1966). More recent strategies also include material efficiency, material substitution and sufficiency. For instance, Kirchherr et al. (2017) define the CE "as an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes". This definition introduces another important concept for the categorization of CE strategies: the 3Rs (reduce, reuse and recycle). These CE strategies are implemented through so-called CE actions, and the preferable impact of these actions are described as CE potentials. The 3R framework can be expanded to 9R as shown in Figure 1.

Figure 1 The 9R framework

Circular economy ↑ Increasing circularity ↓ Linear economy		Strategies	
	Smarter product use and manu-facture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacture or use by consu-ming fewer natural resources and materials
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of mate-rials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
		R9 Recover	Incineration of material with energy recovery

Source: (Kirchherr et al. 2017)

It is expected that the CE can contribute significantly to the achievement of climate targets of the Paris Agreement while enabling further economic growth (European Commission 2018a; Ghisellini et al. 2016). Hence, the European Green Deal was introduced by the European Commission in 2019. One of its aims is to increase the resource efficiency towards a CE in the EU. Considering the challenging decarbonization of the industrial sector, and especially the basic material industry, the concept can contribute considerably to tackle decarbonization challenges (European Commission 2019). In addition, CE can reduce the prospective demand for new process technologies and carbon neutral secondary energy carriers. This is relevant for the decarbonization of the energy system considering the limited availability of RES and to reduce overall system costs (International Energy Agency 2019).

As described, the concept of CE has developed throughout the years and is an umbrella for diverse material-related strategies. While the initial idea was based on the transformation from a linear to a circular economy, and hence on the cycling of materials (Boulding 1966), newer concepts also include principles that can be grouped under material efficiency and material substitution (Hertwich et al. 2020). Reflecting this development, the recycling of materials was typically more focused in the industrial sector (Cullen 2017; Herbst 2017). However, alternative strategies are also gaining attention for the decarbonization of the industry (Hertwich et al. 2020; Shanks et al. 2019).

2.2 Circularity for the building value chain

As described in Lotz et al. (2022), material production for buildings contributes greatly to GHG emissions and is the second largest source of emissions across a building’s lifecycle after the use phase. If low-carbon energy is used during the use phase, material production is responsible for the largest share of GHG emissions (Baldassari et al. 2017). The sector is important as it includes the production of vast amounts of energy-intensive and carbon-intensive products such as concrete and steel (Rehfeldt et al. 2020).

The single most important building product is concrete and its precursor products: cement and clinker. The cement industry faces special challenges due to its high process-related emissions, which account for two-thirds of the emissions generated in the production process. Burning cement clinker in rotary kilns releases chemically bound carbon dioxide from the limestone used. These emissions cannot be avoided through conventional actions, such as switching to carbon-neutral energy sources. But they are closely linked to the raw material and process used (Rehfeldt et al. 2020).

Another important basic material used in the building sector is steel. The sector currently consumes around 38% of the steel in Europe (Eurofer 2021). Reducing the demand for steel products can significantly decrease the GHG emissions related to steel production. In addition, substantial quantities of steel scrap are already used in the construction sector today (Rostek et al. 2022).

Steel recycling and scrap availability is likely to become even more relevant because secondary energy carriers, such as electricity and hydrogen, are needed for carbon-neutral steel production. Therefore, an ambitious increase in circularity and material efficiency is considered necessary for an efficient transformation of the energy system that aims to reduce final energy demand, lower the costs for renewable energy sources and grid expansion and decrease the import of secondary energy sources (Fleiter et al. 2019).

However, the use of steel and concrete for buildings differs depending on the construction period, region, and use type (Pezutto 2017). The web tool *TABULA*, for example, provides typologies for differentiation. Currently, these are available for residential buildings and under development for non-residential buildings (Institut Wohnen und Umwelt GmbH 2012-2016). The typologies determine not only future material demand but also secondary material availability from historic age cohorts.

Consequently, the current and future composition of the building stock has a significant impact on CE potentials. While the current stock is partially represented by databases, like the *EU Buildings Database* or the building stock analysis of the project *Hotmaps* (European Commission 2016; Pezutto 2017), there are diverging scenarios for future stock development. These are determined, for instance, by population development, per capita space demand, and assumptions on urbanization. Generally, residential and non-residential floor space demand increases are expected (Camarasa et al. 2022).

Recent studies show that CE actions addressing buildings could significantly reduce GHG emissions in basic materials industries (Circle Economy 2022; Hertwich et al. 2020; Le Den et al. 2020; Lotz et al. 2021; Material Economics 2018). According to Le Den et al. (2020), up to 31 CE actions can affect material use in buildings. When considering the criteria impact[1], applicability[2], feasibility[3], and measurability[4], this list can be condensed as shown in Table 1.

1 Impact: the known potential impact of the action in terms of material demand or GHG emission reduction for a single product or sector-wide, before 2050. Impact takes into account the applicability of the CE action to the sector (e.g. share of product lines, share of material production, etc.).

2 Applicability: the potential for the action to be applied to the sector and its products.

3 Feasibility: the technical/social/economic feasibility of implementing the action in the sector.

4 Measurability: the possibility to measure the potential impact of the action on a sector's emissions, also depending on data availability and the relative need to make assumptions.

Table 1 CE actions affecting material use in buildings (Le Den et al. 2020)

	Considered CE actions
Refuse	Timber instead of (reinforced) concrete in residential buildings Use by-products from industry as substitute for cement Use innovative binders in cement
Rethink	Reducing floor space demand in residential buildings and offices
Reduce	Reducing the over-specification at design stage
Reuse	-
Repair	Simple renovation of existing buildings
Refurbish	Extended renovation of existing buildings
Remanufacture	Reuse of building elements
Repurpose	Reuse of building materials
Recycle	Recycling of cement
Recover	-

The comparison to the 9R framework (see Figure 1, page 10) shows that the actions do not include the strategies R3-Reuse and R9-Recover. Additional literature research showed that the strategy R3-Reuse could be implemented through protecting cultural heritage buildings (Foster et al. 2020). The strategy R9-Recover is excluded from the scope of this report, because it focuses on energy recovery and not material demand reduction.

3. State of research

3.1 Implementation approaches

3.1.1 Methodological approaches

Three methodological approaches are commonly used to model circularity (Corona et al. 2019). An overview of their characteristics is given in Table 2. Especially the material flow analysis (MFA) is considered promising for the combination with energy system modeling (Kullmann et al. 2021).

Table 2 Comparison of methodological approaches

	Input-output analysis	Life cycle assessment	Material flow analysis
Modeling objective	Modeling economic dependencies, extended to environmental and socioeconomic impact	Modeling resource demand and environmental impacts of products or services	Modeling material and energy stocks and flows from a system perspective
Modeling level	International, national (macro level)	Product/service focus (micro level)	Micro, meso and macro level
Modeling scenarios	Mostly used for retrospective modeling due to large number of assumptions for prospective modeling	Indeterminacy of technology and trade patterns	Extrapolating system behavior by stock driven modeling based on trend identification
Modeling CE	Not used for CE modeling because no consideration of specific technologies or system dynamics	Considering specific technologies and thus compliant with CE requirements	Considering specific technologies and system dynamics
References	Corona et al. 2019; Pauliuk et al. 2015; Villalba et al. 2018	Corona et al. 2019; Pauliuk et al. 2017a	Corona et al. 2019; Herbst 2017; Villalba et al. 2018

3.1.2 Existing studies and gaps

Four studies were identified that analyze the GHG emission reduction of a CE in typical basic material use sectors on a macro level (see Table 3). It shows that the studies originate from scientific and non-scientific sources and were published in recent years. This reflects the development of the industrial discourse (see section 2.1). Furthermore, the analyses covered different regions, usually considering a time frame until 2050 or 2060. Important basic material end-uses are (residential) buildings and passenger cars, which are including large quantities of the energy-intensive basic materials steel and/or concrete. In accordance with the methodological approaches shown in section 3.1.1 the dynamic MFA extended with LCA is commonly used. Diverse CE strategies were covered, whereas recycling and material efficiency were focused upon.

Table 3 Comparable studies

	Hertwich et al. 2020	Le Den et al. 2020	International Energy Agency 2019	Material Economics 2018
Time frame	Until 2060	Until 2050	Until 2060	Until 2050
Spatial frame	G7-countries, China, India	EU	Global	EU
Use sector	Residential buildings, passenger cars	Construction	Buildings, passenger cars	Buildings, passenger cars
Methodology	Dynamic MFA combined with LCA	Dynamic MFA combined with LCA	Dynamic MFA combined with LCA	Dynamic MFA
CE strategies	Material efficiency, material substitution, sufficiency, recycling	Material efficiency, material substitution, sufficiency, recycling	Material efficiency, material substitution, recycling	Material efficiency, recycling

When analyzing typical end-use sectors and their prospective material demand, the so-called service-stock-flow nexus is a promising approach. For this, the future demand for a specific service is translated into the required product stock and thus, material flows (Haberl et al. 2017). As described in the introduction, the building value chain is assessed due to the large quantities of basic material use (Rehfeldt et al. 2020). Additionally, buildings are connected to services like comfortable living, education, or working spaces. Thus, various studies on the service-stock-flow nexus of building-related services show a methodological consensus for a stock-driven MFA (Cao et al. 2018; Fishman et al. 2021; Zhong et al. 2021). One of the key input parameters for this type of analysis is the material intensity (MI) of a product, in this case buildings. A community-driven database for this was assembled and published by Heeren et al. (2019).

Research gaps can be identified in studies of the CE impact and analyses of material use in buildings. Both the modeling of material flows and the quantification of the CE impact are challenged by varying data availability and quality (Herbst 2017). Additionally, existing studies often neglect cross-sectoral impacts (Kullmann et al. 2021). A closer look at material use for buildings also reveals gaps for MI, especially for non-residential buildings (Heeren et al. 2019).

3.2 Status quo and implications for improvement

The bottom-up model FORECAST is used within newTRENDs to support strategic decision-making by simulating future energy demand and GHG emissions and assesses industry transformation pathways. The tool aims to model the decarbonization of the industry sector based on techno-economic assumptions. It considers a broad range of GHG mitigation options like energy efficiency or switching to carbon neutral energy carriers and processes (Fleiter et al. 2018).

Future production quantities are a main input for the model. These are determined partly with an inflow-driven MFA based on sectoral Gross Value Added (GVA) development and statistical production and demand data (Herbst 2017). The CE is also taken into account through exogenous assumptions based on literature review or expert interviews (Fleiter et al. 2018). While this already provides a reasonable estimate of CE potentials for industry decarbonization, this approach needs to be further improved.

The modeling of CE potentials can be improved by explicitly considering material flows and stocks along the entire value chain. Currently, FORECAST focuses strongly on the basic material industries. Therefore, it can only provide estimates of the material demand reductions in downstream processes and especially the use phase. Additionally, considering material stocks enables the determination of material outflows from the use phase and thus, the availability of secondary materials. By actually considering the flows and stocks, the impact of a CE can be determined consistently and endogenously.

According to the summarized methodological approaches and the existing studies, the linkage to a stock-driven MFA is the most promising option for implementing this. Moreover, the approach can serve as a soft linkage between building stock and industrial sector. Within the newTRENDs project, the Invert/EE-Lab building model is suitable for this purpose. In addition, the model results can be improved by an expanded data base with respect to MI. Here, the aim is to distinguish between regions, age cohorts and building types. The implementation of both is described in detail in the following chapter.

4. Method and data

The described model development as well as the improvement of the MI database will also be published in a scientific journal. The draft is finalized and will be submitted soon (Lotz et al. NYP).

4.1 Method

The developed approach allows for the first time an integrated view on the development of the building sector through a soft linkage via a prospective MFA of the building (Invert/EE-Lab) and the industry sector (FORECAST) models. Those models are normally run and analyzed separately.

4.1.1 Prospective MFA

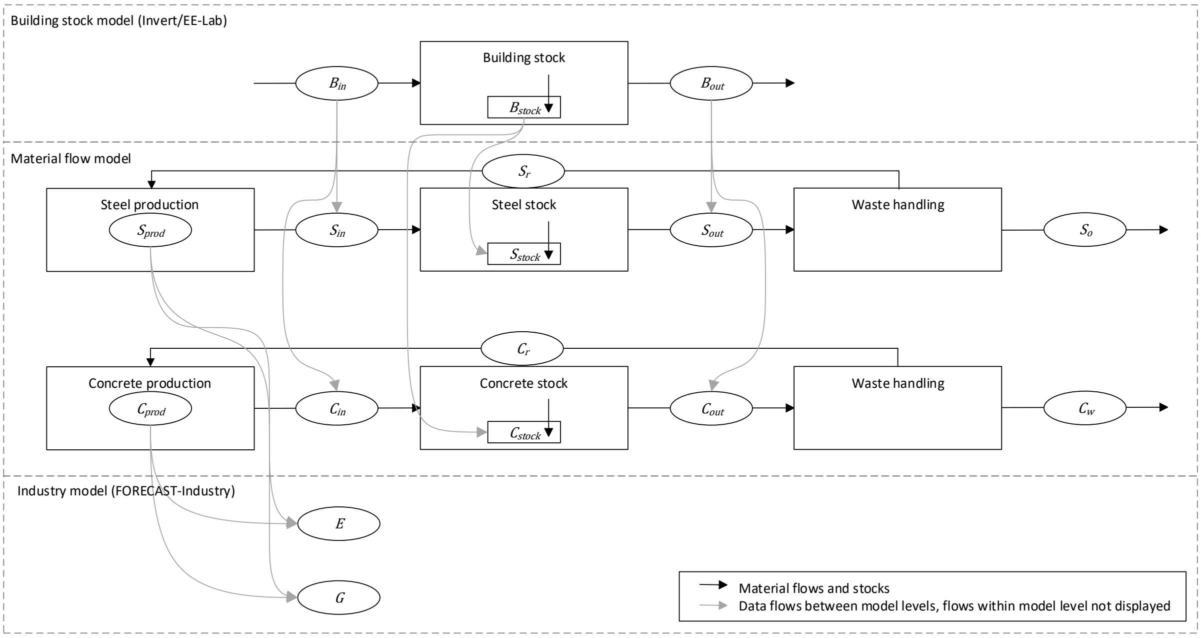
The prospective MFA was developed according to the general structure of a MFA (Pauliuk et al. 2015) and the methodological consensus described in section 3.1.2. The stock drives the prospective extrapolation of the material flow. Thus, three model levels were differentiated:

1. building stocks, inflows and outflows,
2. resulting material stocks, inflows and outflows and
3. resulting energy demand and GHG emissions.

The resulting structure of the model is shown in Figure 2 and is more detailed in the appendix (A.1). The model was implemented using the software framework ODYM published by Pauliuk et al. (2020). The model code will be made available at the end of the project[5]. More information on the model parameters, their specification and source in given in section 4.2.1.

5 H2020-newTRENDs (github.com)

Figure 2 Simplified model structure, source: own representation



Source: newTRENDs - own visualization

The 1st model level

The first model level is carried out within Invert/EE-Lab. The model results provide the construction of new buildings B_{in}, the building stock B_{stock} and the demolition of old buildings B_{out}. Consequently, these are the main drivers for the model results. All three are provided as yearly values for the year t and are distinguished by region r, building type b and age cohort a. This results in:

(1) $B_{in}(t,r,b,a)$
(2) $B_{stock}(t,r,b,a)$
(3) $B_{out}(t,r,b,a)$

Two steps are necessary to translate the building in-/outflow and stock to the material in-/outflows and stocks. The MI is needed in order to calculate the material demand. This parameter describes an estimate of material use per floor area or building volume. Material specific equations are used after the translation of the 1st to the 2nd level. Therefore, these are described in different sections.

The 2nd model level: Modeling the steel production

The MI m_f of a specific steel product f is multiplied by the building in-/outflows and stocks for the calculation of the steel inflow S_{in}, stock S_{stock} and outflow S_{out}. The MI indicates the material use per floor space and thus, does not depend on the year but on the characteristics of the building stock r, b, a and the steel product f. The steel inflow S_{in}, stock S_{stock} and outflow S_{out} are calculated as yearly values distinguished by region r and steel product f. Thus, the following equations are obtained:

(4) $S_{in}(t,r,f) = \sum_{b,a} B_{in}(t,r,b,a) * m_f(r,b,a,f)$
(5) $S_{stock}(t,r,f) = \sum_{b,a} B_{stock}(t,r,b,a) * m_f(r,b,a,f)$
(6) $S_{out}(t,r,f) = \sum_{b,a} B_{out}(t,r,b,a) * m_f(r,b,a,f)$

The production of steel S_p is calculated from the steel inflow S_{in} calculated endogenously and the exogenous parameters for the production losses l_f and the share of the respective production route p_s for a specific steel product f. In contrast to S_{in} the steel production is distinguished by the production process s. Therefore, the following equation result:

(7) $S_p(t,r,s) = \sum_f \frac{S_{in}(t,r,f)}{(1-l_f(t,r,f))} * p_s(t,r,f,s)$

In order to calculate the demand for recycled steel for buildings S_r, exogenous values for the recycled content p_y for each production route is required in addition to the losses during steel production l_s. This results in:

(8) $S_r(t,r,s) = \frac{S_p(t,r,s)}{(1-l_s(t,r,s))} * p_y(t,r,s)$

Steel can be recycled during the production of steel products (new scrap) and during waste management (old scrap). It is assumed that new scrap from buildings is directly recyclced in the same production process. Thus, the use of recycled steel depends on:

- the availability of old scrap determined by the steel outflow from buildings S_{out},
- the availability of new scrap determined by the losses during the production of steel products for buildings l_f and
- the demand for recycled steel for buildings S_r.

Consequently, the proportion of steel not recycled for buildings S_o can be calculated from S_r and the exogenous assumption on losses during the production of steel products l_f.

(9) $S_o(t,r) = \sum_f S_{out}(t,r,f) + \sum_f S_{in}(t,r,f) * l_f(t,r,f) - \sum_s S_r(t,r,s)$

If S_o is:

- larger than 0, then old scrap from buildings is used for other purposes, such as down-cycling for other uses, scrap exports or kept in stock.
- exactly 0, then old scrap from buildings is exclusively used for buildings (re-cycling).
- lower than 0, then old scrap from other uses is used for buildings (down-cycling).

The 2nd model level: Modeling the concrete production

The same approach is used for the calculation of the concrete inflow C_{in}, stock C_{stock} and outflow C_{out}. For this the exogenous MI m_o for the concrete product o is used. So the analogous equations result:

(10) $$C_{in}(t,r,o) = \sum_{b,a} B_{in}(t,r,b,a) * m_o(r,b,a,o)$$
(11) $$C_{stock}(t,r,o) = \sum_{b,a} B_{stock}(t,r,b,a) * m_o(r,b,a,o)$$
(12) $$C_{out}(t,r,o) = \sum_{b,a} B_{out}(t,r,o) * m_o(r,b,a,o)$$

The production of cement C_{ce} is calculated from the concrete inflow C_{in} and the exogenous parameters for the production losses l_o and the share of cement p_m for the production of concrete product o. In contrast to concrete inflow, the cement production is distinguished by the cement type m. Thus, the equation results:

(13) $$C_{ce}(t,r,m) = \sum_o \frac{C_{in}(t,r,o)}{(1-l_o(t,r,o))} * p_m(t,r,o,m)$$

The production of clinker C_{cl} is calculated similarly from the cement production C_{ce} and the exogenous assumptions on production losses l_m and the share of clinker for the cement production p_l. The value is distinguished by the clinker type l.

(14) $$C_{cl}(t,r,l) = \sum_m \frac{C_{ce}(t,r,m)}{(1-l_m(t,r,m))} * p_l(t,r,m,l)$$

Concrete is typically not recycled. Instead, concrete is reused as aggregate during the production of concrete products from cement. This proportion C_r can be calculated from the concrete inflow C_{in}, the losses during concrete production l_o and the recycled content p_x. The latter two are exogenous parameters. Thus results:

(15) $$C_r(t,r,o) = \frac{C_{in}(t,r,o)}{(1-l_o(t,r,o))} * p_x(t,r,o)$$

The proportion of concrete waste C_w can thus be calculated from the concrete outflow and C_r.

(16) $$C_w(t,r) = \sum_o C_{out}(t,r,o) - \sum_o C_r(t,r,o)$$

If C_w is:

- larger than 0, not all concrete waste from buildings is used for the production of concrete.
- exactly 0, all concrete waste is used as aggregate during concrete production for buildings.
- lower than 0 concrete from other sources is used.

The 3rd model level: Energy demand and GHG emissions related to building material inflow

The complete energy demand E_{in} and the total GHG emissions G_{in} of the building value chain result from the energy demand for steel and concrete inflow, $E_{in,s}$ and $E_{in,o}$, and the GHG emissions for the respective material, $G_{in,s}$ and $G_{in,o}$.

(17) $$E_{in}(t,g) = E_{in,s}(t,g) + E_{in,c}(t,g)$$
(18) $$G_{in}(t,g)=G_{in,s}(t,g) + G_{in,c}(t,g)$$

For the steel inflow, exogenous estimates for the specific energy demand e_f and the specific GHG emissions g_f for a steel product f are multiplied with the steel inflow. The specific factors consider energy demand and GHG emissions for all upstream processes covered by the material flow model (see Figure 2, page 18).

(19) $$E_{in,f}(t,r) = \sum_f S_{in}(t,r,f) * e_f(t,r,f)$$
(20) $$G_{in,f}(t,r) = \sum_f S_{in}(t,r,f) * g_f(t,r,f)$$

A similar approach is used for the concrete production based on the specific energy demand e_o and GHG emissions g_o of a concrete product o.

(21) $$E_{in,o}(t,r) = \sum_o C_{in}(t,r,o) * e_o(t,r,o)$$
(22) $$G_{in,o}(t,r) = \sum_o C_{in}(t,r,o) * g_o(t,r,o)$$

The calculation of the energy demand and the GHG emissions allows the calculation of savings related to CE.

The 3rd model level: Interface to bottom-up industrial energy demand and GHG emission modeling

In contrast to the preceding description, for calculating the complete industry sector within FORECAST, the clinker and cement production is required as input. As FORECAST focuses on the basic materials, the production process of concrete is not covered specifically. For this reason, the steel production $S_{p,o}$, the clinker production $C_{cl,o}$ and the cement production $C_{ce,o}$ for the use in other sectors have to be determined exogenously.

The total steel production $S_{p,agg}(t)$ can be calculated from the steel production for buildings $S_{p,b}$ as follows:

(23) $$S_{p,b}(t,r,s) = S_p(t,r,s)$$
(24) $$S_{p,agg}(t,r,s) = S_{p,b}(t,r,s) + S_{p,o}(t,r,s)$$

The same approach is used for clinker $C_{cl,agg}$ and cement $C_{ce,agg}$ based on the clinker production $C_{cl,b}$ and cement production $C_{ce,b}$ for buildings.

(25) $$C_{cl,b}(t,r,l) = C_{cl}(t,r,l)$$
(26) $$C_{cl,agg}(t,r,l) = C_{cl,b}(t,r,l) + C_{cl,o}(t,r,l)$$
(27) $$C_{ce,b}(t,r,m) = C_m(t,r,m)$$
(28) $$C_{ce,agg}(t,r,m) = C_{ce,b}(t,r,m) + C_{ce,o}(t,r,m)$$

The parameters can then be fed into FORECAST to calculate industrial energy demand and GHG emissions (see section 4.1.2).

4.1.2 Linking the models

The developed methodology therefore allows to link two existing bottom-up energy demand models for the building and the industry sector: Invert/EE-Lab and FORECAST. This linkage is established as a stock-driven MFA as described in the previous section (4.1.1).

Invert/EE-Lab

Invert/EE-Lab is a bottom-up model for buildings. It has been used since 2008 for the evaluation of policy and technology-focus scenarios with regard to GHG emissions, energy demand, energy carrier mix and costs. The model provides disaggregated data for the building stock in the EU countries and the United Kingdom. It includes information on age cohorts, building type and building size (Camarasa et al. 2022; Kranzl et al. 2013; Kranzl et al. 2022; Müller 2015; TU Wien et al. 2021).

FORECAST

The FORECAST model aims to develop long-term scenarios for future energy demand of individual European countries until 2050. It is based on a bottom-up modeling approach considering the dynamics of technologies and socio-economic drivers. The model allows to address various research questions related to sectoral energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials, fuel and process switch, CCU/S and their impact on GHG emissions as well as ex-ante policy impact assessments (Fleiter et al. 2018).

4.1.3 Consideration of circular economy

Different CE actions can be represented in the described modeling approach. For this report, eight exemplary actions were selected based on the 9R framework (see section 2.1) and a previous study on the quantification of CE actions (Le Den et al. 2020). These eight actions were identified by matching the 9Rs with the CE actions described by Le Den et al. (2020) (see section 2.2). Where only one action per strategy was available, this action was selected. Further prioritization was only necessary for R0-Refuse and the proposed material substitution. Timber as well as cement substitutes (industry by-products, Celitement or Solidia) can be considered for this. Due to the description of R0-Refuse as "radically different" (Kirchherr et al. 2017), the substitution with timber was selected. Only for one of the Rs, R3-Reuse, no actions were proposed by Le Den et al. (2020). Thus, a literature review on the reuse of buildings was carried out. This resulted in a single proposed action: the protection of cultural heritage buildings (Foster et al. 2020). Additionally, it was decided to combine R4-Repair and R5-Refurbish. R9-Recover is not covered in this report and by the proposed material flow model because it includes exclusively actions focused on energy recovery. An overview of the resulting CE actions is shown in Table 4.

Table 4 CE actions considered in the model

	Considered CE actions (Foster et al. 2020; Le Den et al. 2020)
Refuse	Timber instead of (reinforced) concrete in residential buildings
Rethink	Reducing floor space demand in residential buildings and offices
Reduce	Reducing the over-specification of elements by volume
Reuse	Protection of cultural heritage buildings
Repair Refurbish	Renovation of existing buildings
Remanufacture	Reuse of building elements
Repurpose	Reuse of building materials
Recycle	Recycling of cement
Recover	Out of scope

The implementation in the model is highly dependent on the respective CE action. Table 5 shows these actions in detail for each of the eight measures. Each of them is modeled individually to compare their impacts. In addition, three sets of actions are compared.

Table 5 Considerations of CE actions in the model

	Model mechanism	Model implementation
Refuse	Change in model input parameter MI	m_f and m_o
Rethink	Change in model input parameter building stock (less inflow)	B_{in} and B_{stock}
Reduce	Change in model input parameter, MI	m_f and m_o
Reuse	Change in model input parameter building stock (less outflow)	B_{in}, B_{stock} and B_{out}
Repair Refurbish	Change in model input parameter building stock (less outflow)	B_{in}, B_{stock} and B_{out}

	Model mechanism	Model implementation
Remanufacture	Additional flow from end-of-life to use phase	$S_{el,re}(t,r,f) = S_{out}(t,r,f) * p_{el,re}(t,r,f)$ $S_{in*}(t,r,f) = S_{in}(t,r,f) - S_{el,re}(t,r,f)$ $C_{el,re}(t,r,o) = C_{out}(t,r,o) * p_{el,re}(t,r,o)$ $C_{in*}(t,r,o) = C_{in}(t,r,o) - C_{el,re}(t,r,o)$
Repurpose	Additional flow from end-of-life to use phase	$S_{re}(t,r,f) = S_{out}(t,r,f) * p_{re}(t,r,f)$ $S_{in*}(t,r,f) = S_{in}(t,r,f) - S_{re}(t,r,f)$
Recycle	Additional flow from end-of-life to production	$C_{re}(t,r,m) = \sum_{o} \frac{C_{out}(t,r,o) * p_m(t,r,o,m)}{(1 - l_o(t,r,o))} * p_{re}(t,r,m)$ $C_{ce*}(t,r,m) = C_{ce}(t,r,m) - C_{re}(t,r,m)$
Recover	Out of scope	-

For the definition of the three sets, the measures were grouped as shown in Table 6. A rough distinction is made between measures that are mainly attributable to a change in lifestyle or to a change in construction. Two of the action sets focus upon one of the categories each ("Lifestyle" or "Construction"). The third set is a moderate combination hereof ("Mix"). The order of implementation is determined by the 9R framework (see Figure 1, page 10).

Table 6 Categorization of the considered CE actions

Actions addressing lifestyle	Actions addressing construction
Timber construction	Reduced over-specification
Reduced floor space	Reuse of building elements
Reuse of cultural heritage	Reuse of steel
Renovation of buildings	Cement recycling

4.2 Data

4.2.1 Exogenous model parameter

Several exogenous input parameters are needed for the model described in the preceding chapter (see Table 7).

Table 7 Exogenous model parameters

No.	Parameter type	Symbol	Distinguished by	Model level
1	Material intensity	m_f	g: region b: building type a: age cohort s: steel product	2
2	Material intensity	m_o	g: region b: building type a: age cohort c: concrete product	2
3	Production losses	l_f	t: year g: region s: steel product	2
4	Production share	p_s	t: year g: region s: steel product p: production process	2
5	Production losses	l_s	t: year g: region p: production process	2
6	Recycling share	p_y	t: year g: region p: production process	2
7	Production losses	l_o	t: year g: region c: concrete product	2
8	Production share	p_m	t: year g: region c: concrete product ce: cement type	2

No.	Parameter type	Symbol	Distinguished by	Model level
9	Production losses	l_m	t: year g: region ce: cement type	2
10	Production share	p_l	t: year g: region ce: cement type cl: clinker type	2
11	Recycling share	p_x	t: year g: region c: concrete product	2
12	Specific energy demand	e_f	t: year g: region s: steel product	3
13	Specific GHG emissions	g_f	t: year g: region s: steel product	3
14	Specific energy demand	e_o	t: year g: region c: concrete product	3
15	Specific GHG emissions	g_o	t: year g: region c: concrete product	3
16	Production	$S_{p,o}$	t: year g: region p: production process	3
17	Production	$C_{cl,o}$	t: year g: region cl: clinker type	3
18	Production	$C_{ce,o}$	t: year g: region ce: cement type	3

In addition, the distinguishing factors are specified as shown in Table 8. These are defined according to the data availability and the structure of Invert/EE-Lab and FORECAST-Industry.

Table 8 Specification of the distinguishing factors

	Specification
Year	2020-2050 (one-year steps)
Region	Southern Europe/ warm (Malta, Cyprus, Portugal, Greece, Spain, Italy, France) Central Europe/ moderate (Slovenia, Hungary, Romania, Bulgaria, Ireland, Netherlands, Belgium, Luxembourg, United Kingdom, Slovakia, Germany, Austria, Czech Republic, Poland, Denmark, Croatia) Northern Europe/ cold (Lithuania, Latvia, Estonia, Sweden, Finland)
Building type	Single-family house (SFH) Multi-family house (MFH) Industry (Ind) Retail and warehouses (Ret) Offices (Off) Hotels and restaurants (Hot) Education (Edu) Health (Hea) Other (Oth)
Age cohort	>1945 1945-1969 1970-1989 1990-2010 2010<
Steel type	BF/BOF steel Scrap/EAF steel DRI/EAF steel

	Specification
Steel product	Concrete reinforcing bars Hot rolled bars Wire rod Railway track material Heavy sections Light sections Seamless tubes Hot rolled plate Hot rolled coil, sheet and strip Electrical sheet and strip Tinmill products Other metal coated sheet and strip Non-metallic coated sheet and strip Welded tubes Liquid steel
Clinker type	Clinker
Cement type	Cement
Concrete product	Transport concrete Precast concrete Transport concrete (reinforced) Precast concrete (reinforced)

An overview of the main sources for the exogenous model parameters is shown in Table 9.

Table 9 Main sources for the exogenous model parameters

	Source
Material intensity	Residential building archetypes as described in Nemry et al. 2008, non-residential building archetypes derived from case studies (see also section 4.2.2)
Production losses	Cullen et al. 2012; Rehfeldt et al. 2020; Personal communication with the BTB[6], FDB[7] and HeidelbergCement[8]

6 Bundesverband der Deutschen Transportbetonindustrie e.V. (German association for transport concrete)
7 Fachvereinigung Deutscher Betonfertigteilbau e.V. (German association for precast concrete)
8 German cement producer

	Source
Production share	Rehfeldt et al. 2020; Verein Deutscher Eisenhüttenleute 2015; Personal communication with the BTB, FDB and Cembureau
Recycling share	Rehfeldt et al. 2020; World Steel Association 2022; Personal communication with HeidelbergCement
Specific energy demand	FORECAST; Lotz et al. 2021; Rehfeldt et al. 2020
Specific GHG emissions	FORECAST; Lotz et al. 2021; Rehfeldt et al. 2020
Production	FORECAST;ODYSSEE-MURE 2022; World Steel Association 2022

4.2.2 Approach and data basis for improved MI

MI indicates the material use per unit product. In case of buildings, this is typically indicated as weight per area or per volume (Heeren et al. 2019). This parameter can be defined bottom-up. This requires the volume and material of the building components, as well as the floor space of a representative building. These building representatives or archetypes can be determined via different approaches. For instance, real buildings can be used as samples. Alternatively, synthetically average buildings can be defined. Moreover, combinations hereof are possible (Bischof et al. 2022).

In the following, the latter, the so-called multiple archetype approach, was used to determine material intensities for buildings in the EU and the United Kingdom (Bischof et al. 2022). For this purpose, archetypes were defined according to the distinguishing characteristics summarized in Table 8. These characteristics were determined by the data availability of the sources described in the following. Moreover, an essential specification was that the definition of floor space had to comply with Invert/EE-Lab.

Residential buildings

According to the MI database published by Heeren et al. (2019) and an additional literature research, the residential building archetypes published by Nemry et al. (2008) cover the highest diversity of age cohorts and regions within the EU. The source specifies the material use for various building components: roof, exterior walls, interior walls, floors and ceilings, the basement and foundation as well as windows. The latter is not considered in this report. The differentiation of regions, age cohorts, and components is necessary to take account of temporal and regional differences, such as climatic conditions. However, the age cohorts of these archetypes do not match completely with the age cohorts defined as distinguishing characteristics based on the interface to Invert/EE-Lab (Nemry et al. 2008; TU Wien et al. 2021). Thus, matching the retrospective archetypes for the different age cohorts was necessary. Additionally, two building types, multi-family house and high-rise building (HR), had to be aggregated. Partly this resulted in more than one archetype per age cohort and region. Thus, averages were determined by weighing the material use analogous to the building stock proportion also published by Nemry et al. (2008). An overview of this matching is shown in the appendix 7.A.2.

Non-residential buildings

Building archetypes for non-residential buildings were derived based on the residential buildings and case studies for non-residential buildings. Again, the case studies were selected from the MI database published by Heeren et al. (2019). Additionally, the meta analysis of Bischof et al. (2022) was consulted. On the one hand, the case studies were selected due to their geographical consistency. This means that only case studies from the EU were considered and assigned to the regions mentioned in Table 8 on page 27. Furthermore, it was assessed whether the case studies were consistent among each other. Only those that were not contradictory were taken into account. The selected case studies were merged with the residential archetypes by comparing the building materials, characteristics[9] and typical building components[10]. In general, the residential archetypes were used for the building components, while the case studies were used for the building materials and characteristics. Due to limited data availability, it was assumed that the archetypes for hotels and restaurants, education, and health complied with the building archetype for offices. The available case studies confirmed this, but not enough information on building characteristics is available. To maximize accuracy, the last archetype for other buildings was determined as the average of the other buildings. An overview of the considered case studies and residential archetypes is given in the appendixes 7.A.3 and 7.A.4.

The resulting MI used in the material flow model is also shown in the appendix 7.A.5. Additionally, the MI for exemplary residential archetypes is displayed in Figure 3, showing differences between age cohorts and regions. This overview also includes the MI for materials that are currently not considered in the material flow model since it focuses on the energy-intensive basic materials steel and concrete.

Comparing the age cohorts, it becomes clear that brick was the primary building material for single-family houses (SFH) before 1945. In Southern Europe limestone and fieldstone were used additionally. However, from 1945 these were replaced by concrete and reinforced concrete used in the basement and

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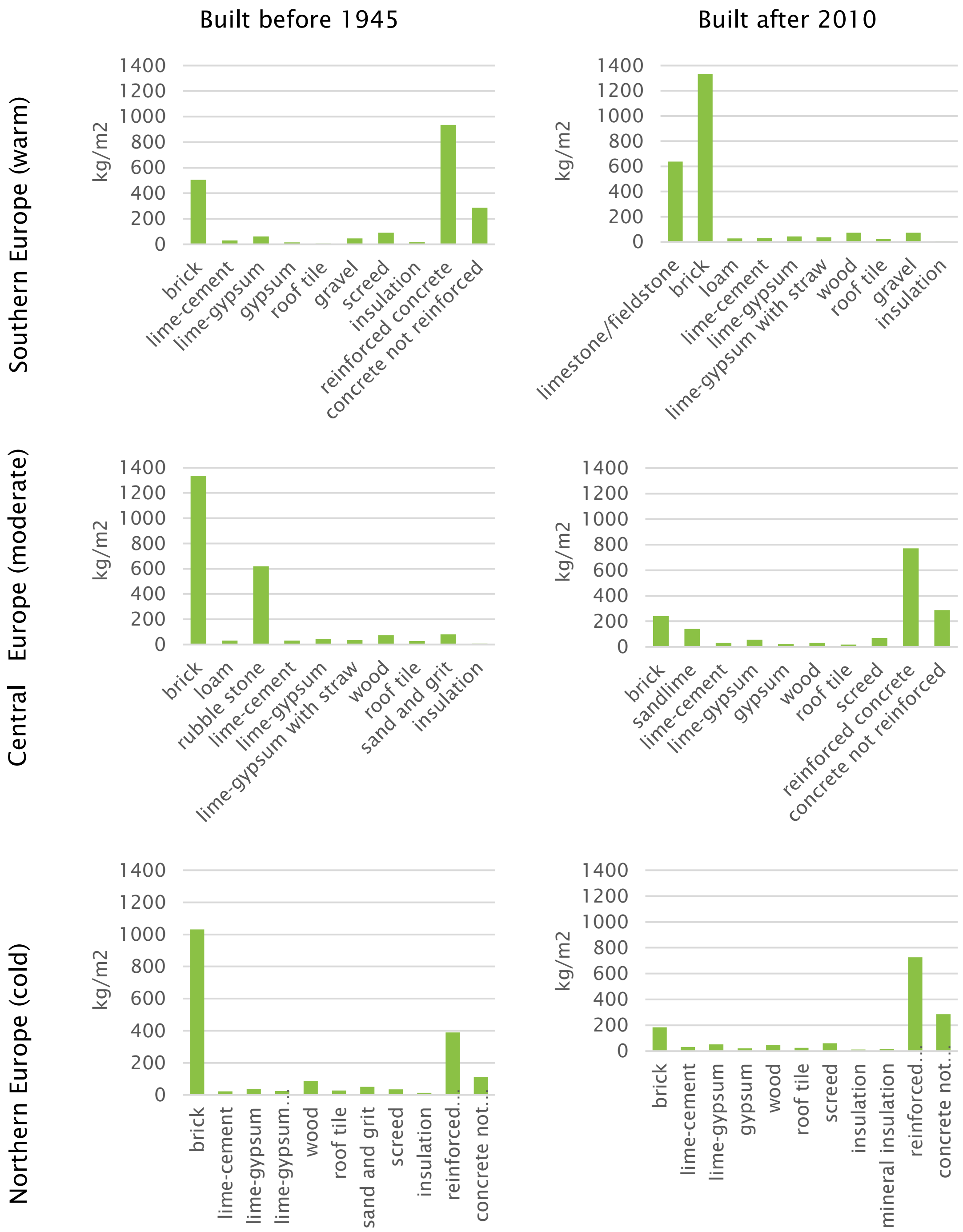
9 Considered buildings characteristics were floor area, number of floors, building height, building width and building length.

10 Considered building components were roof, exterior walls, interior load-bearing walls, interior walls, floor structure, basement and foundation. Consequently, windows, doors, floor coverings and staircases were not considered.

foundations. Thus, the different regions resemble each other in their construction methods. While there is initially less material use in all regions after the change from brick to concrete, the time courses differ. In Southern Europe the MI increases, while in Central and Northern Europe the MI peak in the cohort from 1970 to 1989 and decreases afterwards (see appendix A.5). Additionally, it becomes clear that the MI is highest in Southern Europe for SFH. While the difference between Southern and Central Europe in the pre-1945 cohort is still very low, it becomes more pronounced over time. This is caused by an increasing share of wooden construction in Central Europe, which is not implemented in Southern Europe. Consequently, the difference is less prevalent for multi-family houses (MFH), where no wooden constructions are used in Central Europe. Overall, the least material per square meter is used for SFH and MFH in Northern Europe. Here, insulation material is also used earlier than in the other regions. In addition, timber construction plays a more significant role since approximately half of single- and multi-family houses rely on timber for aboveground construction. In summary, this comparison shows that the chosen approach enabled the consideration of geographical and spatial differences in the EU building stock.

Figure 3 MI of the ten materials with the highest mass share for SFH in the EU



Source: newTRENDs - own calculation based on Nemry et al. (2008)

4.2.3 Parametrization of CE actions

The CE actions were parametrized according to the modeling approach described in section 4.1.3. Again the previous study published by Le Den et al. (2020) as well as additional literature research were considered for the parametrization. Since the parametrization differs according to the model implementation, this is shown separately for each CE action. In addition, the parametrization of the action sets is summarized. The parametrization shown below might be updated or adapted within the newTRENDs project depending on the respective scenario.

Refuse: Timber instead of (reinforced) concrete in residential buildings

According to Le Den et al. (2020) timber can be used to replace building materials. As described in section 4.1.3, this is considered via an changing MI. The initial archetypes from Nemry et al. (2008) were used for the parametrization of the MI, considering an increasing share of wooden construction in residential buildings. Based on this, it could be concluded that wooden construction is only used in buildings less than three stories above ground (Nemry et al. 2008). Therefore, this was only considered for SFH. It is assumed that the maximum potential of wooden construction in SFH for each region is 100%. For the modeling as individual action the share of wooden construction is increased continuously in ten-year steps as shown below. This does not consider limitations due to the amount of wood that is sustainably available.

Table 10 Share of wooden construction in SFH

	2021-2030	2031-2040	2041-2050
Southern Europe (warm)	0%	50%	100%
Central Europe (moderate)	33%	66%	100%
Northern Europe (cold)	50%	75%	100%

Rethink: Reducing floor space demand in residential buildings and offices

It is possible to optimize the floor space use in residential and in office buildings and thus, reduce the demand for new buildings. Estimates from Le Den et al. (2020) were used to recalculate the building stock development due to reduced floor space demand in residential buildings and offices. Accordingly, the maximum inflow reduction for offices is 36% and for residential buildings 11%. For the modeling as individual action, it is assumed that the inflow reduction is increased linearly from 0% to the respective maximum until 2050.

Reduce: Reducing the over-specification of elements by volume

The demand of structural steel and concrete can be reduced by reducing the over-specification of elements by volume (Le Den et al. 2020). For the parametrization of the reduced over-specification, it is again referred to Le Den et al. (2020). According to this study, the material use can be decreased by 12%

for concrete and 41% for steel. The value is increased continuously in ten-year steps as shown below.

Table 11 Reduction of material demand due to reduced over-specification

	2021-2030	2031-2040	2041-2050
Concrete	0%	6%	12%
Steel	0%	20.5%	41%

Reuse: Protection of cultural heritage buildings

Protecting cultural heritage buildings can lead to the reuse of buildings that would have been demolished otherwise (Foster et al. 2020). Huuhka et al. (2016) analyzed reasons for demolishing buildings in Finland. They found that about 43.8% of buildings built before 1950 were demolished because of new construction and abandonment, which we assume can be regarded as avoidable reasons. This value was used as maximum value for the outflow of the oldest age cohort in the material flow model. The value was increased in ten-year steps as shown below.

Table 12 Reduced outflow due to cultural heritage protection

	2021-2030	2031-2040	2041-2050
Reduced outflow	0%	21.9%	43.8%

Repair and Refurbish: Renovation of existing buildings

Similar to the protection of cultural heritage buildings, the renovation of existing buildings can contribute to keep buildings in the stock (Le Den et al. 2020). According to a study from METABOLIC (2022), around 30% of demolition is due to failing technical requirements, suggesting that this share of building outflow can actually be avoided through renovation. This value was used as maximum value for the outflow of all age cohorts in the material flow model. The value was increased in ten-year steps as shown below. This does not consider the limited supply of renovation, due to e. g, labor market constraints.

Table 13 Reduced outflow due to renovation of existing buildings

	2021-2030	2031-2040	2041-2050
Reduced outflow	0%	15%	30%

Remanufacture: Reuse of building elements

It is possible to reuse pre-fabricated building elements after their first lifetime ends. This is supported by designing those elements for disassembly (Le Den et al. 2020). Asam (2008) indicates that about 38% of building elements can be reused based on an assessment in Germany. This value was used as maximum value for the new introduced flow from waste handling to use phase. It does only affect pre-fabricated building elements. The value was increased in ten-year steps as shown below.

Table 14 Reuse-share for building elements

	2021-2030	2031-2040	2041-2050
Reuse-share	0%	19%	38%

Repurpose: Reuse of building materials

Similar to the reuse of building elements, structural steel can be reused after their first lifetime (Le Den et al. 2020). According to Durmisevic et al. (2003), around 14% of steel is reused directly. This value is assumed to increase slightly until 20% and determines the size of the flow from waste handling to the use phase. This estimation is based on a theoretical reuse potential of 10% to 75% and process losses between 61% and 91% (Cooper et al. 2012; Girao Coelho et al. 2020). It only affects the steel flow. The value was increased in ten-year steps as shown below.

Table 15 Reuse-share for structural steel

	2021-2030	2031-2040	2041-2050
Reuse-share	0%	3%	6%

Recycle: Recycling of cement

In addition to the reuse of materials, recycling is also possible. This is already being implemented for steel. In addition, there is also an innovative technology for cement available, the SmartCrusher (Le Den et al. 2020). It has a recovery efficiency of a maximum of 50% (Rutte Groep 2019). This means half of the cement in the waste flow is lost during recycling. Additionally, the technology is very new. Therefore, we assume a maximum share of 20%, although theoretically all cement could be recycled from the concrete outflow. The value was increased in ten-year steps as shown below.

Table 16 Recycling-share for cement (losses not included)

	2021-2030	2031-2040	2041-2050
Recycling-share	0%	10%	20%

Action sets

The same values for the individual actions are used for the two action sets "Lifestyle" and "Construction". These are assumed to be the maximum values. For the third set less ambitious values are considered. Thus, on the one hand, the actual potentials and, on the other hand, a more realistic case is analyzed. The parametrization of the third set "Mix" is shown below.

Table 17 Parametrization of the action set "Mix"

	2021-2030	2031-2040	2041-2050
Refuse (Share of wooden construction in SFH)	Warm: 0% Moderate: 25% Cold: 50%	Warm: 25% Moderate: 37.5% Cold: 50%	Warm: 50% Moderate: 50% Cold: 50%
Rethink (Linear increase of inflow)	Offices: up to 18% Residential buildings: up to 5.5%		
Reduce (Reduction of demand)	Concrete: 0% Steel: 0%	Concrete: 3% Steel: 10.3%	Concrete: 6% Steel: 20.5%
Reuse (Reduction of outflow)	0%	11%	21.9%
Repair /Refurbish (Reduction of outflow)	0%	7.5%	15%
Remanufacture (Reuse-share)	0%	9.5%	19%
Repurpose (Reuse-share)	0%	1.5%	3%
Recycle (Recycling-share)	0%	5%	10%

5. Results

In order to show the functionality and the limitations of the developed model approach and the improved MI data basis, exemplary results are presented in the following chapter. The chapter is divided into a reference calculation without CE and a calculation of the potential impact of a CE. It is focused upon the results of the material flow model in terms of material demand because this is the main model improvement implemented within Work Package 6 of the newTRENDs-project[11].

5.1 Framework data

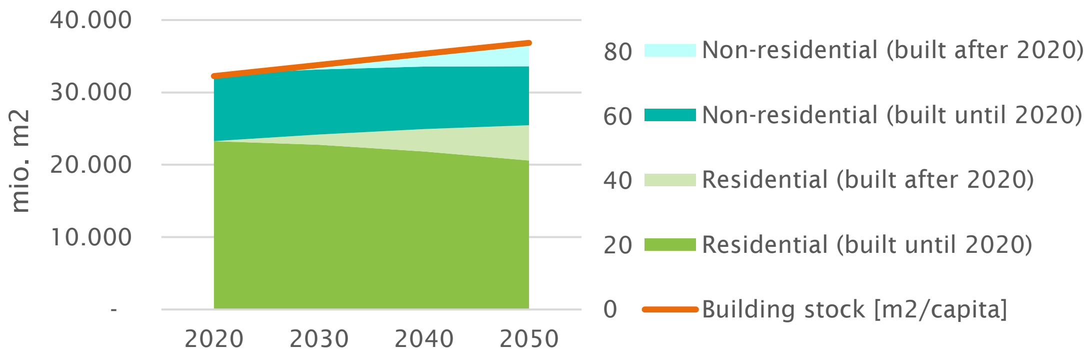
The reference calculation is based on the reference building stock development provided by Invert/EE-Lab. This development has been based on the EU Reference scenario 2020 published by the European Commission (European Commission 2021a). Since the scenario under consideration represents a reference development, no further efforts are considered to decarbonize buildings or industry. However, such scenarios are planned and will be implemented as part of Work Package 3 in the newTRENDs-project[12].

Corresponding with the service-stock-flow nexus (Haberl et al. 2017), the material flow model calculates material inflows from required stocks, which in turn are determined by service demand. Consequently, the building stock has a significant impact on the modeling results. In the present case, the service demand for e.g. comfortable living, education, or workspaces is provided by Invert/EE-Lab as a reference development of the building stock (see Figure 4). Both the total floor space demand and the per capita space demand increase over time. Overall, residential buildings have a higher share than non-residential buildings. Nevertheless, the share of non-residential is increasing slightly over time. The number of buildings built before 2020 is decreasing until 2050. Consequently, the number of new constructions increases over time. It is clear that most of the building stock exists at the beginning of the modeling period. In addition, more buildings are constructed than demolished.

[11] Work Package 6: Circular economy and digitalization in energy demand models related to the sectors industry and tertiary

[12] Work Package 3: Transition Pathways for New Societal Trends and Methodological Improvement in Modeling such Trends

Figure 4 Building stock development (total and per-capita)



Source: Invert/EE-Lab

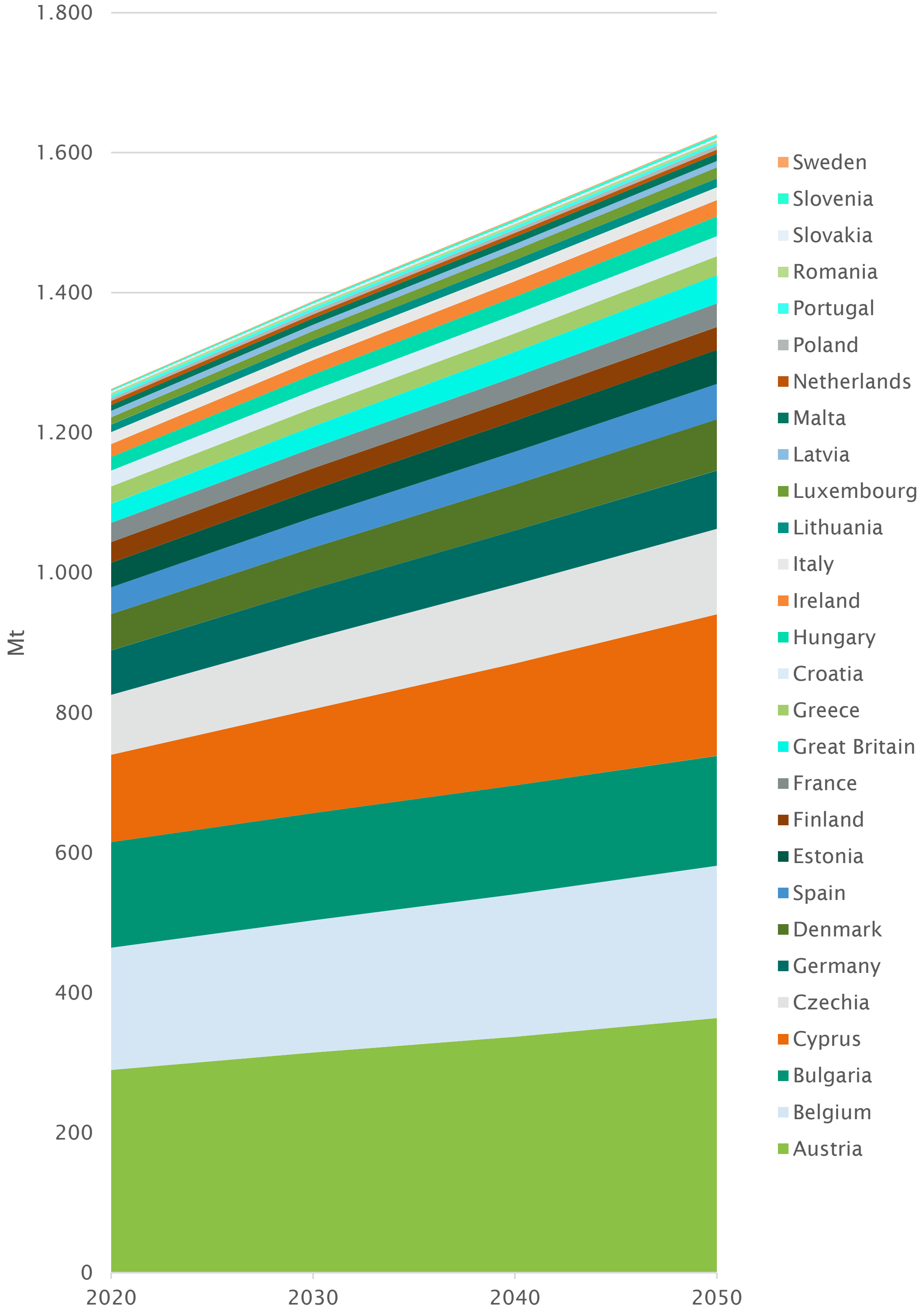
5.2 Reference calculation

The reference calculation will also be published in a scientific journal. The draft is finalized and will be submitted soon (Lotz et al. NYP).

5.2.1 Material stock

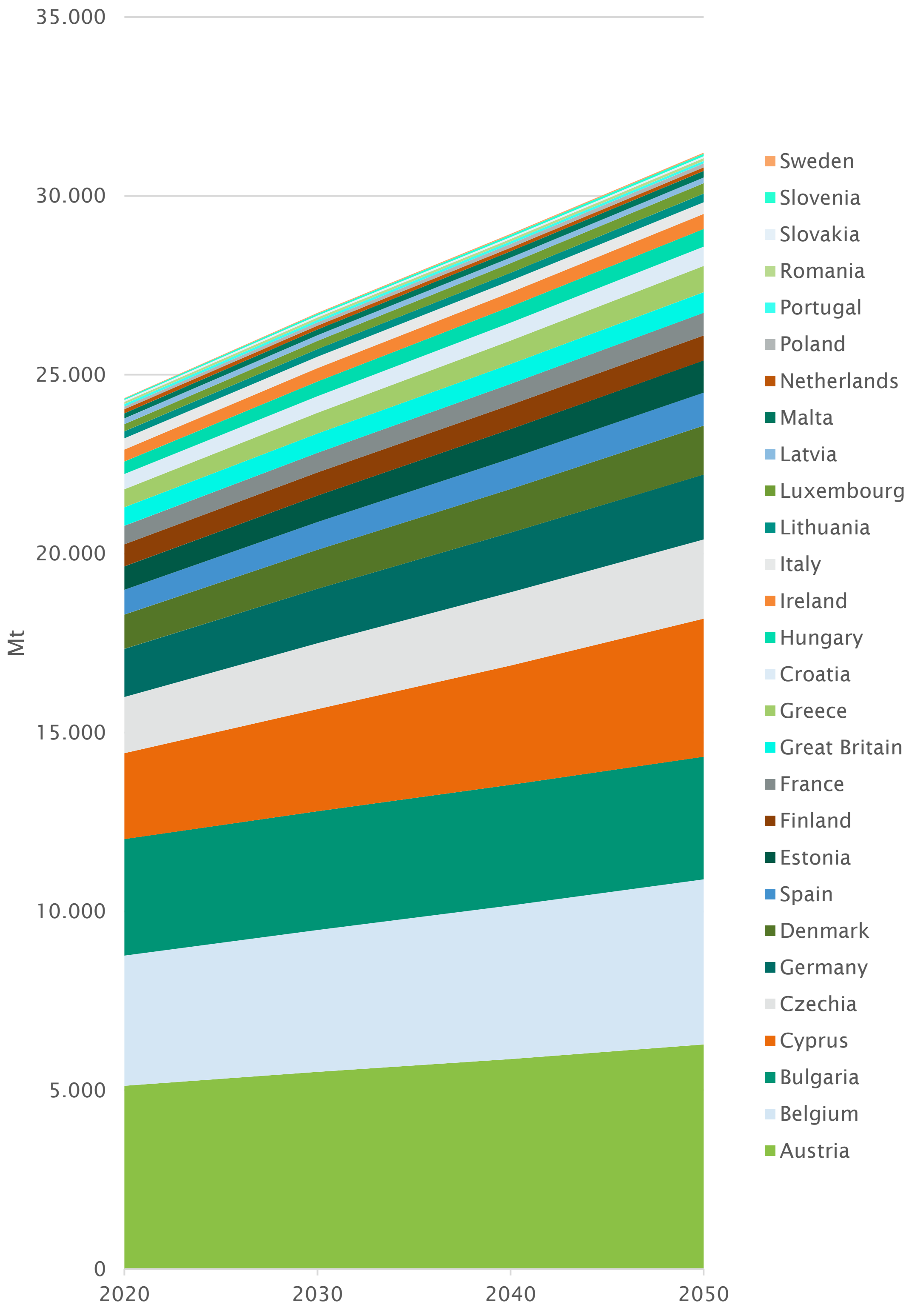
In line with the building stock development, both the steel and the concrete stock are increasing over time (see Figure 5 and Figure 6). In line with the MI, the material stock in Southern and Central Europe is higher than in Northern Europe. Compared to the development of floor space, Southern Europe has a disproportionate share due to the high MI for SFH.

Figure 5 Steel stock in EU buildings differentiated by country



Source: newTRENDs - own calculation

Figure 6 Concrete stock in EU buildings differentiated by country

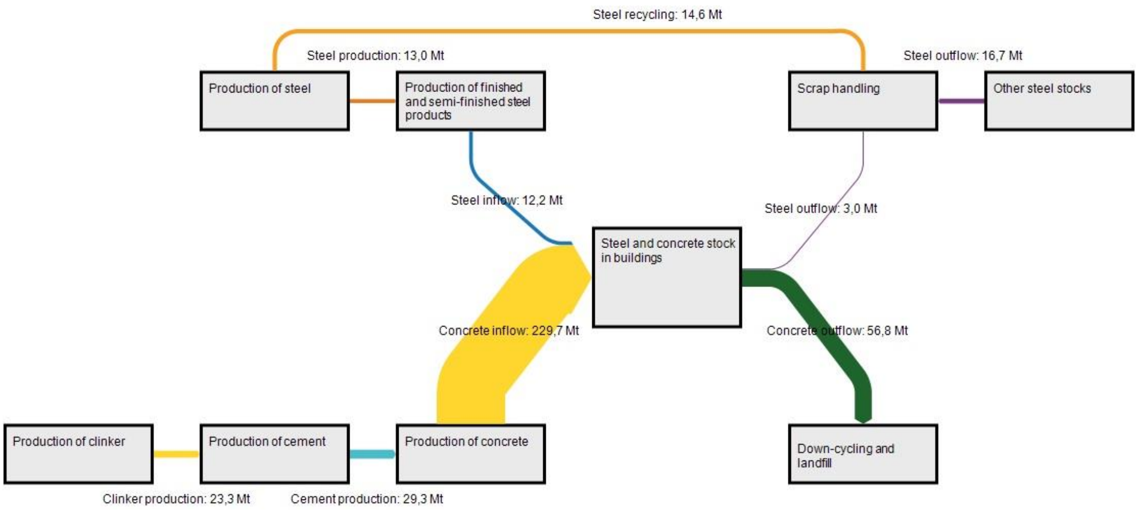


Source: newTRENDS - own calculation

5.2.2 Material flows

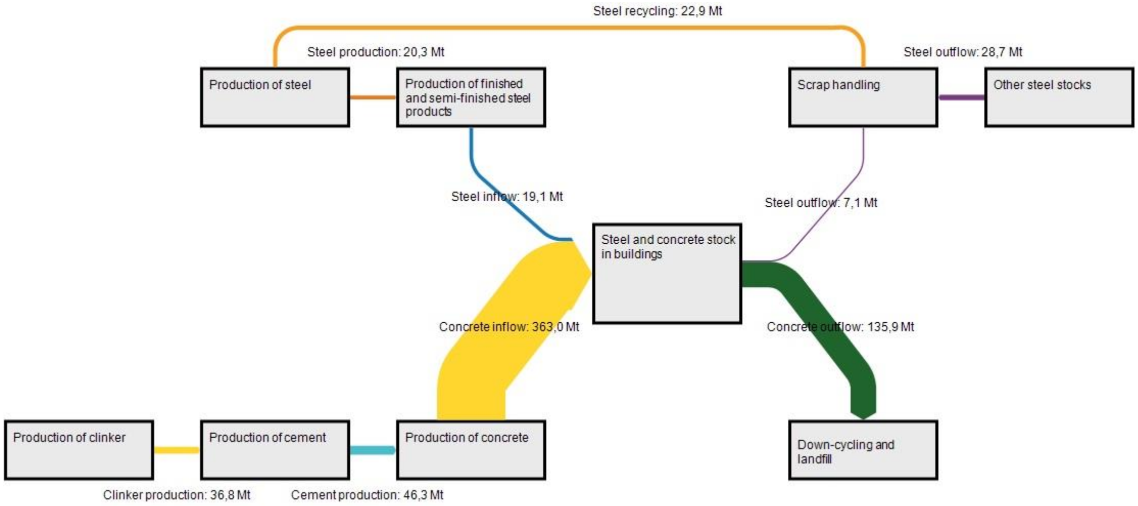
When comparing the steel and concrete flows in 2020 (Figure 7) with 2050 (Figure 8), it is evident that these are also increasing corresponding to the stock development. In general, the material outflow is lower than the inflow. On the one hand, this is caused by the higher level of new construction compared with the demolition. On the other hand, the MI of steel and concrete is lower in the older age cohorts. The increasing inflow of steel in EU buildings, leads also to an increase of steel production from about 12 Mt in 2020 to about 19 Mt in 2050 (+58%). According to the building archetypes, only secondary steel is used. The inflow of concrete for buildings also requires increasing production of concrete, cement and clinker (+58%). The concrete production increases from about 230 Mt in 2020 to 363 Mt in 2050. The cement production rises from 29 Mt to 46 Mt and the clinker production from 23 Mt to 37 Mt.

Figure 7 Steel and concrete flow related to EU building in 2020



Source: newTRENDs - own calculation

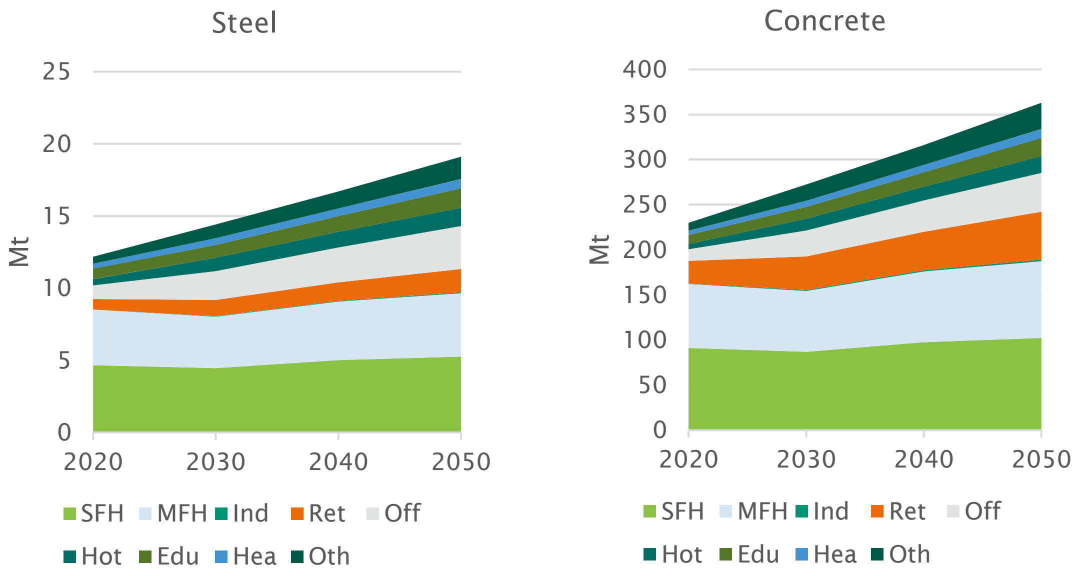
Figure 8 Steel and concrete flows related to EU buildings in 2050



Source: newTRENDs - own calculation

In addition to the aggregated results shown, it is possible to differentiate between building types, as shown in Figure 9. The total material stock is higher in residential buildings than in non-residential buildings since only about 30% of the floor space can be allocated to non-residential buildings. Considering this, it becomes clear that a disproportionate high share of the material stock is allocated to non-residential buildings (about 48% in 2050). This is caused by the higher MI for non-residential buildings (see appendix 7.A.5). These are caused by construction characteristics such as high ceilings, large floor areas or lower number of floors - especially for industry and retail buildings.

Figure 9 Steel and concrete inflow related to EU buildings by building type



Source: newTRENDs - own calculation

5.3 Impact of selected circularity actions

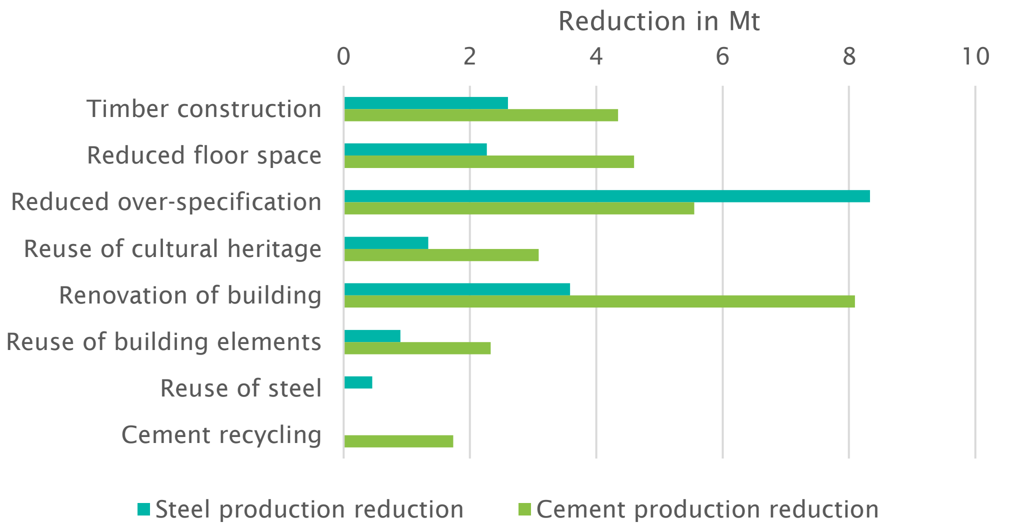
The impact of the selected CE actions can be calculated based on the reference calculation presented before. This will be done initially for the individual CE actions and afterwards for the three defined sets of actions ("Changing lifestyle", "Changing construction" and "Mix").

5.3.1 Individual actions

According to the parametrization, the impact of the selected CE actions on steel and cement production is shown in Figure 10. In contrast to the preceding representations of the material stock and inflow, the material production is presented because some of the actions do have upstream impacts. Also, this is the parameter, which will then be used as input in FORECAST.

The two measures with the highest material demand reduction are the reduced over-specification (R2-Reduce) and the renovation of buildings (R4/R5 - Repair/Refurbish). These are followed by timber construction (R0-Rethink) and reduced floor space (R1-Refuse). The lowest impact can be allocated to reusing steel (R7-Repurpose) and cement recycling (R8-Recycling) as these only affect either steel or concrete. It is noteworthy that despite some exceptions, the underlying structure of the 9R is recognizable. Thus, measures with a low R tend to have a higher impact and vice versa.

Figure 10 Steel and cement production reduction for individual CE actions



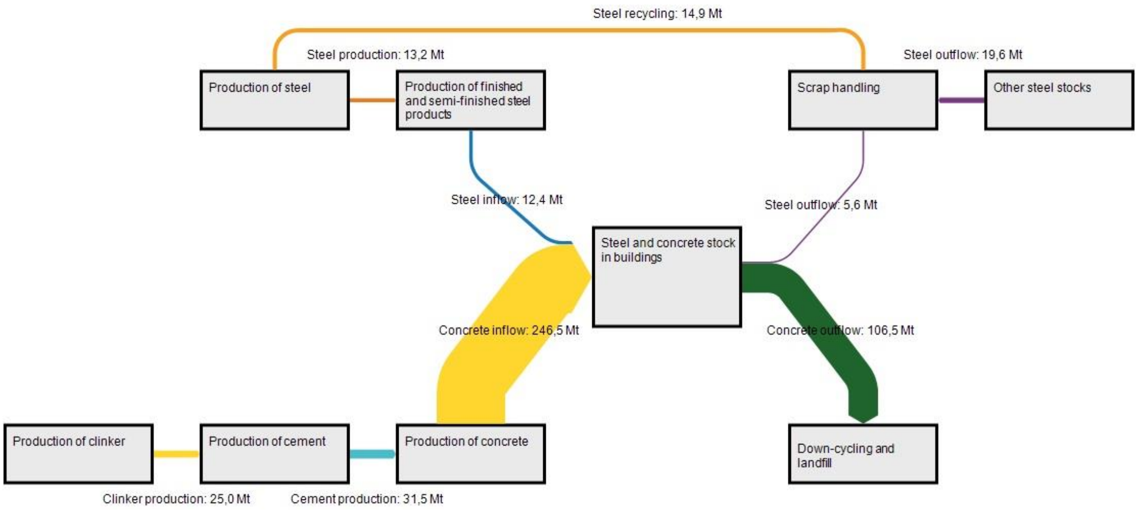
Source: newTRENDs - own calculation

5.3.2 Sets of actions

In addition, three sets of actions were modeled to assess the impact of the implementation order and the interactions of the measures. The first two sets, "Lifestyle" and "Construction", are parametrized identically to the individual actions. The results for "Lifestyle" are shown in Figure 11, and for "Construction" in Figure 12.

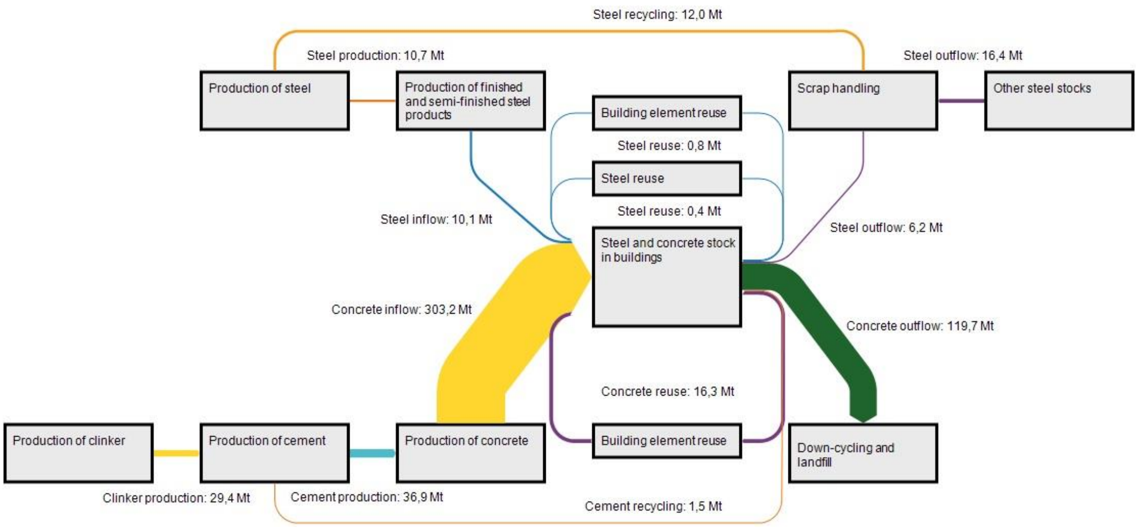
First, there is a visible difference between the representations. While "Lifestyle" follows the same modeling structure as the reference calculation, for "Construction", additional material flows for reuse and recycling have to be considered in the model. Additionally, it is shown that the CE actions addressing lifestyle have a higher impact on concrete demand than those addressing steel demand. In contrast, the actions addressing construction lead to a stronger reduction in the steel inflow. However, the "Lifestyle"-actions seem to have a larger potential when considering the total demand reduction.

Figure 11 "Lifestyle": Steel and concrete flows related to EU buildings in 2050



Source: newTRENDs - own calculation

Figure 12 "Construction": Steel and concrete flows related to EU buildings in 2050



Source: newTRENDs - own calculation

Since these sets are parametrized identically to the individual actions, comparing the cumulated impact is interesting to assess the relevance of interactions. This is shown in Table 18. It becomes clear that the interaction of measures addressing lifestyle reduces the impact more than the measures addressing construction. In fact, the impact of this set is only slightly lower than the individual actions. This may be caused by buildings having a long lifetime, and the available material outflow for reuse and recycling is not significantly reduced until after the model period due to reduced over-specification.

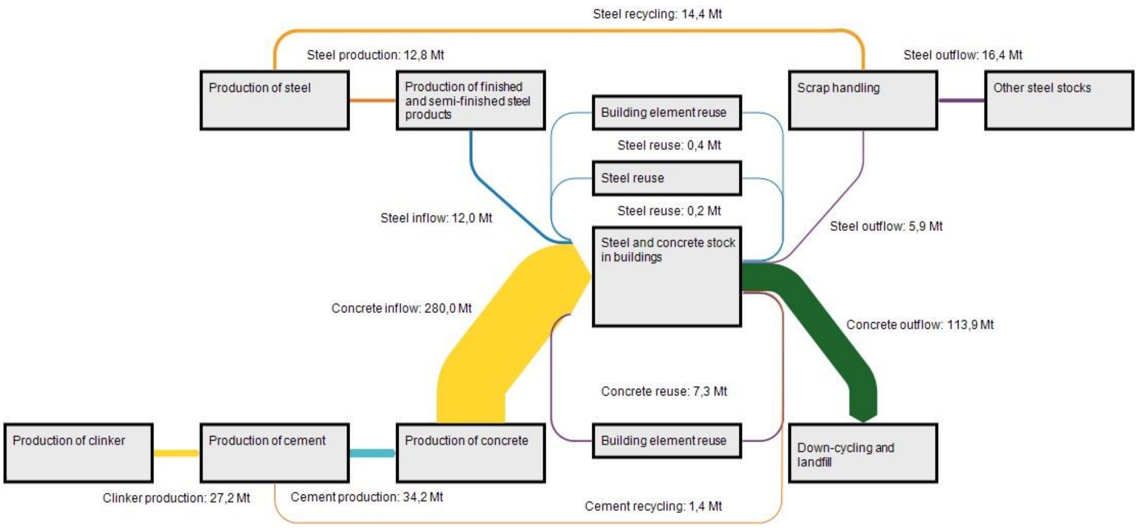
Table 18 Comparison of individual actions and action sets

	"Lifestyle" (Individual actions/set)	"Construction" (Individual actions/set)
Steel production reduction in Mt	9.8/7.1	9.7/9.6
Concrete production reduction in Mt	20.1/14.8	9.6/9.4

Source: own calculation

Besides the two presented sets, a third set, "Mix", has been modeled (see Table 10). This set combines all of the selected actions. In contrast to the other two sets, the parametrization is less ambitious since only half of the potential of the other sets was exploited (see Table 17, page 36). The results of the "Mix"-set were between the other two sets, indicating that a well-balanced set of actions, which addresses both lifestyle and construction methods makes a relevant contribution without having to go to extremes.

Figure 13 "Mix": Steel and concrete flows related to EU buildings in 2050



Source: newTRENDs - own calculation

6. Discussion

The described implications, limitations, and potentials for improvement will also be published in a scientific journal. The draft is finalized and will be submitted soon (Lotz et al. NYP).

6.1 Implications of the results

The results based on the reference scenario from Invert/EE-Lab showed that the demand for steel and concrete will increase until 2050. This is caused by the increasing floor space demand and not by changes in the construction methods. In fact, the per capita material and floor space demand increase as well. This leads to increasing material production of steel and concrete. Although the use of steel in EU buildings is expected to be mainly secondary steel, this development is challenged by the future availability of steel scrap. The results showed that the outflow of steel from buildings is significantly lower than the inflow. This is caused by the increasing demand for steel and the long lifetime of buildings. Thus, scrap from other sources is necessary to meet the need for secondary steel for buildings. The results also imply that the growing demand for steel and concrete would lead to an increase in industrial energy demand and GHG emissions in the EU.

Consequently, it is assumed that the reduction of material demand in context of CE can contribute significantly to industry decarbonization (Fleiter et al. 2019; Worrell et al. 2017). The results of the analysis carried out within this study confirmed this. In line with the results of other studies (Circle Economy 2022; Hertwich et al. 2020; Le Den et al. 2020; Lotz et al. 2021; Material Economics 2018), it became clear that these strategies can have a significant impact on reducing the embedded energy demand and GHG emissions of buildings. This supports that the CE gains momentum in the context of decarbonization (Fishman et al. 2021). However, a consistent policy framework is necessary to exploit these potentials along the building value chain. The existing policy framework needs to be further improved (Lotz et al. 2022). In addition, it can require restructuring the complete value chain and related business models (Lieder et al. 2016).

The secondary production route is already more relevant for construction steel production because steel used in buildings is typically made from secondary steel (Verein Deutscher Eisenhüttenleute 2015). While lower energy demand and GHG emissions can be allocated to this route, it is challenged by scrap availability (International Energy Agency 2020). While the model results confirmed that the available secondary material from buildings is significantly lower than the demand, scrap availability from other sectors remain unclear. At present a typical down-cycling route is using scrap from the automotive industry for buildings (Pauliuk et al. 2017b). Currently, only 55% of scrap in the EU is used due to contamination with tramp elements. This, may prospectively increase up to 75% (Dworak et al. 2022). Additionally, the EU is a net exporter of scrap, while the share of the secondary production route has decreased in the last few years (Rostek et al. 2022). However, an increase in the EU recycling rate could lead to declining recycling rates outside the EU. Consequently, the system perspective and, thus, the consideration of imports and exports must be critically taken into account when analyzing scrap availability. Consequently, the primary production of steel for buildings could gain relevance for the production of construction steel in two cases: Firstly, in case the recycling processes are improved, and steel from the automotive industry is not down-cycled. Secondly, if the available scrap from the building and other sectors is insufficient to cover the demand.

To avoid the future use of GHG-intensive basic materials such as (primary) steel and cement in buildings, an ambitious CE is indispensable. In addition to its direct reduction effect on industrial GHG emissions, it reduces the final energy demand and thus lowers the costs of expanding renewable energies, grid expansion and the import of secondary energy sources (International Energy Agency 2019).

6.2 Limitations and potential for improvement

While the modeling approach is generally able to answer the research questions posed, the results are highly dependent on the input data. Consequently, these are the main limitation of the model improvement within Work Package 6 of newTRENDs. Here, a distinction between four external and one internal parameter types can be made. The four external types are the MI, production characteristics (losses and shares), recycling shares and the parametrization of the CE actions. Since the first parameter, the MI, was developed as part of the project, it will be focused on. The same applies to the parameterization of the CE actions. Additionally, the floor space demand provided by Invert/EE-Lab will be discussed as an internal parameter since it has significant impact on the results according to the service-stock-flow nexus (Haberl et al. 2017).

The source used for the residential building MI corresponds with comparable EU building typologies, such as the *TABULA WebTool* published by Institut Wohnen und Umwelt GmbH (2012-2016) or the *Building stock analysis* within the project *Hotmaps* published by Pezutto (2017). Nevertheless, these do not provide the required detail for the definition of building archetypes. Since these sources focus on the building envelope, they lack detail on building components for the definition of building archetypes. Consequently, they were not included.

For non-residential buildings, a different approach was used because no consistent source was available. This approach is based on a variety of case studies on material use in non-residential buildings. The MI for non-residential buildings can be compared to Deetman et al. (2020). The values shown in Table 19 are in a comparable order of magnitude. However, Deetman et al. show a lower geographical differentiation and do not consider age cohorts. Consequently, the deviations show that the MI are subject to uncertainty.

Still, both the residential and non-residential archetypes could be further improved. On the one hand, the retrospective archetypes could be compared with top-down statistics on material use in buildings as shown by Kohler et al. (1999). On the other hand, the prospective archetypes could be diversified by experts from the construction industry. This would allow to consider alternative building practices and use concepts beyond business-as-usual in transformation pathways.

Table 19 Comparison of non-residential MI with literature

	Steel	Concrete
Offices in kg/m² (Deetman et al. 2020/developed MI)	24-256/0-143	393-2118/0-1877
Retail and warehouses in kg/m² (Deetman et al. 2020/developed MI)	26-121/0-97	349-1009/0-3110
Hotels and restaurants in kg/m² (Deetman et al. 2020/developed MI)	51-113/0-143	93-1073/0-1524
Other in kg/m² (Deetman et al. 2020/developed MI)	40-132/0-116	702-1543/0-1837

Besides the comparison to other building archetypes or typologies, the results can be compared with other studies and statistics. In general, the model results are lower than the results for the per-capita steel and concrete stock in a comparable study by Deetman et al. (2020). Since the MI are in a comparable order of magnitude compared to Deetman et al. (2020), the deviation can also be attributed to the floor space demand considered.

Also, compared to steel and concrete consumption statistics, the modeled results appear low (see Table 20). This deviation remains even when the end-use shares are taken into account. However, it has to be considered that the archetypes underlying the calculated MI do not consider all building components and do not include remodeling and renovation activities in the building stock. At the same time, there are also uncertainties in the statistics, such as the time of data collection and sectoral allocation. So overall, matching bottom-up and top-down data is challenging. This supports the proposal of comparing bottom-up building archetypes with top-down building and production statistics.

Table 20 Comparison with steel and cement consumption statistics

	Steel	Cement
Consumption* in Mt, 2018	160 (World Steel Association 2022)	170 (CemNet 2022)
Production for construction in Mt, 2018	56 (Eurofer 2021)	-
Modeled value in Mt, 2020	12	46

* Production minus net (indirect) exports

Furthermore, the building stock development provided by Invert/EE-Lab has significant impact on the results. Overall, the development complies with the EU reference scenario (European Commission 2021a). Nevertheless, uncertainty arises since Invert/EE-Lab was developed to consider energy demand during the building use phase. Unheated buildings, as they occur especially in non-residential buildings, are thus underrepresented. Accordingly, deviations from current building statistics are possible. Additionally, the prospective development may vary significantly based on the scenario assumptions. It should be considered that the development presented here corresponds to a reference scenario and thus extrapolates current trends. Therefore, it considers an increasing floor space demand in total and per capita. This development is consistent with comparable scenarios as shown in the scenario comparison by Camarasa et al. (2022). Alternative scenarios, which consider lifestyle changes, such as the described reduced floor space per capita, would lead to different results. Another scenario assumption that may affect the results are the considered lifetime of the different building types. This has an influence, both on the building in- and outflows. The lifetime assumptions considered within Invert/EE-Lab are described by Müller (2015). Again, alternative scenarios considering the extended use of buildings due to e.g. renovation, would lead to different results for the steel and concrete demand. This shows the importance of discussing scenario assumptions for developing and evaluating scenarios in line with the sustainable development goals of the EU.

In addition to these factors, which have an influence on the results of the reference calculation, the parameterization of the CE actions has a significant impact on the calculation of their impact. Since this was based on a quantification from a previous study (Le Den et al. 2020), these results can be improved by a further literature review and additional interviews with experts in the respective field. Due to the necessary restructuring of the value chains and the development of new business models (Lieder et al. 2016), the quantification is determined not only by technical but also, in particular, behavioral and political aspects. Consequently, this may also differ for different scenarios. Again, this highlights the relevance of reconciling scenario settings profoundly.

Nevertheless, the developed modeling approach and building archetypes allow the consideration of such changing scenario settings.

In addition to these limitations and potential improvements in the existing modeling approach, it would also be relevant to extend it. This could include other materials, such as insulation materials or material for technical building systems. In this way, the connection between the EU Renovation Wave Strategy and material-based emissions could be mapped (European Commission 2020). Besides other materials the modeling for further CE actions could be relevant. These could be the measures that were not considered after the pre-selection in this report or measures that were not covered by Le Den et al. (2020). Other actions may also be relevant for other materials, such as plastics for insulation. Finally, comparable analyses of other products relevant for the industry sector could improve the understanding of material demand in different end-use sectors. For instance, the automotive industry as the second largest steel customer (Eurofer 2021), or the packaging industry as the largest plastics customer (SYSTEMIQ 2022), would be relevant.

7. Conclusion

This focus study aimed to improve the modeling of CE for industry decarbonization. Even though the bottom-up simulation tool FORECAST already considered the impact of circularity actions exogenously within industry transformation pathways, this was improved by explicitly modeling material flows along the entire value chain and considering the impact of CE actions endogenously. This was done for a typical end-use good, buildings, and the related basic materials: steel and concrete.

In the previous chapters, the model approach developed for this purpose and the extended data basis were described in detail. While the model approach will be published at the end of the newTRENDs project[13], the improved database can be found in the appendix (A.5) of this report. Both were tested in a reference calculation. The results showed that the steel and concrete demand for buildings will increase by around 58% until 2050. The considered CE actions could reduce this demand significantly. The extreme sets "Lifestyle" and "Construction" could reduce steel production by around 35% resp. 47% and the cement production by up to 32% resp. 20% in 2050. In contrast, the "Mix"-set with the less ambitious parametrization could reduce steel production by around 38% and cement production by about 26%. This indicates that a well-balanced set of actions, which addresses both lifestyle and construction methods makes a relevant contribution without having to go to extremes. Overall, CE can contribute significantly to material demand reduction and thus, industry decarbonization.

In summary, the methodological approach is suitable to answer the research questions described in the introduction. In addition, methodological advancements were made via the development of an interface that allows to link two bottom-up energy system models, which normally consider the building and the industry sector separately. Furthermore, existing data on non-residential buildings has been validated and expanded. Through this work, it was possible to map the impact of eight CE actions. By selecting the actions on the basis of the 9R framework, it can be ensured that the model approach is also capable of mapping further measures. The results can be further improved by validating and enhancing the developed data basis and reconciling the building stock development regarding unheated spaces. In addition, the parametrization of the CE actions should be validated. Beyond the newTRENDs project, it would be relevant to assess further materials, end products, and related CE actions.

Overall, the work described here leads to an improved consideration of CE in the simulation of industry transformation pathways with the bottom-up energy demand model FORECAST. CE can contribute significantly to achieving the European climate targets. Consequently, scenario analyses considering CE for industry decarbonization can support the political debate and decision making.

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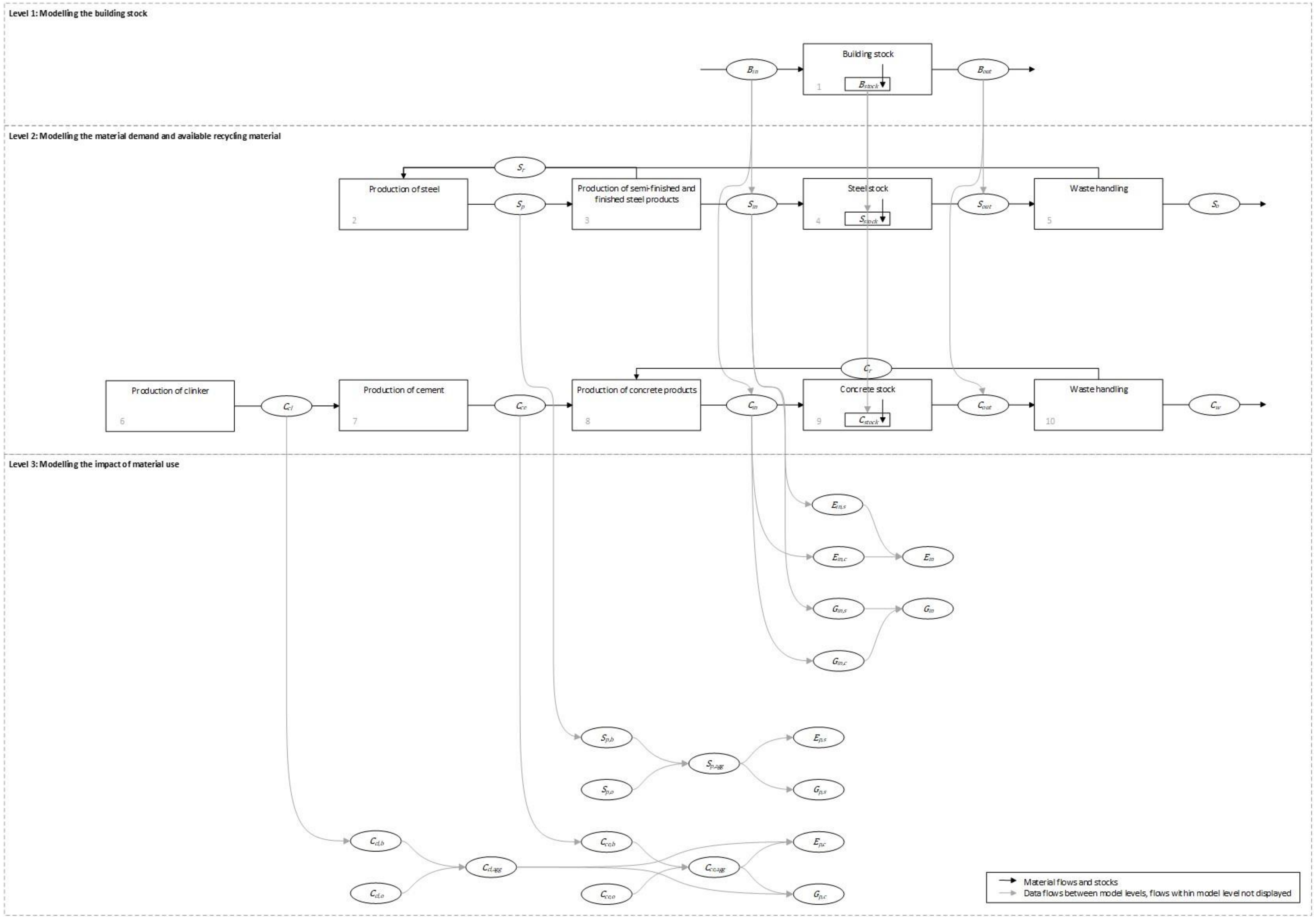
13 H2020-newTRENDs (github.com)

A.1 Detailed model structure

Figure 14 Detailed model structure



Source: own representation

A.2 Matching of residential archetypes

Table 21 Matching of residential archetypes, source: own representation based on Nemry et al. 2008; TU Wien et al. 2021

Archetype / Nemry et al.	SFH_warm_>1945	SFH_warm_1945-69	SFH_warm_1970-89	SFH_warm_1990-2010	SFH_warm_2010<	SFH_moderate_<1945	SFH_moderate_1945-69	SFH_moderate_1970-89	SFH_moderate_1990-2010	SFH_moderate_2010<	SFH_cold_<1945	SFH_cold_1945-69	SFH_cold_1970-89	SFH_cold_1990-2010	SFH_cold_2010<	MFH_warm_>1945	MFH_warm_1945-69	MFH_warm_1970-89	MFH_warm_1990-2010	MFH_warm_2010<	MFH_moderate_>1945	MFH_moderate_1945-69	MFH_moderate_1970-89	MFH_moderate_1990-2010	MFH_moderate_2010<	MFH_cold_>1945	MFH_cold_1945-1969	MFH_cold_1970-1989	MFH_cold_1990-2010	MFH_cold_2010<
Z1_SI_001	X																													
Z1_SI_002	X																													
Z1_SI_003	X																													
Z1_SI_004		X	X																											
Z1_SI_005_ex		X	X	X																										
Z1_SI_005				X																										
Z1_SI_006_ex		X	X	X																										
Z1_SI_006				X																										
Z1_SI_007_ex		X	X	X																										
Z1_SI_007				X	X																									
Z1_SI_008	X																													
Z1_MF_001																X														
Z1_MF_002																X														
Z1_MF_003																	X	X												
Z1_MF_004_ex																	X	X	X											

Archetype Nemry et al.	SFH_warm_>1945	SFH_warm_1945-69	SFH_warm_1970-89	SFH_warm_1990-2010	SFH_warm_2010<	SFH_moderate_<1945	SFH_moderate_1945-69	SFH_moderate_1970-89	SFH_moderate_1990-2010	SFH_moderate_2010<	SFH_cold_<1945	SFH_cold_1945-69	SFH_cold_1970-89	SFH_cold_1990-2010	SFH_cold_2010<	MFH_warm_>1945	MFH_warm_1945-69	MFH_warm_1970-89	MFH_warm_1990-2010	MFH_warm_2010<	MFH_moderate_>1945	MFH_moderate_1945-69	MFH_moderate_1970-89	MFH_moderate_1990-2010	MFH_moderate_2010<	MFH_cold_>1945	MFH_cold_1945-1969	MFH_cold_1970-1989	MFH_cold_1990-2010	MFH_cold_2010<
Z1_MF_004																			X											
Z1_MF_005																	X	X	X											
Z1_MF_006_ex																	X	X	X											
Z1_MF_006																			X											
Z1_MF_007																	X	X												
Z1_MF_008_ex																		X	X											
Z1_MF_008																			X	X										
Z1_HR_001_ex																		X	X											
Z1_HR_001																			X	X										
Z1_HR_002																		X												
Z2_SI_001						X																								
Z2_SI_002						X																								
Z2_SI_003						X																								
Z2_SI_004							X																							
Z2_SI_005							X	X																						
Z2_SI_006_ex								X	X																					
Z2_SI_006									X																					
Z2_SI_007_ex								X	X																					
Z2_SI_007									X																					
Z2_SI_008_ex								X	X																					
Z2_SI_008									X	X																				

A.3 Annex: Matching of non-residential archetypes (industry, retail and warehouse)

Table 22 Matching of non-residential archetypes (industrial, retail and warehouse)

Archetype Case study/ archetype*	Ind_warm_>1945	Ind_warm_1945-1969	Ind_warm_1970-1989	Ind_warm_1990-2010	Ind_warm_2010<	Ind_moderate_>1945	Ind_moderate_1945-1969	Ind_moderate_1970-1989	Ind_moderate_1990-2010	Ind_moderate_2010<	Ind_cold_>1945	Ind_cold_1945-1969	Ind_cold_1970-1989	Ind_cold_1990-2010	Ind_cold_2010<	Ret_warm_>1945	Ret_warm_1945-1969	Ret_warm_1970-1989	Ret_warm_1990-2010	Ret_warm_2010<	Ret_moderate_>1945	Ret_moderate_1945-1969	Ret_moderate_1970-1989	Ret_moderate_1990-2010	Ret_moderate_2010<	Ret_cold_>1945	Ret_cold_1945-1969	Ret_cold_1970-1989	Ret_cold_1990-2010	Ret_cold_2010<
BRGM 2012: commercial																X	X	X	X	X										
BRGM 2012: industrial	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X															
Rodrigues et al. 2018: industrial	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X															
Bonamente et al. 2015: industrial	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X															
Lederer et al. 2021: service																X	X				X	X	X	X	X	X	X			
Lederer et al. 2021: industrial						X	X	X	X	X	X	X	X	X	X															
Sprecher et al. 2022: commercial																		X	X				X	X				X	X	
Gruhler et al. 2017: consumer markets																		X	X		X	X	X	X				X	X	
Rai et al. 2011: warehouse																				X					X					X
MFH*	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

*It is referred to the he building archetype of the respective age cohort and region.

Source: own representation based on the case studies mentioned in the table and TU Wien et al. 2021

A.4 Matching of non-residential archetype (office)

Table 23 Matching of non-residential archetype (office)

Archetype Case study/ archetype*	Off_warm_>1945	Off_warm_1945-1969	Off_warm_1970-1989	Off_warm_1990-2010	Off_warm_2010<	Off_moderate_>1945	Off_moderate_1945-1969	Off_moderate_1970-1989	Off_moderate_1990-2010	Off_moderate_2010<	Off_cold_>1945	Off_cold_1945-1969	Off_cold_1970-1989	Off_cold_1990-2010	Off_cold_2010<
BRGM 2012: old offices	X														
BRGM 2012: commercial		X	X												
Asdrubali et al. 2013: office		X	X	X	X		X	X	X	X					
Lederer et al. 2021: service						X	X	X	X	X					
Sprecher et al. 2022: office						X	X	X	X	X					
Junnila 2004: office															X
Wallhagen et al. 2011: office											X	X	X	X	
Ylmén et al. 2019: office															X
MFH*	X	X				X	X		X		X	X	X	X	
HR*			X	X	X			X		X					X

*It is referred to the building archetype of the respective age cohort.

Source: own representation based on the case studies mentioned in the table and TU Wien et al. 2021

A.5 Material intensities

Table 24 Material intensities

Archetype	Steel use* in kg per m^2	Concrete use in kg per m^2
SFH_warm_>1945	0	0
SFH_warm_1945-69	48	963
SFH_warm_1970-89	53	1029
SFH_warm_1990-2010	60	1134
SFH_warm_2010<	62	1161
SFH_moderate_<1945	0	0
SFH_moderate_1945-69	32	733
SFH_moderate_1970-89	55	1062
SFH_moderate_1990-2010	54	1048
SFH_moderate_2010<	51	1006
SFH_cold_<1945	26	474
SFH_cold_1945-69	42	1038
SFH_cold_1970-89	49	982
SFH_cold_1990-2010	43	900
SFH_cold_2010<	48	964
MFH_warm_>1945	0	0
MFH_warm_1945-69	41	958
MFH_warm_1970-89	53	1075
MFH_warm_1990-2010	48	1131
MFH_warm_2010<	40	958
MFH_moderate_>1945	0	0
MFH_moderate_1945-69	82	1352
MFH_moderate_1970-89	75	1203
MFH_moderate_1990-2010	53	925
MFH_moderate_2010<	71	1196
MFH_cold_>1945	52	922
MFH_cold_1945-1969	85	1388
MFH_cold_1970-1989	58	965
MFH_cold_1990-2010	34	669
MFH_cold_2010<	28	606
Ind_warm_>1945	0	0
Ind_warm_1945-1969	64	1758
Ind_warm_1970-1989	64	1758

Archetype	Steel use* in kg per m²	Concrete use in kg per m²
Ind_warm_1990-2010	64	1758
Ind_warm_2010<	64	1758
Ind_moderate_>1945	0	0
Ind_moderate_1945-1969	9	240
Ind_moderate_1970-1989	64	1758
Ind_moderate_1990-2010	64	1758
Ind_moderate_2010<	64	1661
Ind_cold_>1945	0	0
Ind_cold_1945-1969	106	1797
Ind_cold_1970-1989	102	1750
Ind_cold_1990-2010	102	1750
Ind_cold_2010<	112	1870
Ret_warm_>1945	0	0
Ret_warm_1945-1969	64	1758
Ret_warm_1970-1989	64	1758
Ret_warm_1990-2010	64	1758
Ret_warm_2010<	64	1758
Ret_moderate_>1945	0	0
Ret_moderate_1945-1969	0	0
Ret_moderate_1970-1989	97	3110
Ret_moderate_1990-2010	97	3110
Ret_moderate_2010<	68	2560
Ret_cold_>1945	0	0
Ret_cold_1945-1969	93	1639
Ret_cold_1970-1989	89	1595
Ret_cold_1990-2010	64	1008
Ret_cold_2010<	64	1008
Off_warm_>1945	0	0
Off_warm_1945-1969	38	1416
Off_warm_1970-1989	143	1877
Off_warm_1990-2010	38	986
Off_warm_2010<	38	986
Off_moderate_>1945	0	0
Off_moderate_1945-1969	32	441
Off_moderate_1970-1989	77	1069
Off_moderate_1990-2010	116	1524
Off_moderate_2010	116	1524

Archetype	Steel use* in kg per m²	Concrete use in kg per m²
Off_cold_>1945	54	774
Off_cold_1945-1969	54	774
Off_cold_1970-1989	32	515
Off_cold_1990-2010	32	515
Off_cold_2010<	43	596
Hot_warm_>1945	0	0
Hot_warm_1945-1969	38	1416
Hot_warm_1970-1989	143	1877
Hot_warm_1990-2010	38	986
Hot_warm_2010<	38	986
Hot_moderate_>1945	0	0
Hot_moderate_1945-1969	32	441
Hot_moderate_1970-1989	77	1069
Hot_moderate_1990-2010	116	1524
Hot_moderate_2010	116	1524
Hot_cold_>1945	54	774
Hot_cold_1945-1969	54	774
Hot_cold_1970-1989	32	515
Hot_cold_1990-2010	32	515
Hot_cold_2010<	43	596
Edu_warm_>1945	0	0
Edu_warm_1945-1969	38	1416
Edu_warm_1970-1989	143	1877
Edu_warm_1990-2010	38	986
Edu_warm_2010<	38	986
Edu_moderate_>1945	0	0
Edu_moderate_1945-1969	32	441
Edu_moderate_1970-1989	77	1069
Edu_moderate_1990-2010	116	1524
Edu_moderate_2010	116	1524
Edu_cold_>1945	54	774
Edu_cold_1945-1969	54	774
Edu_cold_1970-1989	32	515
Edu_cold_1990-2010	32	515
Edu_cold_2010<	43	596
Hea_warm_>1945	0	0
Hea_warm_1945-1969	38	1416

Archetype	Steel use* in kg per m²	Concrete use in kg per m²
Hea_warm_1970-1989	143	1877
Hea_warm_1990-2010	38	986
Hea_warm_2010<	38	986
Hea_moderate_>1945	0	0
Hea_moderate_1945-1969	32	441
Hea_moderate_1970-1989	77	1069
Hea_moderate_1990-2010	116	1524
Hea_moderate_2010	116	1524
Hea_cold_>1945	54	774
Hea_cold_1945-1969	54	774
Hea_cold_1970-1989	32	515
Hea_cold_1990-2010	32	515
Hea_cold_2010<	43	596
Oth_warm_>1945	0	0
Oth_warm_1945-1969	47	1530
Oth_warm_1970-1989	116	1837
Oth_warm_1990-2010	47	1244
Oth_warm_2010<	47	1244
Oth_moderate_>1945	0	0
Oth_moderate_1945-1969	23	334
Oth_moderate_1970-1989	78	1524
Oth_moderate_1990-2010	104	1827
Oth_moderate_2010	99	1720
Oth_cold_>1945	36	516
Oth_cold_1945-1969	69	1088
Oth_cold_1970-1989	53	901
Oth_cold_1990-2010	49	803
Oth_cold_2010<	58	877

*The only relevant steel product are concrete reinforcing bars according to the building archetypes.

Source: own calculation based on the sources displayed in A.2, A.3 and A.4

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