Modelling the Renovation of Buildings in Europe from a Circular Economy and Climate Perspective

METABOLIC

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List of abbreviations

BE	Building element
BIM	Building Information Modelling
BM	Building material
BP	Building product
CDW	Construction and Demolition Waste
CE	Central and Eastern Europe
CO_2	Carbon dioxide
CRA	Circular Renovation Action
DfD	Design for Disassembly
DTI	Danish Technological Institute
EC	European Commission
EPB	Energy Performance of Buildings
ERT	Energy renovation type
EU-27	27 European Union countries
EWC	European Waste Catalogue
EWC-Stat	European Waste Classification for Statistics
G7	Group of Seven
GFA	Gross Floor Area
GHG	Greenhouse Gas
GDP	Gross Domestic Product
HW	Hazardous waste
IEA	International Energy Agency
JRC	Join Research Commission
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LoW	List of Waste
MFA	Material Flow Analysis
NE	Northern Europe
NEN	Nederlands Normalisatie-instituut
NHW	Non-hazardous waste
NMD	Nationale Milieu Database
NRT	Non-energy renovation type
PM	Particulate Matter
RSD	Relative Standard Deviation
SE	Southern Europe
UN	United Nations
WE	Western Europe

Glossary

Biodiversity.

The variability among living organisms from all sources, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part. This includes diversity within species, between species, and in ecosystems. It includes cultivated species and varieties and agricultural ecosystems as well as natural ecosystems and their components. (EEA, n.d.a).

Building element.

A main component of a building.

Building Information Modelling.

Building Information Modelling is the foundation of digital transformation in the architecture, engineering, and construction industry. (Autodesk, n.d.)

Building material.

Any material used in construction, such as steel, concrete, brick, masonry, glass, wood, etc. (EEA, n.d.b).

Building product.

Any building part that can be removed from site after renovation or demolition to be commercialised for reuse. (Icibaci, 2019).

Building stock.

Existing buildings in use in a determined geographical area (Icibaci, 2019).

CO_2 sequestration.

The process of removing CO_2 from the atmosphere and depositing it in a reservoir (UNCC, n.d.).

Construction and demolition waste.

Rubble and other waste material arising from the construction, demolition, renovation, or reconstruction of buildings or parts thereof, whether on the surface or underground. Consists mainly of building material and soil, including excavated soil. Includes waste from all origins and from all economic activity sectors (EEA, n.d.c).

Circular Renovation Action.

Renovation actions that support the following circular economy objectives: less material need, use of biobased materials, high content of recycled materials, long-term/high durability, clean materials free of hazardous materials, and recycling of renovation waste. (Wahlström, 2021).

Design for disassembly.

A concept in which buildings and products are designed intentionally for material recovery, value retention, and meaningful next use (C2Ccertified, 2017).

Energy renovation type.

A renovation activity that improves the energy performance of a building.

European waste catalogue.

A hierarchical list of waste descriptions established by European Commission decision 2000/532/EC2. It is divided into 20 main chapters, most of which are industry based but some of which are based on materials and processes. (EEA, n.d.d).

European Waste Classification for statistics.

A substance-oriented classification of waste for statistical purposes. It categorises hazardous and non-hazardous waste. (UN, 2010).

Gross floor area.

Relates to total floor area of a building, within the external walls.

Greenhouse gases (GHGs).

The atmospheric gases responsible for causing global warming and climate change. The major GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). (UNCC, n.d.).

Group of Seven (G7).

The Group of Seven is an informal grouping of several of the world's advanced economies: Canada, France, Germany, Italy, Japan, the United Kingdom, the United States, and the European Union. The G7 was set up in 1975 as an informal gathering of the leaders of these countries. (Government of Canada, n.d.).

Hazardous waste.

Waste that causes danger or likely to cause danger to health or the environment, because of their chemical reactivity, toxicity, explosivity, corrosivity, radioactivity, or other characteristics. (EEA, n.d.e).

Life cycle assessment.

A process of evaluating the effects that a product or building has on the environment throughout the entire period of its life. The key elements are: identification or quantification of the environmental loads involved, evaluation of the potential environmental impact of these loads, and assessing the options available for reducing the environmental impact. (EEA, n.d.a).

Life-cycle costing.

A process of evaluating all the costs that will be acquired during the lifetime of a building, product or service. Also whole-life costing (EC, n.d.a).

Life cycle inventory.

Provides additional information to help understand and evaluate the magnitude and significance of the environmental impact of a product, building, or service throughout its life cycle (Zhang, 2014).

List of waste.

The waste classification in the EU for administrative purposes, i.e. for permits and supervision in the field of waste generation and management (Eurostat, 2010).

Material flow analysis.

A Material Flow Analysis is a systematic assessment of the flows and stocks of materials within a system. (Icibaci, 2019).

Mitigating climate change.

A human intervention to decrease emissions or strengthen the signs of greenhouse gases (IPCC, 2018).

Non-hazardous waste.

Waste not causing danger or likely to cause danger to health or the environment, because of their chemical reactivity, toxicity, explosivity, corrosivity, radioactivity, or other characteristics.

Non-energy renovation type.

Renovation activity that does not improve the energy performance of a building.

Other metals.

Umbrella material type used in modelling, covers the metals Aluminium, Brass, Lead and Zinc.

Relative standard deviation.

Relative standard deviation (RSD) is a special form of the standard deviation (std dev). The RSD tells you whether the “regular” std dev is a small or large quantity when compared to the mean for the data set.

Technical lifespan.

The time at which advances in technology have made a product unacceptably obsolete (Icibaci, 2019).

Executive summary

Objectives

The purpose of the project is to assess the impact of Circular Renovation Actions on the circular economy and climate in Europe by measuring two main variables: material consumption in mass and GHG emissions. These Circular Renovation Actions have been previously identified by the EEA. Implementation of these actions on the EU-27 building stock is linked to a set of factors like policy, building practices, and industry standards, but altogether determine the impact on the circular economy and the climate by the renovation sector in Europe.

More specifically, under this contract, we aim to:

1. Make use of an existing model or develop a new one to simulate the European building stock
2. Conduct modelling of specific renovation scenarios based on the current status of the European building stock
3. Create a baseline understanding of the impact of the different renovation actions in order to facilitate the effective implementation of circular economy practices in the built environment
4. Assess the benefits of each renovation action and identify the optimal synergies among them that optimise circular economy and climate benefits

The final deliverable of this project is this technical report and a developed model in an open-source format. This technical report contains a description of the method, all results, and relevant conclusions and perspectives. An important part of the results is a clustered list of Circular Renovation Actions, which can be used to inform policy making regarding the circular renovation strategies in the EU-27 (see Chapter 4).

Model

The Urban Mining Model has been developed by Metabolic as a bottom-up model, estimating material stock based on the characteristics and size of individual buildings, scaling those up to higher spatial scales (neighbourhood, city, and country).

Elements in the stock are generally differentiated according to a typology that crosses criteria relating to function, form, and age—for example, housing units in a building of less than three floors built between 1945 and 1960. This approach requires a good knowledge of the 'inner structure' of the stock, and allows both the quantity and the quality of materials to be assessed (Augiseau & Barles, 2017, p. 158). Inventories of construction materials are often done in order to obtain this type of detailed knowledge of the 'inner structure'.

An important assumption for bottom-up material flow analysis is that buildings can be divided into groups or types which have the same material intensity. Criteria such as construction period, use of a building (e.g. residential or non-residential), or location (e.g. country or climate zone) are used to differentiate between building types (Wiedenhofer et al., 2015).

The bottom-up modelling is based on an existing model developed by Metabolic. The model was developed and published in 2020, together with SGS Search and the Dutch Economic Institute for the Built Environment (EIB, Metabolic, & SGS Search, 2020). The goal of the publication was to conduct a baseline assessment of the annual material flows and environmental impacts of the Dutch construction sector and to provide a prognosis until 2030. This publication was commissioned by the

Dutch Transition Team Circular Construction Economy (part of the Ministry of Economic Affairs and Climate), and currently informs policy geared towards achieving a more circular sector.

- The model is developed using reference buildings for twelve different building typologies from the Netherlands (Figure 1.1). These reference buildings are derived from building inspections and inventories by SGS Search.
- The twelve building typologies are further refined into four construction year bins (<1945, 1945-1970, 1970-2000, >2000) to account for historical variability of building methods. Furthermore, the twelve different typologies have been grouped together to form nine distinct building types. These building types correspond to the typologies the European Commission uses in their EU Building Database.

Conclusions

As mentioned above there are four objectives this research tries to answer. Below is a summary of the results from this modelling exercise regarding each of them.

Objective 1 & 2: Create an understanding of the current and future European building stock

As seen in the modelling of the scenarios, the reuse of products and the recycling of materials do not create a flow of building products and materials sufficient to close the circularity loop with renovation materials alone. This means that the renovation material flows will be always deficient in terms of material quantity; there will be more material inflowing than outflowing. Therefore a broader scope must be adapted to look for more solutions beyond simply closing material cycles within renovation activities, such as preventing the need for material altogether and using less impactful and more regenerative materials.

Scenario 1: Business as Usual

If current renovation practices in the EU-27 continue as usual, the energy and non-energy related renovation activities will consume 918,000 kt of virgin materials from 2022-2050. The embedded impact connected to the production of these materials is the emission of 978,000 kt of embedded GHG emissions.

Inflowing materials

The majority of material demand will come from countries within Western Europe. Together they will demand 447,000 kt of all material consumption related to renovation activities in the EU-27 from 2022-2050. This translates to 48.6% of all material consumption. This comes as no surprise, since the majority of buildings are also located in this region. The top three materials entering the EU-27 building stock from 2022-2050 are: insulation materials (28%), ceramics (16%), and wood (12.5%). Concrete is a close runner-up with 12.2 % of the total material demand. Together, these four materials make up 68.7% of all materials entering the building stock. From all GHG emissions related to the renovation of the EU-27 building stock (978,000 kt) these materials make up 38% of all GHG emissions. Only 21% of all material consumption is related to energy-related renovation activities. The other 79% is caused by non-energy renovations.

Outflowing materials

Based on the modelling it can be assumed that less material is leaving the EU-27 building stock due to renovation than there is entering. In total 386,000 kt of mass is removed from the EU-27 building stock during the timescope of this research. The materials flowing out of the building stock because of renovation are: insulation (39%), wood (16%), gypsum (10.6%), and glass (10.1%).

Scenario 2: Policy Compliant

If current renovation practices were increased to meet targets set by the EU, the energy and non-energy related renovation activities in the EU-27 will consume 1,090,000 kt of virgin materials. This is an increase of 18.7% when compared to the BAU scenario. The biggest absolute increase can be seen in the consumption of steel (with an increase of 51,000 kt), insulation (with an increase of 50,100 kt), and glass (with an increase of 20,100 kt).

Connected to the consumption of these materials are 1,520,000 kt of embedded GHG emissions. This is an increase of 47% when compared to the BAU scenario. The biggest absolute increase of GHG emissions can be found in the consumption of steel, 'other metals' (such as aluminium, brass, lead and zinc), and insulation. The relative increase in impact in regards to their initial GHG emissions is the largest with 'other metals', steel, and copper. The biggest absolute and relative increase in material consumption for renovations takes place in Central and Eastern Europe (81,700 kt of material, which represents an increase of 50%). The majority of this rise in material consumption is caused by energy-related renovation types, which increase by 162%. The other regions all increase their material consumption related to energy renovation types by +/- 49%.

Scenario 3: Ambitious

If current renovation practices were increased to have all buildings undergo a deep energy renovation before 2050, the energy and non-energy related renovation activities in the EU-27 will consume 1,940,000 kt of virgin materials. This is an increase of 112% when compared to the BAU scenario. Connected to the consumption of these materials are 3,950,000 kt of embedded GHG emissions. This is an increase of 304%. This large rise in GHG emission is mainly caused by steel (increases emissions by 131,000 kt), 'other metals' (86,000 kt), and insulation material (36,600 kt).

Based on the Ambitious scenario, the materials used for renovation of the European building stock increases by 112%. This surplus is mainly caused by a significant increase of energy-related renovation types. The majority of this increase is caused by a big influx of renovation in both energy (an increase of 450%) and non-energy renovation types (an increase of 70%).

Objective 3: Understanding the impact of individual actions

As a high-level conclusion for this section, the table below demonstrates how important it is to try to reduce new construction activities as a whole. In other words, the most impactful Circular Renovation Actions are linked to extending the lifespan of the existing buildings. This is related to the fact that construction activities require much more material than renovation activities. This research is therefore indicating that policy and other related action drivers should focus on promoting a mindset change.This mindset change can materialise in certain specific actions: deteriorated buildings being renovated, buildings only used at certain times of the day being complemented with adjacent uses, housing sizes being reduced, or unused buildings being filled with program and inhabitants.

The results of the modelling activities allow for an assessment of the impact the Circular Renovation Actions have on both virgin material consumption and GHG emissions until the year 2050. The table below gives an overview of the impact of these actions per scenario (*BAU, Policy Compliant,* or *Ambitious*).

Overview of Circular Renovation Actions and scenarios

Action category	Action	BAU		Policy		Ambitious	
		Reduction of virgin material use (kt)	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**
Reducing use of resources	1.1 Renovating instead of building	**203,900**	**135,600**	**203,900**	**135,600**	**203,900**	**135,600**
	1.2 Adaptive reuse	**182,341**	**98,199**	**182,341**	**98,199**	**182,341**	**98,199**
	1.3 Choice of material/product with a long lifespan*	**-8,337**	**14,820**	**-10,175**	**3,163**	**-22,057**	**-4,508**
	1.4 Saving of material in production	**19,103**	**28,524**	**27,007**	**50,424**	**44,188**	**83,479**
Waste prevention	2.1 Increased lifespan of a building	**277,407**	**150,776**	**277,407**	**150,776**	**277,407**	**150,776**
	2.3 Use of demountable products	**3,556**	**4,250**	**7,905**	**31,278**	**26,616**	**142,565**
Use of recyclable materials	3.1 Use of materials with high recycled content	**278,579**	**100,992**	**322,758**	**132,342**	**479,402**	**231,587**
Use of biobased materials	4.1 Choice of bio based material**	**-39,609**	**85,278**	**-65,301**	**115,750**	**-110,328**	**174,617**
	4.2 Nature-based solution***	**-224,064**	**-29,777**	**-230,805**	**-30,773**	**-299,850**	**-33,013**
Increased recycling rates	5.1 Reusing secondary products	**99,049**	**103,085**	**106,000**	**125,100**	**170,900**	**229,100**

* 1.3: Benefits of extended lifetime of building products will not occur before 2050
** 4.1: The total mass of used products will increase
*** 4.2: Installation of green roofs and façades requires additional material and GHG emissions; GHG absorption is not taken into account

Further analysis of these results provide the following insights:

- The highest reduction of GHG emissions can be generated by increasing the lifespan of existing buildings (Action 2.1+2.2) via the renovation of faulty foundations.
- Renovating buildings instead of building new properties (Action 1.1) generates the second-highest impact and the third-highest in saving virgin material consumption.
- Reusing building components (Action 5.1) has the third-highest impact, which is not in the top four of saved virgin material consumption.
- The fourth largest impact is generated by increasing the use of secondary materials in the production of new products (Action 3.1). This action has the highest impact on virgin material consumption among all the Circular Renovation Actions. Here, only technical feasibility and not availability of secondary materials has been taken into account. Therefore, this action might decrease in potential impact if availability is indeed taken into account.
- Even though the recycling of secondary materials during the production of new building products (Action 3.1) ranks fourth in reduction of GHG emissions during the BAU scenario, it will surpass all other actions if the renovation rate goes up to the Ambitious scenario.

- The analysis indicates that Actions 1.3, 4.1, and 4.2 do not lead to a reduction in virgin material consumption. This is because the impact of certain renovation actions take place only after 2050 (Action 1.3) and the increased need for 'heavy' materials such as soil and biobased insulation material needed to implement Actions 4.1 and 4.2.

Objective 4: Understanding the impact of clustering actions

The combining of several Circular Renovation Actions into clusters provides a strategic focus towards reducing virgin material consumption and environmental impact. Note that the impact and ranking of these Circular Renovation Actions has been done solely with regard to environmental impact and reduction of virgin material consumption. The potential financial impact, conflicting policy goals, availability of material, and (lack of) technical infrastructure has not been taken into account. The table below provides an overview of the impact of these clusters per scenario (*BAU, Policy Compliant,* or *Ambitious*).

The three clusters each have the common goal of reducing virgin materials consumption and GHG emissions. Yet each of them addresses these goals from a different perspective, and this helps to create a different momentum for the Circular Renovation Actions. At the same time, this clustering helps decision makers and policy developers to target circularity in the built environment from three different perspectives. A broad approach to the challenge of circularity as proposed by this research is needed to ensure the success of circular strategies within such a large and complex sector. Toward this end, the first cluster focuses on prolonging the lifetime of buildings. The second cluster focuses on reducing material consumption by introducing new value chains of recycled and reused materials into the built environment. The third cluster focuses on reducing the material consumption from a technological perspective and from a material science approach, bringing the use of more efficient, biobased, and nature-based materials and solutions to the fore.

Action category	Action	BAU		Policy		Ambitious	
		Reduction of virgin material use (kt)	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**
Cluster 1: Increased lifespan	1.1 Renovating instead of building	**655,311**	**399,395**	**NA**	**NA**	**NA**	**NA**
	1.2 Adaptive reuse						
	1.3 Choice of material/product with a long lifespan						
	2.1 Increased lifespan of a building						
Cluster 2: Reducing material consumption	2.3 Use of demountable products	**346,348**	**195,452**	**401,829**	**280,602**	**642,082**	**595,134**
	3.1 Use of materials with high recycled content						
	5.1 Reusing secondary products						
Cluster 3: New generation materials	1.4 Saving of material in production	**64,147**	**113,802*/ 180,228**/ 230,223*** **	**55,272**	**166,174*/ 267,248** / 318,720*** **	**84,794**	**259,096*/ 425,524**/ 425,601*** **
	4.1 Choice of biobased material						

	4.2 Nature-based solution						

* Saving of GHG emissions due to reduced virgin material consumption
** Saving of GHG emissions due to reduced virgin material consumption, if biogenic carbon storage is taken into account
*** Saving of GHG emissions due to reduced virgin material consumption, if biogenic carbon storage and storage of carbon during lifecycle is taken into account

The largest saving of virgin material consumption can be generated by extending the lifespan of existing buildings with Circular Renovation Actions in Cluster 1. The combination of these four Circular Renovation Actions provide a material saving 655,311 kt and 399,395 kt of embedded GHG emissions. This represents 75.6% of all materials needed for renovating the EU-27 building stock and 43.2% of all embedded GHG emissions related to the inflow of material demand.

Based on the combination of the three Circular Renovation Actions in Cluster 2, up to 346,348 kt of virgin material consumption can be reduced in the BAU scenario and 195,452 kt of GHG emissions. This represents roughly 39.9 % of all material consumption related to renovation activities in the BAU scenario and 21.1% of all GHG emissions. Based on the increase in renovation rates through the different scenarios, a large differentiation can be seen between the prevented material consumption of Cluster 2 and the saved emission of GHGs. Based on the increased renovation rates, 1.8 times more virgin material consumption is prevented in the Ambitious scenario, compared to the BAU scenario. When comparing the prevented emission, three times more GHG emissions are prevented in the Ambitious scenario compared to the BAU scenario.

Based on the combination of the three Circular Renovation Actions in Cluster 3, up to 64,147 kt of mineral material consumption can be reduced. This decrease is nullified by the increased consumption of biobased materials (mainly soil for the green roofs and façades). Even though the overall consumption of materials increases, a significant reduction of GHG emissions is generated. The reduction amounts to 113,802 kt of GHG emissions, attributed to the lower production impacts of using biobased alternatives. This impact is scaled up even further to 230,223 kt of GHG emissions saved if biogenic carbon storage in both production and use-phase is taken into account.

In the Policy Compliant scenario, Cluster 2 will overtake Cluster 1 in terms of GHG savings, but Cluster 3 will not. In the Ambitious scenario, both Cluster 2 and Cluster 3 will overtake Cluster 1 in terms of GHG savings. This implies that if the ambitions concerning renovations within the EU are fulfilled, much can be gained by creating a policy for sourcing materials that are less impactful than regular virgin materials.

Introduction

The construction industry contributes roughly to 39% of annual global carbon dioxide emissions and accounts for 36% of global energy use (UN Environment & International Energy Agency, 2017). In order to transition to a sustainable society and reduce global carbon emissions, the construction sector needs to play an important role if we want to succeed in this goal.

While in recent years the focus has been on energy efficiency of buildings to reduce their energy consumption as well as associated carbon emissions, also referred to as operational carbon, the embodied carbon of buildings has recently been gaining attention. An example is the Global Status Report 2018 from the Global Alliance for Buildings and Construction (IEA, 2018), which contains a chapter looking at minimising the carbon footprint of building materials, i.e. embodied carbon. According to this report, CO_2-emissions resulting from material use in buildings account for 28% of the annual buildings-related CO_2-emissions, corresponding to roughly 11% of the annual global CO_2-emissions. The International Resource Panel (2020) concludes that CO_2-emissions from the material cycle of residential buildings in the Group of Seven (G7) and China could be reduced by at least 80% by 2050 through a series of material efficiency strategies, and highlights a more intensive use of homes, designs composed of fewer materials, and improved recycling of construction materials as the most promising strategies.

Recent EEA work has explored the links between circular actions in buildings and their positive effect on mitigating climate change (EEA, 2020). The implementation of circular economy principles in buildings has the potential to contribute to the reduction of buildings' whole life-cycle carbon emissions. Buildings have a key role in delivering results fitting the objectives of various environmental policy agendas, such as circular economy and climate change mitigation. However, given the fact that 85-95% of the current European building stock will still exist in 2050 (EC, 2020), opportunities for delivering these results lie mainly with the renovation of existing buildings.

In this context, the EEA has undertaken work to identify a list of Circular Renovation Actions which can be directly implemented in European buildings and that have a high potential to increase the circularity of buildings, and at the same time mitigate GHG emissions, by:

1. Minimising waste, e.g. through extending buildings' life spans.
2. Increasing the recyclability of generated waste.
3. Minimising resource consumption, e.g. through using less material in a renovation project.
4. Regenerating natural systems by using renewable resources, i.a.

While operational carbon reductions in the EU are addressed by policy pillars such as the Energy Performance of Buildings Directive (EC, 2010), the Energy Efficiency Directive (EC, 2012), including the EPB standards, and the Renovation Wave for Europe (EC, 2020), concrete strategies and targets for embodied carbon are still lacking at the EU level.

At Member State (MS) level or industry level, countries such as Sweden, Finland, France, and Denmark have developed roadmaps or strategies for reducing whole-life carbon, however no similar roadmap or strategy exists at the EU level. Therefore, to accelerate policy development and market initiatives—at both the EU and MS levels—it is crucial to develop an EU roadmap for the reduction of buildings' GHG emissions. This need is addressed by the Commission, which by 2023 will develop a 2050 roadmap for reducing whole life-cycle carbon emissions in buildings.

Developing a robust roadmap requires the following critical steps:

1. Establish a baseline for whole life carbon: Where are we today?

2. Estimate the expected future level of whole life carbon: Where will we be in 10-30 years? Where do we want to be?
3. Identify solutions to reduce whole life carbon and quantify their impact: Which solutions are available? What is their reduction potential?

Answering these questions requires detailed data on construction activities, deep renovations, building types, regional differences, energy carriers, etc. These critical types of data form the basis for the assessment of whole life carbon. Additionally, and equally important, transparent LCA data are needed to quantify the carbon emissions related to the production of building materials as well as the energy use. And finally, insight and data on carbon reduction solutions are needed to be able to identify robust solutions for the building in a life cycle perspective.

State of the built environment and the circular economy in Europe

For all EU-27 countries, a fully circular metabolism for construction materials seems highly unlikely before 2050. Slow population growth and continued GDP growth result in a steady growth of the materials stored in the building stock towards 2050. The amount of material fed through construction and renovation far exceeds the material outflow (EC, 2021). This dynamic is exacerbated by the potential longer lifetimes of buildings, which means that the outflow catches up with the inflow slowly. On the other hand, extending the lifetime of existing buildings requires an inflow of non-structural materials, such as wood, ceramics, and insulation materials. However, since the inflow is expected to exceed the outflow, it means that the availability of materials 'mined' from the built environment will not be sufficient to supply the demand for new construction materials before 2050. Therefore, similar to Deetman et al. (2020), this study shows substantial challenges for achieving an EU-level, fully circular economy for the built environment in coming decades.

Additionally, instead of solely focusing on material quantities, from an 'urban mining' perspective, the quality of materials is of equal importance. While the material quantity provides insight into the maximum potential—the maximum extracted quantity of materials without considering disassembly processes, supply chain losses, sorting and/or processing—the material quality eventually determines the possibilities for reuse and recycling. As pointed out by the European Commission (2016) and Wahlström et al., (2020), knowledge about potential contamination of certain building materials is crucial (e.g. the work of Oberender and Butera (2016) for Denmark), as well as knowledge about the technical quality—and losses—of materials during and after disassembly. Additionally, it is important to consider that each country in the EU-27 has their own regulations and legal frameworks that influence the potential for reuse and recycling.

From a circular economy perspective, material reuse should be prioritised instead of recycling, to keep the value of material as high as possible. To facilitate reuse, future research should focus on modelling building elements (e.g. window frames, heating installations, and doors) instead of aggregated material fractions (e.g. PVC, glass, metal, wood, etc.). After calculating the amount and potential quality of these building elements, it is possible to determine how much physical space will need to be reserved in spatial planning to create 'urban mining hubs', locations where building elements can be stored and processed before reuse in a nearby construction site. To close material loops and transition towards a circular economy, these hubs will be a critical piece of infrastructure.

To improve the recycling potential of building elements, a lot of work is conducted on developing material passports. Material passports can act as a design optimisation tool and as an inventory of all materials embedded in a building. This information can be used to display the recycling potential and environmental impact of buildings (Honic, Kovacic, & Rechberger, 2019). Most material passports are based on building information modelling (BIM), and they generally focus on capturing the building elements stored in new buildings, that is, capturing materials in new or to-be-built buildings. The model presented in this research can be seen as a 'historical BIM-model' that calculates materials already stored in the built environment. Therefore, the model presented in this study can also be used to bridge this data gap and capture the materials and building elements already stored in the built environment. The combination of this model and upcoming BIM models will be able to fully cover all the materials stored in the built environment now and in the future.

Building stock

To calculate the material stock and flows in Europe (EU-27) in 2020, several input datasets are required. First, data on the building stock composition in 2020 across the EU-27 is needed. Using the stock quantities as a baseline, the flows are subsequently calculated using construction, demolition, and renovation rates. The rates represent the quantity of buildings constructed, demolished, and renovated in 2020 in the EU-27. Finally, the stock and flow quantities are multiplied with the material intensities that represent the four regions, building types, and construction year bins (Figure 0.1).

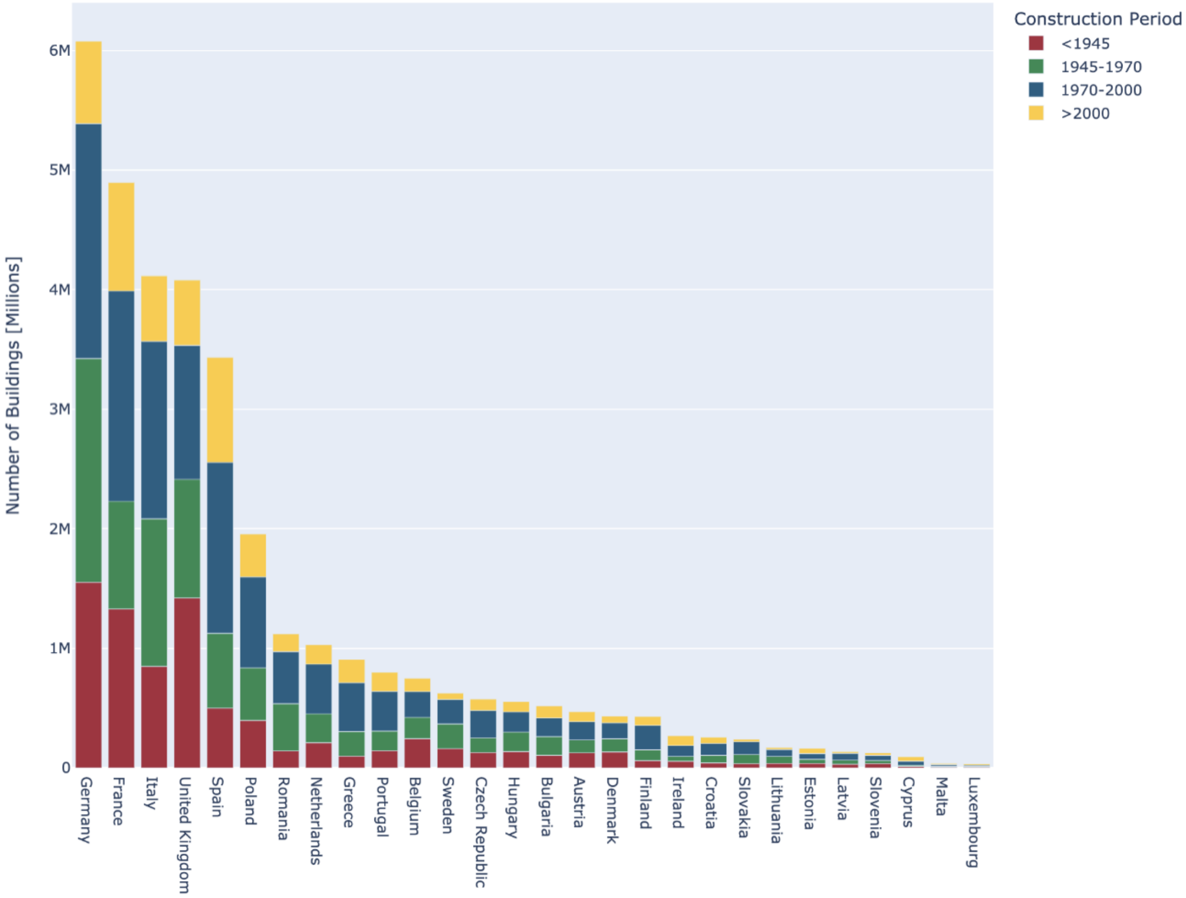


Figure 0.1 Number of buildings [millions] for each country in Europe (EU-27), split between four construction age categories

In light of the circular economy objectives, building stock modelling has gained prominence in the scientific field over the last few years. Augiseau & Barles (2017) did a meta-analysis on 31 scientific studies on modelling construction materials stocks and flows. The studies they reviewed had distinct goals: forecasting and comparing future input and output flows, studying the influence of several socio-economic parameters on future flows, estimating the present or future stock as well as its evolution, studying urban metabolism, and analysing the interaction between flows and stock.

From these studies, Augiseau & Barles (2017) distilled several main methodological approaches. The methods they studied are either static or dynamic, bottom-up or top-down, and retrospective or prospective. They found that these methodological approaches are often combined to account for potential uncertainty.

However, most studies use the less accurate top-down approaches. Top-down modelling uses estimations starting with macroeconomic or statistical data and extrapolating trends. Top-down approaches work especially well when flows of construction and demolition waste (CDW) have been closely monitored within the specific geographical area and timeframe in question. In these cases, modelling can rely on actual measurements with a limited number of assumptions to fill potential data gaps. In practice, data availability and accuracy are typically rather limited, and the outcome may be uncertain.

On the other hand, bottom-up modelling is based on inventories of individual items and the material intensities of those items (Wiedenhofer et al., 2015). A bottom-up approach is usually based on a division of the stock into categories (housing, business premises, etc.), and then by the application of material ratios or intensities (for example, in tonnes/m²) (Bergsdal et al., 2007; Sandberg et al., 2014, 2016).

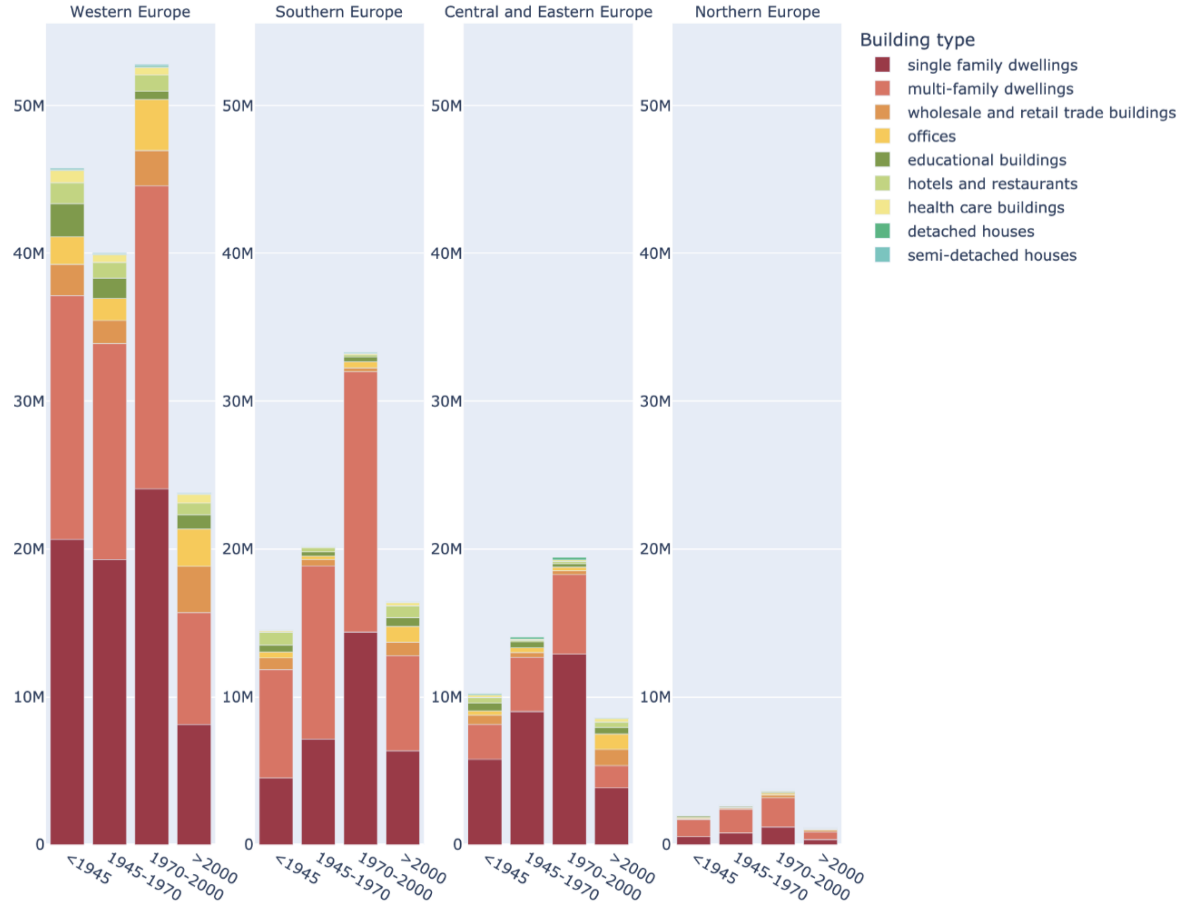


Figure 0.2 Number of buildings [millions] for each region in Europe (EU-27), split between four construction year periods and nine building types

Geographic regions

This definition of the four regions was originally inspired by EuroVoc (EUR-Lex, n.d.), however, some changes were applied to this grouping in order to better reflect building traditions and waste similarity:

1. Northern Europe: Norway, Sweden, Finland. Norway is included because of its membership to the EEA, even though it is officially outside of the EU-27. Denmark, Estonia, Latvia, and Lithuania were at the same time excluded from this region, as neither Danish nor Baltic CDW composition include a large prevalence of wood, as observed in the other Nordic countries.
2. Southern Europe: Cyprus, Greece, Italy, Malta, Portugal, Spain (same as EuroVoc).
3. Central and Eastern Europe: Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia. Estonia, Latvia, and Lithuania were added to this group, as Baltic building practice is considered similar to that of other Central or Eastern European countries, rather than to that of Nordic countries, based on the observed share of wood waste in the CDW data.
4. Western Europe: Austria, Belgium, Denmark, France, Germany, Ireland, Luxembourg, and the Netherlands. Denmark has been added to this group, as Danish building practices are considered similar to that of other Western European countries, rather than to that of Nordic countries, based on the observed share of wood waste in the CDW data.

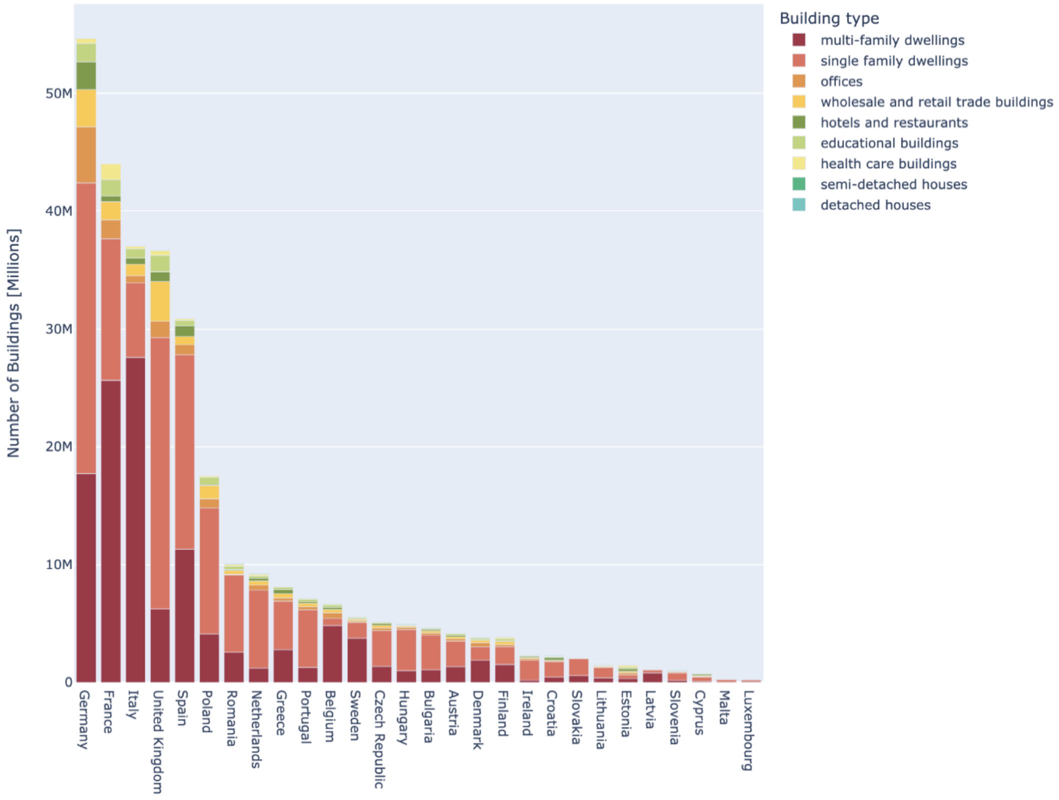


Figure 0.3 Number of buildings [millions] for each country in Europe (EU-27), split between the nine building types

Renovation rates and scenarios

Three different renovation scenarios create insight into the impact of increased policy pressure on both renovation activities and climate impact. One scenario in which current renovation practices continue until 2050 is called the Business as Usual Scenario. The Policy Compliant Scenario is a second scenario that models what would happen if renovation activities were increased to reach the sustainability targets in 2030 and 2050. As these targets are usually related to energy consumption the majority of the increased renovation rates can be found there. As literature (Schimaschar, 2011) states that there usually is a correlation between both energy and non-energy related renovation activities this was taken into account. The third scenario, the Ambitious Scenario, focuses on large-scale renovation activities in which all the buildings of the EU-27 would undergo major renovations to increase energy efficiency. Here the same correlation between energy and non energy related renovation activities was taken into account.

To outline the current impact of renovation activities, a material intensity is connected to different renovation activities. Ipsos & Navigant (2019) sets out a list of renovation types and divides these into energy and non-energy renovations. They divide both into three levels of intensity for energy renovations: deep, medium, and light. According to Schimaschar (2011), non-energy renovations can be divided into complete, partial, and particular renovations. The definitions are used to link the renovation types to a specific intensity level of renovation. The following definitions are set out:

- Energy renovations:
    - Deep renovation: saving >60% of energy consumption.
    - Medium renovation: saving 30-60% of annual energy consumption.
    - Light renovation: saving <30% of annual energy consumption.
- Non-energy renovations:
    - Complete renovation: complete renovation of the building.
    - Partial renovation: renovating or replacing one component of the building is affecting all occupants.
    - Particular renovation: carried out by private individuals for a specific part of a building.

Mapping of material flows connected to renovation activity

For each of these renovation activities, a certain set of affected building materials and/or products has been defined for all different housing typologies. For the modelling of the scenarios it is assumed that all components of the specific building are removed and replaced by current day alternatives. For example, if a façade from a building built in 1970 is removed, it will be replaced with a façade that would be applied in modern day building practices.

As the amount of products related to different scenario intensities differ, the amount of material consumed by each will also be different. Based on the scenarios described in the section above, the different scenario intensities are scaled in the policy compliant and ambitious scenario, creating different in- and outflows of material for different scenarios.

LCA

Life Cycle Assessment (LCA) is an internationally-standardised methodology used to quantify in a transparent and systematic manner the environmental impacts related to the lifecycle of materials, services and products. By taking into account the full life-cycle of the product, from the extraction of raw materials through production and use to final disposal (including recycling, reuse, and energy recovery), as well as several environmental impact categories potentially affected by the product system, LCA avoids the issue of burden-shifting from e.g. one life-cycle phase to the other, or from one environmental issue to the other.

While international standards for building LCA exist, as well as detailed calculation guidelines for e.g. how to account biogenic carbon in building products (ISO, 2018), a number of critical parameters (e.g. reference study period, reference service life, considered life cycle phases, level of detail/building components and reference unit) as well as aspects (e.g. input data quality, calculation tools) can significantly affect the final results, their usability, and comparability across countries, as demonstrated by a recent project carried out by DTI for the Danish Housing and Planning Agency (Butera et. al, 2021). Setting a common framework for the building LCA methodology at the EU or regional level is a crucial step in the process of establishing a baseline for whole life carbon.

The project team's expertise on LCA methodology will be used to assess, evaluate, and form the basis for defining baselines for embodied carbon as well as operational carbon across Europe.

Reading guide

This report on the impact of Circular Renovation Actions on the consumption of virgin materials and emission of GHG is comprehensive, but it is not designed to be read cover-to-cover. As such, different stakeholders might want to focus on the different aspects of it. This reading guide includes an overview of the content of each chapter.

Chapter 1: Methodology

Urban mining

This part of the report describes an extensive methodology, considering the Urban Mining Model. This model, developed in coordination with the EIB and JRC (EC, 2021), works according to bottom-up modelling principles and creates an overview of current and future renovation material flows.

Scope & Scenario modelling

The scope of this project is determined based on both spatial and time factors. The clustering of EU-27 countries is described in this chapter. The scenario modelling describes how different renovation activities are clustered into packages. The packages define the depth of the renovation and are then combined into three scenarios, based on direction from policy documents and directives from the EEA. These scenarios (Business as Usual, Policy Compliant, and Ambitious) are used to forecast the impact of certain renovation activities on the EU-27 building stock if the intensity of renovating was increased during the timescope of the project (2022-2050).

Circular Renovation Actions

The Circular Renovation Actions are obtained via work previously done by the EEA. These actions focus on material savings, reuse of materials, recyclability, and nature-based solutions. In this chapter, the actions are described in detail and a methodology is included, which describes in detail how the actions are modelled, with reference to external sources. It is important to note that these actions are not geared towards energy renovations, but can be implemented to all existing renovation activities.

Chapter 2: Data projections and results

Outputs and results of the different scenarios

Based on the methodology described in Chapter 1, this Chapter 2 contains the results of the different scenarios (Business as Usual, Policy, and Ambitious). These results are split between the different defined geographic regions and showcase both the consumption of virgin material (split by material type) and connected GHG emissions per year.

Impact of Circular Renovation Actions

Based on the results of the different scenarios, the impact of the Circular Renovation Actions is modelled. These results showcase both the consumption of virgin material and connected GHG emissions per year.

Chapter 3: European Roadmap

Strategy

Based on the results from different Circular Renovation Actions, three clusters are made. These clusters are ordered by theme: increased lifespan, reducing material consumption, and new generation materials. The clusters are modelled to create an overview of the potential material and environmental impact until 2050.

1. Modelling methodology

1.1 The Urban Mining Model: assessing building stocks and flows

The Urban Mining Model has been developed by Metabolic as a bottom-up model, estimating material stocks based on the characteristics and size of individual buildings, scaling those up to higher spatial scales (neighbourhood, city, and country).

The construction and demolition rates are expressed as a relative value compared to the building stock. The rates represent either the number of buildings or square metres of buildings that are removed from the stock or added to the stock. For instance, the demolition rate for residential buildings in Central and Eastern Europe is 0.014 in 2020 in comparison to the building stock from 2019. This represents an annual 1.4% decrease from the stock. So, if the overall stock would be 1000 buildings, 14 would be removed as a result of demolition in 2020. The challenge is that construction and demolition rates are generally known on the level of percentage of residential and non-residential buildings constructed or demolished (as compared to the total stock in a given year). However, demolition rates are rarely known per building type or year of construction. To assess these rates, we apply statistical modelling using probability distributions.

1.1.1 Methodology for Bottom up modelling and assessing renovation material flows

Bottom-up modelling is based on inventories of individual items and the material intensities of those items (Wiedenhofer et al., 2015). A bottom-up approach is usually based on a division of the stock into categories (housing, business premises, etc.), and then by the application of material ratios or intensities, for example, in tons/m^2 (Bergsdal et al., 2007; Sandberg, Sartori, & Brattebø, 2014; Sandberg et al., 2016).

Elements in the stock are generally differentiated according to a typology that crosses criteria relating to function, form, and age—for example, housing units in a building of less than three floors built between 1945 and 1960. This approach requires a good knowledge of the 'inner structure' of the stock, and allows both the quantity and the quality of materials to be assessed (Augiseau & Barles, 2017, p. 158). Inventories of construction materials are often done in order to obtain this type of detailed knowledge of the 'inner structure'.

The challenges with a bottom-up approach are the associated inaccuracies due to the scaling of the material compositions from inventories. General material compositions cannot be validated easily due to high spatio-temporal variations in construction practices.

Furthermore, new construction projects tend to be documented in more detail, including BIM models and even digital material passports, while past construction, renovation, and demolition projects are generally poorly described and documented, with mere 2D paper drawings that often do not include details on materials used. Trust in general estimates tends to be weak, so wide ranges may need to be applied to compensate for the low reliability of data.

An important assumption for bottom-up material flow analysis is that buildings can be divided into groups or types which have the same material intensity. Criteria such as construction period, use of a building (e.g. residential or non-residential) or location (e.g. country or climate zone) are used to differentiate between building types (Wiedenhofer et al., 2015).

1.1.2 Metabolic's Urban Mining Model

The bottom-up modelling is based on an existing model developed by Metabolic. The model was developed and published in 2020 together with SGS Search and the Dutch Economic Institute for the Built Environment (EIB, Metabolic, & SGS Search, 2020). The goal of the publication was to conduct a baseline assessment of the annual material flows and environmental impacts of the Dutch construction sector and to provide a prognosis until 2030. This publication was commissioned by the Dutch Transition Team Circular Construction Economy (part of the Ministry of Economic Affairs and Climate), and currently informs policy geared towards achieving a more circular sector.

- The model is developed using reference buildings for twelve different building typologies from the Netherlands (Figure 1.1). These reference buildings are derived from building inspections and inventories by SGS Search.
- The twelve building typologies are further refined into four construction year bins (<1945, 1945-1970, 1970 - 2000, >2000) to account for historical variability of building methods. Furthermore the twelve different typologies have been grouped together to form nine distinct building types, these building types correspond to the typologies the European Commission uses in their EU Building Database (EC, n.d.c.).

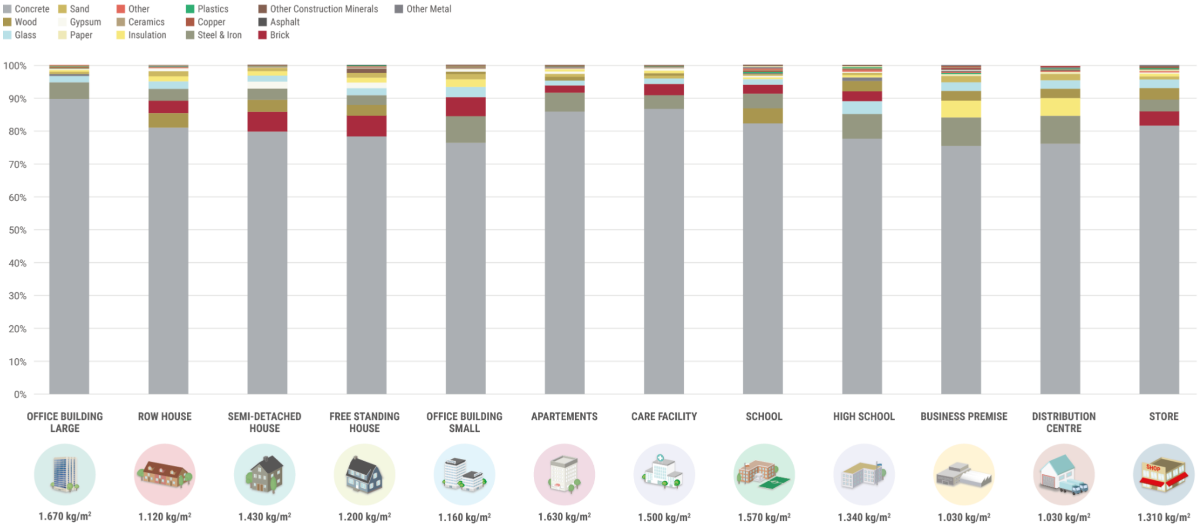


Figure 1.1 Twelve building typologies from the Netherlands.

The inventories by SGS Search provided insight into the occurrence of 150 distinct building products (e.g. the number of doors and window frames) as a function of the size, type, and age of the reference buildings. Based on this data, the model was constructed as described by Equation 1 and Equation 2.

- Equation 1 - Building product (i), for building (j), equals the multiplication of building size (k) in square metre, with the material composition for a specific building type (m), with the material composition of a specific construction year(n). Building products are expressed in their functional unit, for instance m3 sand, m2 exterior doors, and m2 wooden floors.

$$building\ products_{i,j} = building\ size_k \cdot building\ type_m \cdot construction\ year_n$$

- Equation 2 - The total material fraction equals the sum product of the building product (i), for building (j), multiplied with the material fraction (q) for each building product (i). The material fraction is expressed in kg or kg/m2.

$$total\ material\ fraction = \Sigma\, building\ products_{i,j} \cdot material\ fraction_{i,q}$$

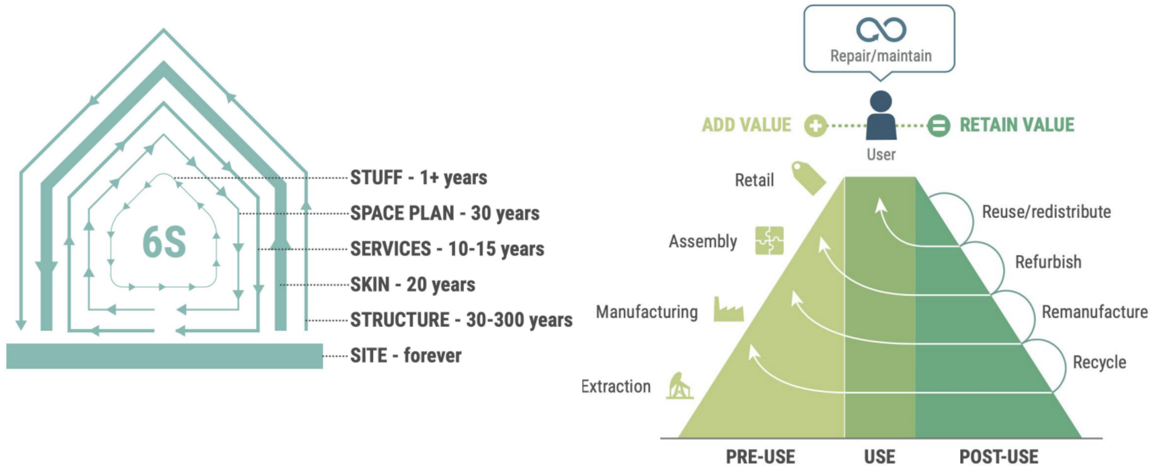


Figure 1.2 Shearing layers of Brandt (left) and value pyramid (right)

Using Equation 1 and Equation 2, the model provides insights on:

- Building product quantities of 150 unique building products for each of the twelve building typologies and five construction year bins. The building products are expressed in different units, e.g. pieces, m, m^2, or m^3.
- Material composition and mass of 78 unique materials for each of the twelve building typologies and five construction year bins.

1.1.3 From building stock model to renovation material flows

Based on Metabolic's Urban Mining Model described in the previous section, the selection of building products is used to create material intensities sets for the different renovation types. For example, for the renovation type 'Renovation/installation of the bathroom or toilet' the building products related to a bathroom or toilet for a specific building typology are selected and assumed to be replaced. This means that the materials related to the products replaced are modified and therefore the mass, lifespan, or environmental impact of that building product—and therefore the renovation type—are different.

For certain renovation types, there is variability in the building products outflowing and inflowing. This means that depending on the age cohort of the building that is renovated we might exchange a certain product for a new version of it with different materials, mass, costs or environmental impact. For example, for the renovation type 'Installation of thermal insulation on the roof', it may be assumed that an older building contains little or no insulation, and that with the renovation the appropriate amount of insulation is installed, matching with the newest age cohort of that same building type. This amount is defined based on the increase needed to reach the energy efficiency described in chapter 1.3. For this reason the mass of inflowing material might be greater than the mass of outflowing material for many renovation types.

1.2 Scope of the research

This analysis incorporates the four geographic regions as defined by EuroVoc (Figure 1.3), but the groups were modified to include Denmark as a Western European country for one main reason: the building environment of Denmark is more similar to the Western European group than to the Northern European countries, where wood has a bigger impact and importance. For each of these regions, calculations can provide the average renovation rate per level of intensity based on the amount of actions that take place in each of the countries within the specific area. For all of the countries in the four regions, the percentage of renovated stock is given per level of intensity: deep, medium, or light for energy renovations; complete, partial, or particular for non-energy renovations. Using these rates, an average renovation rate per geographic region is calculated, based on intensity and type of building (residential, non-residential).

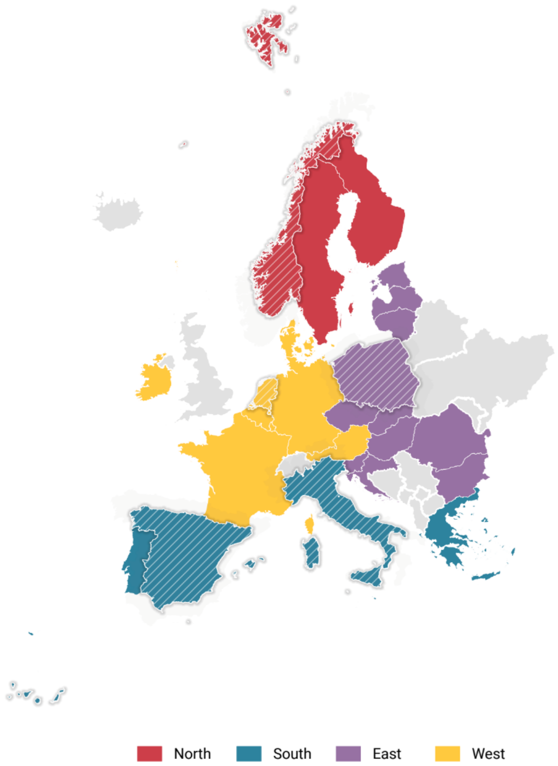


Figure 1.3 Geographic regions Europe (EU 27).

The study scopes the EU and Norway territory from 2022 until 2050. Nevertheless if needed, some forecast or predictions will be given in order to fully understand the impact or a certain Circular Renovation Action in the European built environment. To represent each of these geographic regions, certain reference countries were chosen. These are marked in Figure 1.3 with a dashed line.

- North: Norway.
- East: Poland.
- South: Italy and/or Spain.
- West: the Netherlands.

1.3 Scenario modelling

1.3.1 Description of circular scenarios

To outline the current impact of the building stock and expected future levels, three circular scenarios are established; Business as Usual, Policy compliant and Ambitious. To model the impact of these scenarios insight must be gained in the in- and outgoing material flows (quantity) and their embedded climate impacts (GHG emissions). Different renovation rates are proposed for these scenarios (see chapter 1.3.3) in which both energy and non-energy renovation activities are increased.

Renovation activities are depending on building stock diversion, geographical differentiation, type of renovation, and renovation intensity. Ipsos & Navigant (2019) divides the EU-27 building stock into residential and non-residential buildings. The number of renovation activities differs per country, according to Ipsos & Navigant (2019). The research done by Ipsos outlines the building energy renovations in the EU, per country, between 2012 and 2016. Geographical differentiation is therefore taken into account.

Ipsos & Navigant (2019) sets out a list of renovation types and divides these into energy and non-energy renovations. Both can be divided into three levels of intensity. Ipsos & Navigant (2019) outlines three intensities of energy renovations: deep, medium, and light. According to Schimaschar (2011), non-energy renovations can be divided into complete, partial, and particular renovations. In these studies more in depth information is given on what materials are involved to execute these renovations (See table 1.1 and 1.2) The following definitions are detailed as follows:

- Energy renovations:
    - Deep renovation: saving >60% of energy consumption.
    - Medium renovation: saving 30-60% of annual energy consumption.
    - Light renovation: saving <30% of annual energy consumption.
- Non-energy renovations:
    - Complete renovation: complete renovation of the building.
    - Partial renovation: renovating or replacing one component of the building is affecting all occupants.
    - Particular renovation: carried out by private individuals for a specific part of a building.

By understanding how often what renovation type is happening (deep, medium, light, etc.) in what country, and what material was impacted by these actions (table 1.1 and 1.2) the material flows of the three scenarios was modelled. The modelling proposes a replacement of outgoing material with the material equivalent from the newest reference building in the Urban Mining Model. For example; If in a deep energy renovation (see table 1.1) a window from a building in the cohort 1945-1970 is removed. It will be replaced with a window from the >2000 cohort. These renovation types were only used to model the three different scenarios (bau, policy, ambitious). In the modelling of the circular renovation actions these renovation types were not used.

Table 1.1 Type of energy renovations and depth of renovation

Renovation types	**Deep**	**Medium**	**Light**
Replacement of windows	X	X	X
Replacing a building entrance door	X		X
Installation of thermal insulation on the façade (incl. cavity wall insulation)	X	X	
Installation of thermal insulation of the roof	X	X	
Installation of thermal insulation on the ground plate (floors)	X	X	X
Installation of thermal insulation inside basements	X	X	X
Installation of thermal insulation on the attic's floor	X	X	
Replacement or first-time installation of a space heat generator	X		
Replacement or first-time installation of a water heater (incl. solar thermal collector on the roof)	X		
Replacement or first-time installation of a radiator	X		
Replacement or first-time installation of a floor heating system	X		
Replacement or first-time installation of a mechanical ventilation system	X		
Replacement or first-time installation of a space cooling system (air conditioner)	X		
Installation of a photovoltaic system (solar modules for electricity generation on	X		

the roof)			
(Automatic) shading system for windows to avoid overheating in summer	X		
New lighting installations (lamps)	X	X	X

Table 1.2 Type of non-energy renovations and depth of renovation

Renovation types	**Complete**	**Partial**	**Particular**
Facade renovation without applying insulation	X	X	
Roof renovation without applying insulation	X	X	
Building extensions without applying insulation	X	X	
Electric installations	X	X	
Interior wall painting, plastering or wallpapering	X		X
Interior flooring	X		X
Renovation/installation of the bathroom or toilet	X		X
Renovation/installation of the kitchen	X		X
Grinding & painting doors or window frames	X		X
Renovation/installation of stairs	X	X	
Dry-wall or ceiling constructions	X	X	
Renovation/installation or replacement of elevator	X	X	

1.3.2 Construction and demolition: baseline scenario

To model the impact of the three scenarios, a baseline scenario is required to use as a point of departure. The baseline scenario is a result from a research project conducted by the JRC (EC, 2021). This baseline sets out different input parameters for the EU-27 building stock. These parameters include the EU-27 countries, the different regions, nine building types divided over both residential and utility uses, and generic building materials. As the JRC research focuses on the entire building sector (demolition, construction, and renovation) this study is used as a reference to model the impact that lies outside the scope of renovation.

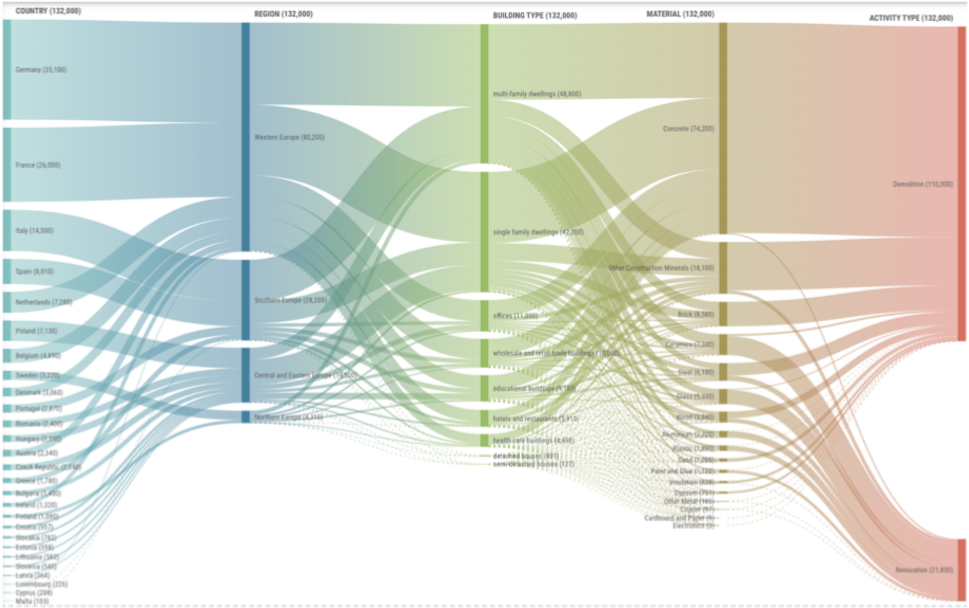


Figure 1.4 Parameters for baseline scenario: EU 27 countries, regions, building types, materials and activity type

1.3.3 Scenario 1: BAU

The first scenario aims to replicate the current state of affairs regarding renovation in the European built environment, in other words, what will happen if we keep renovating at the same rate as we currently are (Table 1.3).

1.3.3.1 Rates

Table 1.3 Renovation rates, Business as Usual Scenario; per type of renovation and depth of renovation

	Business-as-usual	
Renovation of EU-27 stock	**Annual rate residential (%)**	**Annual rate non-residential (%)**
Total energy related renovation	**5.32%**	**6.76%**
Light	4.25%	3.95%
Medium	0.96%	2.45%
Deep	0.12%	0.36%
Non-energy related renovation	**17.17%**	**14.06%**
Particular	9.08%	9.90%
Partial	7.98%	6.56%
Complete	0.10%	0.12%

1.3.3.2 Specifications

The rates have been defined based on two studies from Ipsos & Navigant (2019) and Schimaschar

(2011).

1.3.4 Scenario 2: Policy Compliant

This second scenario aims to predict what will happen if we increase the amount of deep renovations according to policy documents (Table 1.4). This pays special attention to the Renovation Wave for Europe (EC, 2020), which describes that the objective is to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations. The goal of these renovations are to cut GHG emissions, boost recovery, and reduce energy poverty.

1.3.4.1 Rates

Table 1.4 Renovation rates, Policy Compliant scenario, per type of renovation and depth of renovation

	Policy Compliant	
Renovation of EU-27 stock	**Annual rate residential (%)**	**Annual rate non-residential (%)**
Total energy related renovation		
Light	4.25%	3.95%
Medium	1.92%	2.45%
Deep	0.24%	0.72%
Non-energy related renovation		
Particular	9.08%	9.90%
Partial	7.98%	6.56%
Complete	0.22%	0.48%

1.3.4.2 Specifications

The rates have been defined based on a study from Schimaschar (2011) and Ipsos & Navigant (2019). Firstly, the rates for energy related renovations have been duplicated following the Renovation Wave Strategy (EC, 2020), but to avoid unlikely scenarios (where a house undergoes a 'deep' or 'medium' renovation several times before 2050) the rate of non energy related renovations has been increased only by the same value as the energy related renovations. This is based on the fact that more than 90% of residential energy renovations take place in combination with non-energy renovations, according to Ipsos & Navigant (2019).

1.3.5 Scenario 3: Ambitious

The goal of this scenario is to assess how renovations will increase until 2050 if we increase the amount of deep renovations to the degree that all buildings in the EU-27 stock will have undergone a complete / deep renovation before 2050 (Table 1.5).

1.3.5.1 Rates

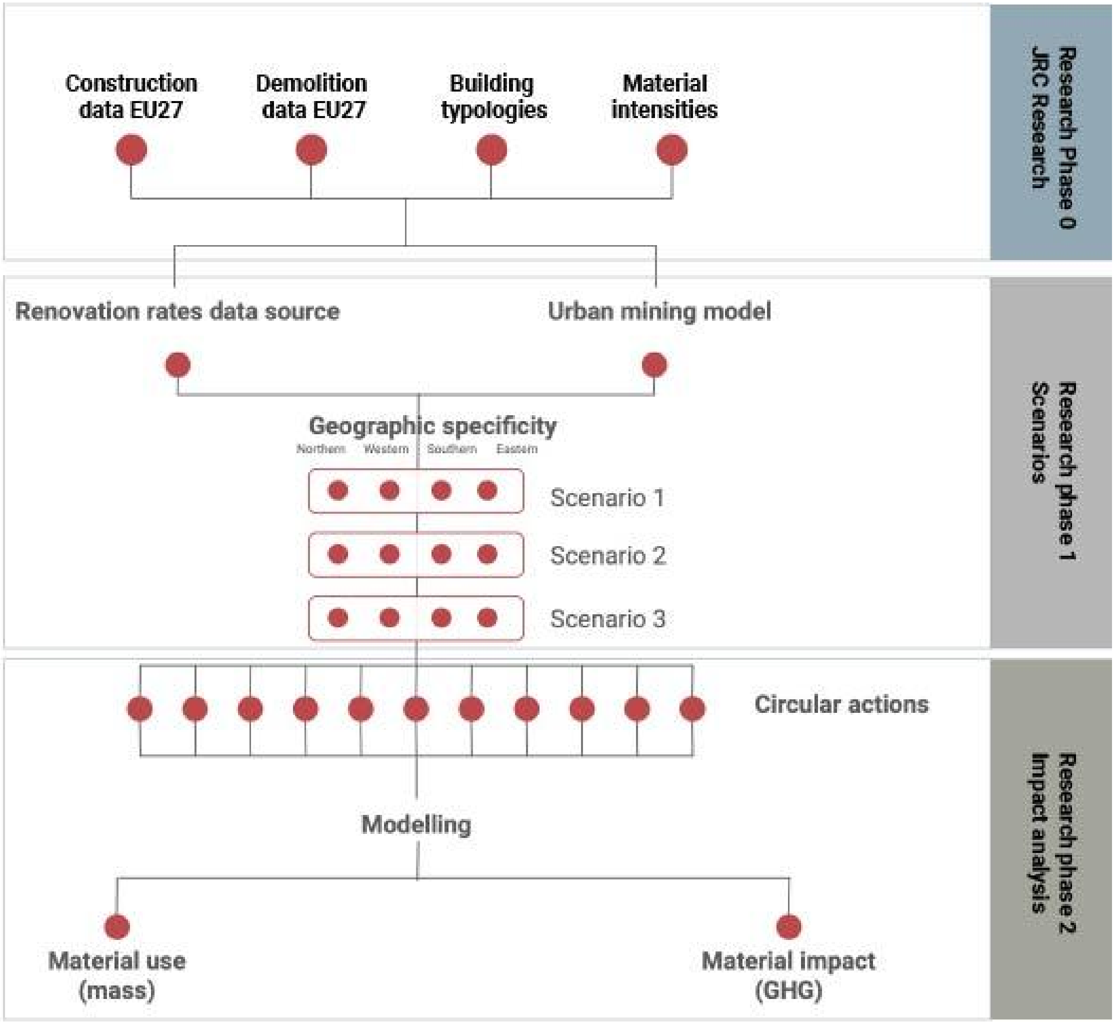
Table 1.5 Renovation rates, Ambitious scenario, per type of renovation and depth of renovation

Renovation of EU-27 stock	Ambitious	
	Annual rate residential (%)	Annual rate non-residential (%)
Total energy related renovation		
Light	4.25%	3.95%
Medium	0.96%	2.45%
Deep	2.64%	1.15%
Non-energy related renovation		
Particular	9.08%	9.90%
Partial	7.98%	6.56%
Complete	3.60%	3.60%

1.3.5.2 Specifications

The rates have been defined based on a study from Schimaschar (2011) and Ipsos & Navigant (2019). If we project that 3.6% of the current building stock is renovated every year until 2050, this means that all the buildings of the current building stock will be renovated (or at least the total number will be equivalent). Therefore the rates for energy related renovations are meant to sum up about 3.6% between medium and deep renovations (since light renovations do not have a significant impact in terms of materials or GHG). On the other hand, the deep non-energy related renovations are set to 3.6% following the same logic (particular and partial non-energy related renovations have a very small impact according to our models).

1.3.6 Modelling overview



The modelling approach can be divided in three layers (see image above):

- **Material flows per scenario:** The renovation rates and the material intensities for the different renovation types described in chapter 1.1.3 are used to describe the material flows for each scenario as described in 1.3.3. Based on the renovation rate for each country and the different renovation types, a rate for each renovation type can be derived. The renovations are assumed to be uniformly distributed across the different renovation types within the different levels of intensity.
- **Impact per Circular Renovation Action**: These material flows are used as a baseline for the renovation actions described in the following chapters.
- **Comparative analysis:** The impact of each renovation action can then be calculated by comparing them with the baseline flows.

1.4 Methodology for modelling Circular Renovation Actions

1.4.1 Description of Circular Renovation Actions

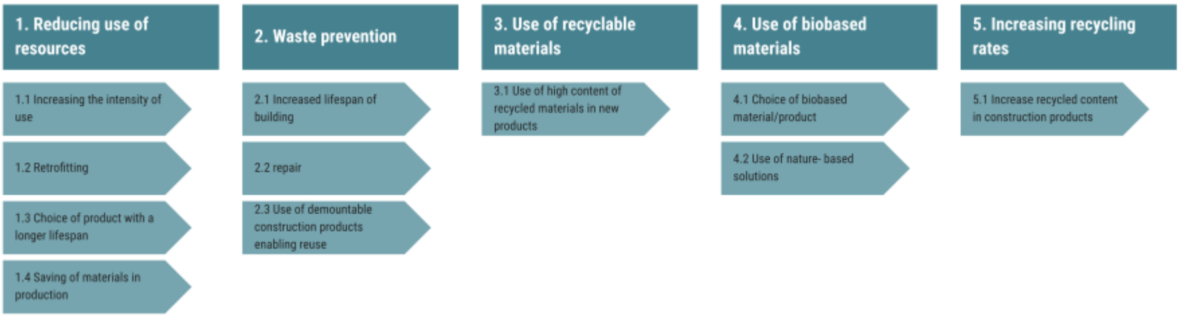
The Circular Renovation Actions are a set of processes, interventions, or upgrades of the urban environment that have been developed by the EEA in previous research projects. These actions are organised into the following five groups or levels that address the common impact type of a set of actions (see Figure 1.5):

1. Reducing the use of resources.
2. Waste prevention.
3. Use of recyclable materials.
4. Use of biobased materials.
5. Increasing recycling rates.

The main goal of these actions is to cover most of the possible approaches to a circular economy in the built environment. The intention behind providing such a big range of actions is to get to a full understanding of the real impacts of different approaches in order to upgrade the built environment to achieve the European targets for 2050. It is important to note that some of these actions overlap, e.g. biobased materials (Action 4.1) will replace certain mineral-building products which would have used secondary materials (Action 3.1).

This study aims to estimate the climate benefit from circular renovation and to use this to create clear climate targets for the year 2050. Each action required the development of a different methodology that will be described in the following pages of this report. This approach to the calculation of each circular action has been based on desk research, the Urban Mining Model, and Metabolic's expertise in the field.

Figure 1.5 Circular economy goals and related actions in renovation in Europe



1.4.2 Renovating instead of building (1.1)

This Circular Renovation Action focuses on the reduction of virgin material consumption by the prevented need for additional buildings. This is done by transforming existing spaces into multipurpose spaces by combining functions operating at different times, within a so-called mixed-use space. This creates optimal use of the available space and reduces the need for additional building space or buildings. Hence virgin material consumption and the corresponding emission of GHG is being reduced.

Based on desk research, a set of functions has been created that can also be combined. Table 1.6 gives an overview of the functions that can share a (multipurpose) space or building (Floornature, 2014). The first column lists the original function of a specific space or building. The second column contains the function that could use the space from the initial function in a mixed-use fashion. Table 1.6 also shows the percentage of saved floor area by applying this Circular Renovation Action. For example: combining canteens of office buildings with restaurants will result in a saving of 2.81% of additional floor area needed for restaurants. Since this floorspace is no longer needed it is assumed these buildings will also not be constructed. This will result in a saving of virgin material consumption and GHG emissions. Below, it is further described how the percentages are determined for each of the mixed use functions. A lot of the data for this Circular Renovation Action could only be found for Dutch cases. This might result in uncertainties when upscaling the data to the European level.

Table 1.6 Mixed use functions and percentage of saved floor area

Main user function	Additional function	Percentage
Office canteen	Restaurant	2.81%
Lunchroom	Restaurant	0.67%
Office	Yoga school	0.09%
Office	Concert venue	0.04%

Table 1.7 Building types and functions and building stock in a central urban area

Building type	m2 building stock	Source
Offices	88,050,000	EC, 2021
Hotel and restaurants	36,185,382	EC, 2021
Lunchrooms	24,300	Spronsen & partners, 2016
Yoga schools	74,888	Ondernemende sportaanbieders, n.d. De nieuwe yogaschool, n.d. De Yogaschool, n.d.
Small concert venue	34,400	EM Cultuur, 2019

Synergy 1: Office canteens and restaurants

For combining office canteens and restaurants, only office buildings in central urban areas are considered. These will be able to attract the most ‘foot traffic’, and so they are deemed to have the highest success rate. According to NVM Business (2021) 27.0% of the floor area from office buildings is located in central urban areas.

The floor area of canteens is determined using the total floor area of office buildings in the Netherlands, the average occupancy and the floor area per occupant. The percentage of floor area that can be assigned to canteens amounts to 10.4% (NEN, 2010 and ARBO podium, n.d.), of the total floor area of an office. The total floor area of offices in central urban areas that can be assigned to office canteens will therefore be 2.81%. Hence, 2.81% of the total floor area of office buildings can be used as a restaurant.

Synergy 2: Lunchrooms and restaurants

Estimating the floor area of lunchrooms and restaurants is needed to determine the potential of combining lunchrooms and restaurants. According to Spronsen & Partners (2016), the Netherlands counted 3,000 lunchrooms in 2016. The average floor area of a lunchroom is 81 m^2, which results in a total floor area of 243,000 m^2 in the Netherlands.

The total floor area of hotels and restaurants was extracted from the Urban Mining Model and amounts 361,185,382 m^2. The share of lunchrooms within hotels and restaurants therefore accounts for 0.67% of the total floor area of hotels and restaurants.

Synergy 3: Office and yoga school

Floornature (2014) devised a creative solution to combine offices with yoga schools. As a yoga space does not require many attributes and can effortlessly be set up, this is a logical combination of functions. Existing offices can share their space with yoga schools on evenings and weekends. Other functions that are not reliant on many attributes could be combined with offices in this manner as well.

Analysing different yoga schools in the Netherlands led to the estimation of the average floor area of a yoga school, which is determined to be 202 m^2. The Netherlands counts 370 yoga schools, which are all affiliated with the yoga school association, in accordance with Ondernemende Sportaanbieders (n.d.). This leads to a total floor area of 74,888 m^2 of yoga schools and can save 0.09% of the floor area of office buildings.

According to NVM Business (2021), 5% of the total floor area of office buildings can be assigned to office buildings with a floor area between 500 and 1,000 m^2. Office buildings with a floor area between 1,000 and 2,500 m^2 account for 20% of the total floor area. This means that the yoga schools can be accommodated in the office buildings with a floor area between 500 and 1,000 m^2.

Synergy 4: Office and concert venue

Floornature (2014) devised a creative solution to combine offices with small concert venues. Existing offices can share their space with small concert venues on evenings and weekends.

In accordance with EM Cultuur (2019) 2019 counted 172 small (< 400 m2) concert venues, with an average floor area of 200 m2, with a total floor area of 34,400 m2. Medium-sized and large concert venues were left out, because of the supply of systems and other requisite equipment that would be necessary.

The total floor area needed for small concert venues will be a share of the total floor area of offices. The percentage of floor area that can be saved by combining offices and small concert venues would be 0.04%.

1.4.3 Adaptive reuse (1.2)

This Circular Renovation Action focuses on preventing the consumption of (virgin) materials by applying the principles of adaptive reuse. According to the Metropolitan Research Institute (2019) Adaptive reuse means the process of converting a building to a new use that is different from that which its design reflects, for example, converting offices to a residential building. Good adaptive use projects retain a building's historic character while accommodating new functions. To scope the research of this Circular Renovation Action, 15 European countries were reviewed (under which are four reference countries used for this study, please see Chapter 1.2). The overarching trend on the topic of adaptive reuse in all countries was the conversion from non-residential to residential functions. The exact transformation rates were only found for the Netherlands and Norway (which are the reference countries for Northern and Western Europe). The average of these adaptive reuse rates of Norway and the Netherlands was used to project the conversion rate from non-housing to housing units in the other two geographic regions.

Case study 1: The Netherlands

Based on available data from the National Agency of Statistics (Centraal Bureau voor Statistiek, CBS) it is assumed that on average, 11,024 new dwellings per year are added to the Dutch building stock via the practice of adaptive reuse (Table 1.8). The previous function of these buildings is also known (1.9). Based on an average dwelling size of 65 m^2 GFA (CBS, 2018) it is assumed that 837,940 m^2 GFA of housing was added to the Dutch housing stock via the practice of adaptive reuse.

Table 1.8 Amount of homes created by adaptive reuse in the Netherlands

Year	New housing units
2015	10,770
2016	10,235
2017	10,235
2018	12,210
2019	12,480
2020	10,215
Average	**11,024**

Table 1.9 Housing transformations based on the original function in the Netherlands

Original function	% of transformed functions
Office spaces	35.23%
Rest	23.76%
Societal functions	22.10%
Store	12.40%
Industrial	6.52%

Scaling up to increase impact

To understand the maximum potential of using adaptive reuse strategies as a Circular Renovation Action, it is necessary to understand what percentage of the building stock is vacant and could be transformed according to these principles. This research should specifically focus on the adaptation of empty buildings as these will prevent the need for virgin building material. The reasoning is, if one adapts a building in which an existing function is still housed, this function will need to find other housing and therefore demand new construction.

The average empty stock was researched per function, as mentioned in Table 1.9. If possible more spatial aspects were taken into account which would make any transformation more suitable (e.g. proximity to central urban areas). Once this vacant stock was established, the transformation rate was projected over the next 28 years. This period was selected to make the annual savings of virgin material more realistic, since it is not possible to renovate all vacant building stock in one year. The results of this research can be found in Table 1.10. Below, the office building is explained as an example:

- There is 88 million m^2 GFA of office space in the Netherlands. On an annual basis, 295,150 m^2 GFA is being transformed into housing. This is 0.3% of the total stock.
- In the Netherlands, 6.3% of all offices are empty, which would mean they could be transformed into housing units.
- Not all locations are fit for transformation; local factors such as liveability should also be considered. According to the Dutch Enterprise Agency (RVO, 2021), up to 33% of office spaces could be transformed into apartments if the surrounding liveability of the area is also taken into account.
- This would result in 1,819,150 m2 GFA of office space available for transformation.
- It is assumed that there will be no big influx of new 'empty offices' and therefore the vacant office space with a high potential for adaptive reuse will be spread over the next 28 years (2022-2050) which will result in an annual increase of 0.22% of additional national office building stock that can be renovated.

Table 1.10 Potential increase of the annual adaptive reuse rate

Building type	m2 total stock	m2 transformed	% of stock transformed annually	m2 currently suitable for transformation	Yearly possible increase (%)	Source
Wholesale and retail trade buildings	175,050,000	158,454	0.091	1,000,000	0.22	Rabobank, 2021
Offices	88,050,000	295,152	0.335	1,819,150	0.22	Rabobank, 2021
Educational buildings	64,960,000	185,137	0.28	342,548	0.06	Centraal beheer, 2018
Hotel and restaurants	34,976,700	99,547	0.28	199,810	0.072	No literature (assume same as retail)
Healthcare buildings	64,960,000	99,547	0.153	371,094	0.13	No literature (assume same as retail)

Case study 2: Norway

The same methodology was applied for Norway. Based on data from the Central Bureau of Statistics Norway (Statistisk Sentralbyrå) it is assumed that in 2016, 2,423 dwellings were added because of adaptive reuse strategies in existing buildings. Of these added dwellings, 944 were due to the rebuilding of residential buildings, 1,330 were built in industrial buildings, and 149 were the rebuilding of garages, outhouses and annexes linked to dwellings (Statistiek Sentralbyrå, 2017). Based on the average building size for these different typologies of buildings, 185,290 m^2 GFA was added to the Norwegian housing stock based on adaptive reuse renovations (166,620 m^2 GFA was added in industrial buildings, 18,670 m^2 GFA was added in annexes). The scaling potential of these two typologies was cross-referenced with the vacant stock and spread evenly over the timeframe of this research (2022-2050) which resulted in the potential yearly increase. For example, Table 1.11 below shows that the additional percentage of total stock that could potentially be transformed is 6.4%. When distributed over 28 years, that amounts to 0.23% extra transformed space per year.

Table 1.11 Potential yearly increase of vacant stock Northern Europe

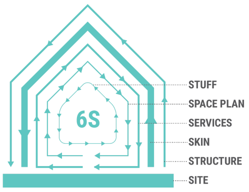
Old function to housing	Annual amount of total stock (%)	Scale potential based on vacant spaces (%)	Yearly increase (%)
Offices	0.31	6.4	0.23
Wholesale and retail trade buildings	0.42	4.7	0.17

NOTE: Based on current developments regarding the COVID-19 pandemic, the possibility of extra office/store spage becoming vacant and fit for transformation was researched. Based on national research for the Netherlands, there was no indication or significant scientific research projecting additional empty spaces. Therefore, it was not made part of this modelling exercise.

Material intensity

This action specifically focuses on the transformation of existing buildings to prevent new construction, and therefore, the need for virgin materials. To map the saving of virgin materials (and prevented GHG emissions) this action is modelled based on Stewart Brand's shearing layers model (1994). Which layer will be removed from the building is decided based on the year of construction and transformation. Based on Van der Voordt (2007) the following actions based on the different layers of the building are assumed (see Table 1.12).

Table 1.12 S-layers being altered in adaptive reuse practices

S-layer	Building > 1945	Building < 1945	
Structure	No action	No action	
Skin	Replace insulation material	Replace with new skin	
Spaceplan	Replace with new interior spaceplan	Replace with new space plan	
Services	Replace with new installations and services	Replace with new installations and services	

Based on Table 1.12, it can be assumed that for most adaptive reuse practices, the services, the spaceplan, and in some cases the skin will be replaced. Even though the majority of the S-layers will be replaced or altered, the majority of material and environmental impact of the building will remain intact. As the structure (foundation and load bearing structure) is responsible for the majority of the material consumption and embedded GHG-emission, the savings will still be significant.

1.4.4 Choice of materials/product to lengthen lifespan (1.3)

This Circular Renovation Action focuses on using components and/or elements with a longer technical lifespan for the renovation of the European building stock. The goal is to lengthen the renovation cycle which will reduce the need for virgin material (and embedded GHG emissions) in the future.

- To model this action, the critical component for all renovation types have been assigned.
- The critical component is the component with the shortest technical lifespan within a renovation type. When deciding if a component is the critical component, the geometrical and assembly obstacles were also taken into account. For example, if one can repair the critical

component without damaging the other components, and from a financial perspective it would also make sense to do so, it would not be dubbed a critical component.

In this example (Table 1.13) the critical component is the machinery of the air conditioning unit. The technical lifespan of these components is based on the data from the Nationale Milieu Database (NMD, n.d.). It focuses on the environmental impact and technical lifespan for building components used in the Dutch building sector. No significant deviation was found for other countries. The technical lifespan of the NMD is therefore used across all geographic regions.

Table 1.13 Example critical component per renovation type and technical lifespan

Renovation type (old)	Building product	West Europe / Apartment building / 1990	Technical lifespan
Replacement or first-time installation of a space cooling system	Air conditioning (ventilation shafts)	Air ducts / corners	35
		Machinery	20
		Rosters	35

To model this action and replace the critical component in each of the renovation types, two strategies were applied:

- **Strategy 1:** The critical component will be replaced with an alternative with a longer technical lifespan. In the case of the example in Table 1.13, this entails finding machinery that has a longer lifespan.
- **Strategy 2:** The entire outgoing product will be replaced by an alternative technology that will provide the same service, but has a longer technical lifespan based on the NMD. An example of this can be found in Table 1.14.

Table 1.14 Example alternative technology per renovation type and technical lifespan

Renovation type (old)	Building product	West Europe / Apartment building / 1990	Technical lifespan
Replacement or first-time installation of a space cooling system	Climate ceiling (cooling panels)	Metal sheet	50
		Aluminium piping	50
		Insulation	50
		Attachment units	50
		Piping	50

In this example, an alternative system with a lifespan of 50 years (instead of 20) was chosen. This will reduce the need for installing new air conditioning units (with fitting shafts etc.) by 2.5 times over the same timeframe. When selecting the alternatives the only parameter on which they were selected is the longer lifespan. Technical and financial feasibility and embedded GHG impact were not taken into account.

As the scope of this project focuses on the period 2022-2050 it was decided to only focus on renovation types (energy and non-energy) with a technical lifespan of 30 years or less. Lengthening these will be the only type which will have influence on the use of virgin materials and embedded GHG emissions during the timeframe of this project. This will result in a reduction of the virgin material consumption and GHG emission towards the end of the scope of this project. The majority of the environmental gain will be generated after 2050. This is because the majority of the products which are replaced with alternatives have a lifespan longer than 30 years. This means that the benefit will only start to become visible after the initial lifespan of the original products has passed.

Based on the lengthened technical lifespan the renovation, the intensities for both energy and non-energy renovation types were altered (different materials going into the EU-27 building stock for certain renovation actions) and lengthened (as the technical lifespan is lengthened because of other products, the action will not take place as frequently). In the example of the climate ceilings above, this would mean the following: from 2022 onwards (where relevant) all space cooling systems installed will be climate ceilings (50-year lifespan) instead of air conditioning units (20-year lifespan). From 2042 onwards, there will be a benefit of reduced renovations from not having to replace air conditioning units. This benefit will be fully realised in 2072, after the technical lifespan of the replacement product has expired, in which it will in total have reduced the number of renovations required by 2.5 times.

1.4.5 Saving of materials in façade production (1.4)

This Circular Renovation Action focuses on the reduction of virgin material consumption and GHG emissions via the reduction of material needs during the production of building products used for renovation activities. Both during the conventional method of new construction and during renovation of buildings, vast amounts of waste are produced from cutting the cladding pieces and adapting insulation to the geometry of the building (Torres, 2021). This aspect is the reason to look more critically into the processes of both new construction and renovation. The use of prefabricated buildings, building elements, and products can significantly reduce the amount of waste, and at the same time have a positive impact on the environment.

Prefabricated buildings and building elements are slowly becoming a trend within the circular economy. To assess the potential of saving materials in production, we look at how much material can be saved by using prefabricated building elements versus regular construction. It is assumed that prefabricated façades are the most relevant at the moment and are applied the most. This action will therefore exclusively focus on prefabricated façades.

Based on research on modular façades done by Torres (2021), it is assumed that a significant percentage of material savings can be achieved in comparison to conventional construction methods. Prefabricated modular systems have been assessed; the savings of production materials required by using prefabricated façades versus normal façades are outlined in Table 1.15.

To model these percentages correctly, in the Urban Mining Model, the products and percentages of savings are linked to specific renovation types. For example, the cladding and insulation of a prefabricated façade can be assigned to the energy related renovation 'Installation of thermal insulation on the façade'. Cladding and insulation are both modelled within this renovation type and therefore the percentage of saving can be deducted from the total mass from cladding and insulation. Within the timeframe of 2022-2050, the façades that are in need of a renovation are renovated by implementing a prefabricated façade.

Table 1.15 Percentage of material savings due to prefabricated building products

Renovation type	Product	Percentage of saving
Installation of thermal insulation on the façade	Cladding	30.00%

Installation of thermal insulation on the façade	Insulation	20.00%
Façade renovation without applying insulation	Construction	25.00%

1.4.6 Increased lifespan of buildings (2.1 + 2.2)

Due to their similarities in nature, action 2.1 and 2.2 has been merged into one action; The increased lifespan of buildings. This Circular Renovation Action focuses on the reduction of virgin material consumption by reducing the need for new buildings by increasing the lifespan of existing buildings. This action was modelled by:

- Researching the most common reasons for demolition.
- Which of Brand's shearing layers (1994) are affected.
- Which actions could be taken to prevent demolition.

Based on the research, the most prevalent reason for demolition is economic reasons which can not be fixed by renovation activities. However, around 30% of demolition was due to failing technical requirements (SEV, 2020). Over time, important characteristics of building materials and elements can decrease in quality, due to:

- Ageing.
- Deterioration.
- Infestation by harmful contaminants.

This causes buildings to no longer meet current building standards. The reduction in quality of the building materials and elements of different building layers can lead to the decision to demolish a building instead of renovating it (Thomsen, 2010).

Building layers that influence demolition are mainly the structure (including the foundation) and the building services. Since building materials have the largest share and highest impact on mass and GHG emissions, only these are considered in this action.

The result of this action will be the potential lifetime extension of buildings, and hence postponing the need for demolition.To model this action, the building layers that lead to a building being demolished—structure and foundation—are analysed. Based on desk research, interventions which can strengthen the original structure, remove harmful contaminants, and increase the quality of compound building materials and elements are determined. Each of the interventions is related to a potential lifetime extension in years and the relevancy to the residential and non-residential building stock (IEA, 2018). The interventions are categorised by type of structure and type of material. Tables 1.16 and 1.17 show the different types of interventions for a wooden and concrete structure.

To model these interventions, the average potential lifetime extension per material is assigned to the structural material (wood, concrete, and masonry) of the building stock. The average lifetime extensions are listed in Table 1.18. The potential lifetime for masonry is expected to be an average of concrete and wood, since masonry buildings are mostly constructed out of masonry and wood, and considering the characteristics of masonry and concrete, the intervention will partly overlap.

The reduction in construction necessary comes from the lifetime extension of buildings that would otherwise be demolished. Based on the maximum lifetimes for residential and non-residential buildings, of 75 and 50 years respectively (W/E adviseurs, 2020), it can be estimated that the percentage of new construction can decrease.

To model the number of buildings and m^2 floor area being demolished by cause of the condition of a building (e.g. ageing, deterioration, and infestation by harmful contaminants), the studies from Huuhka & Lahdensivu (2014) and SEV (2020) are used as a starting point. Huuhka (2014) indicates that 47.0% of the buildings being demolished in Finland are caused by the condition of the building. SEV (2020) indicates that 33.0% of the buildings in the Netherlands are being demolished due to the condition of the building. These percentages are linked to the geographical regions Northern and Western Europe. The percentages of Eastern and Southern Europe are determined by averaging the percentages of Northern and Western Europe. Table 1.19 shows the percentages of buildings being demolished due to the condition of the building, per geographic region.

Table 1.16 Potential wood interventions for the increased lifespan of buildings

Interventions wood	Potential lifetime extension (years)	Average (years)	Relevant to residential stock (%)	Relevant to non-residential stock (%)	Source
Foundation					
Wooden elements can be repaired with epoxy (large repairs need reinforcements)	15	15	16%	5%	Crow, 2013
Structure wood					
Wooden elements can be repaired with epoxy (large repairs need reinforcements)	20+	20	16%	5%	Crow, 2013
Partly replacement of wooden element, new and old element are glued together	10+	10	16%	5%	Crow, 2013
Slant wooden surfaces in direct contact with moisture to prevent rot	10	10	16%	5%	Crow, 2013
Reinforce wooden beams with steel slabs in case of tears	10	10	16%	5%	Crow, 2013
Hollow wooden cracks and fill them with epoxy	5-10	7.5	16%	5%	Crow, 2013

Table 1.17 Potential concrete interventions for an increased lifespan of buildings

Interventions (reinforced) concrete	Potential lifetime extension (years)	Average (years)	Relevant to residential stock (%)	Relevant to non-residential stock (%)	Source
Prevent substances from coming in	5-10	7.5	58%	65%	Sika, 2012 & Crow, 2013
Moisture management	5-10	7.5	58%	65%	Sika, 2012 & Crow, 2013
Concrete renovation	5-25	15	58%	65%	Sika, 2012 & Crow, 2013
Structural strengthening	10-25	17.5	58%	65%	Sika, 2012 & Crow, 2013
Enhancement of physical durability	5-10	7.5	58%	65%	Sika, 2012 & Crow, 2013

Durability against chemicals	5-10	7.5	58%	65%	Sika, 2012 & Crow, 2013
Conservation of passivity	5-25	15	58%	65%	Sika, 2012 & Crow, 2013
Enhance the resistance performance	5-10	7.5	58%	65%	Sika, 2012 & Crow, 2013
Control of cathodic areas	10-30	20	58%	65%	Sika, 2012 & Crow, 2013
Cathodic protection	10-30	20	58%	65%	Sika, 2012 & Crow, 2013
Control of anodic areas	10-30	20	58%	65%	Sika, 2012 & Crow, 2013

Table 1.18 Potential average lifetime extension, per building material and building category

Material	Potential average lifetime extension (years)	Relevant to residential stock (%)	Relevant to non-residential stock (%)
Concrete	11.80	58%	65%
Wood	13.25	16%	5%
Masonry	12.50	19%	7%

Table 1.19 Percentage of demolished buildings as a result of the condition, per geographic region

Geographic region	Reduction (%)
Western Europe	33.0%
Northern Europe	47.0%
Eastern Europe	40.0%
Southern Europe	40.0%

1.4.7 Use of demountable products enabling reuse (2.3)

This Circular Renovation Action focuses on the use of demountable products to enable reuse after their first lifecycle. As these products will be reused in other building and/or renovation projects they will replace new products and therefore reduce the need for virgin materials and prevent GHG emissions.

The traditional methods of renovating buildings centres on the dismantling and knocking down of certain parts of a building using force. This means that products and elements will be damaged making it almost impossible to find high value reuse possibilities. Although this demolition-like approach is quick, its environmental and economic impacts are overwhelming. A more sustainable approach to the end-of-life disposal of building materials is building deconstruction, which is the disassembly of buildings piece by piece to maximise material reuse (Kibert, 2008).

Accordingly, an efficient deconstruction procedure upholds the waste hierarchy by giving top priority to waste prevention through material reuse and recycling. The goal of disassembly is to eliminate demolition waste (Gorgolewski, 2006) and to ensure the recovery of components during usage or at the end-of-life of buildings (Kibert, 2008). According to Dorsthorst and Kowalczyk (2002), less than 1% of existing buildings are fully demountable. By applying Design for Disassembly (DfD) measures, many products can be reused with minimal refurbishment and environmental impact.

The yearly demand for products and components models for these actions, and regular products are replaced by DfD products or assembly methods. By using products which are suited for Dfd the high value reuse of these products can be made more feasible. This high-value reuse will reduce the demand for new building products and therefore virgin materials in the future.

When designing for disassembly, these five parameters need to be taken into account:

- Connections (e.g. glue, nails, screws).
- Assembly (e.g. reachable connections).
- Geometry (e.g. standardised dimensions).
- Material (e.g. non-toxic materials).
- Management (e.g. documentation, alternative ownership).

To model this action, all building products (not materials) were reviewed to see if they could be applied according to DfD principles, based on these five parameters. The products were categorised into three categories.

- Not suitable for DfD:
  - Products that can't be reused because of technical innovation (e.g. single glazed windows).
  - Products that can't be reused because of application methods (e.g. PUR-insulation foam).
- Suitable for DfD and currently available in the market:
  - Products that can be applied according to DfD principles (e.g. roofpanes).
- Suitable for DfD with minor innovation:
  - Products that can be applied according to DfD principles if minor innovation takes place (e.g. non loadbearing brick façade which could be made without mortar).

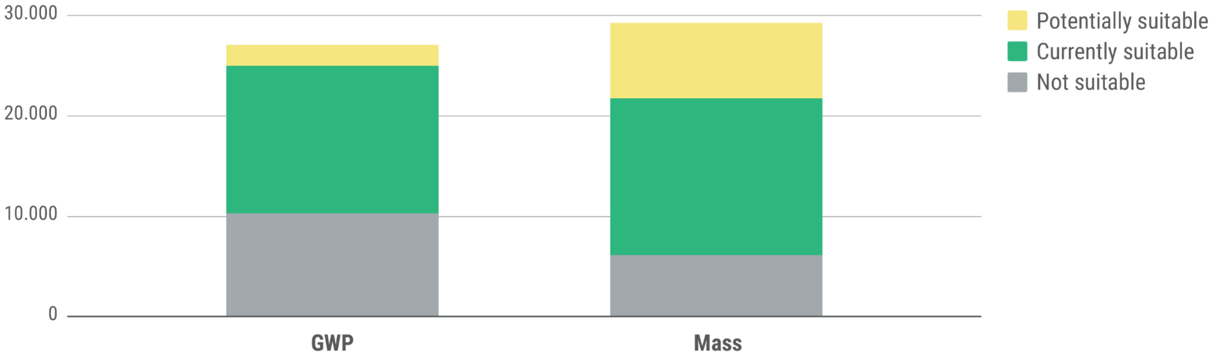


Figure 1.6 Yearly GWP and mass per DfD category

These three categories were used to model inflow and outflow of material. Over 46% of products (mass) we are currently using could be installed using DfD principles. These products are responsible for 52% of GHG emissions. An additional 35% of all products could be applied according to DfD principles with a certain level of innovation (e.g. new types of glue which can be disassembled). These products are responsible for 8% of all GHG emissions. As certain types of carbon intensive products such as single glass and insulation are not suitable for DfD measures, there is a large discrepancy between the mass and GHG emission saving potential of DfD measures (see Figure 1.6).

Understandably, the value of the building and its components after its end of life is not guaranteed, making the case for DfD a lot harder. According to Oyedele et al. (2013) the benefits of applying DfD principles outweigh the cost if the value of the building components is retained via reuse at their end-of-life. It was assumed that half of all materials that we would apply according to DfD principles 'now' would be reusable if they came out of the building stock after the technical lifespan of the renovation type to which they were tied. This means that they would replace virgin material in future renovation types.

Similar to action 1.3 the benefit of this action starts to become visible towards the end of the timescope (2050). Additional benefits will be created after the year 2050 and should be taken into account when assessing this Circular Renovation Action.

1.4.8 Use of materials with high recycled content (3.1)

This Circular Renovation Action focuses on the prevention of virgin material consumption by increasing the percentage of secondary material in new building products. This is done by modelling the need for 'raw' materials for the three different scenarios (BAU, Policy, Ambitious). A more detailed description of these scenarios can be found in chapter 1.3. Based on the demand for material the technical maximum (see table 1.20) of secondary material is added to replace virgin material consumption. This is done taking into account the current amount of secondary materials used in building products. With the advance in low energy or low environmental impact building designs, the environmental impacts or energy consumption of the operating phase becomes substantially reduced. The proportion of energy consumed during the manufacturing and demolition phase becomes more and more significant. Recycling of building materials (Thormark, 2002) could reduce the environmental impact associated with the materials in the building and could reduce the total life cycle energy significantly (Blengini, 2009). Recycling of steel or aluminium could provide savings in embodied energy by more than 50% (Chen et al. 2001). In addition, the recycling or reusing of building wastes could reduce the landfill demands.

This Circular Renovation Action will have a positive impact on:

- The amount of 'waste' material which is currently being downcycled
- The need for virgin material in renovation projects
- The embodied impact of products needed to execute renovation activities in the EU-27 + Norway

For modelling this action, three main research tasks were executed. Firstly, the current standard of secondary material use in the production of new building products. Secondly, the technical maximum application of secondary materials in each of the 12 material categories, which are used for mapping the renovation flows. This will be used to assess the saving of virgin material consumption. Thirdly, the environmental impact of recycling secondary materials into products. As the energy associated with the end-of-life phase was rarely included in most of the LCA studies (Blengini, 2010) the environmental impact of recycling secondary materials was modelled based on literature review, interviews and sector reports (see Table 1.20).

When modelling the impact of this action, the availability of secondary materials was not taken into account. The environmental impact of recycling the secondary materials (GHG emissions) is taken into account when mapping the overall reduction of environmental impact.

Table 1.20 Secondary material use; current standard and technical maximum; in Western Europe

Western Europe			
Material	**Current standard secondary material use**	**Technical maximum secondary material use**	**Source**
Concrete	3%	30%	Betonakkoord, 2021
Sand lime brick	20%	40%	Calduran, n.d.
Brick	0%	25%	KNB, n.d.
Wood	15%	30%	Gemax, 2020
Insulation	10%	50%	Construction21, 2018
Glass	8%	100%	FEVE, 2016
Gypsum	5%	30%	Siniat, n.d.
Ceramics	8%	25%	KNB, n.d.
Plastic	17%	75%	Staley, 2009
Steel & Iron	95%	95%	Bouwen met staal, n.d.
Aluminium	95%	98%	MRF, 2016
Copper	95%	98%	MRF, 2016

1.4.9 Choice of biobased materials/products (4.1)

This Circular Renovation Action focuses on the reduction of GHG emissions via the use of biobased materials to replace mineral building materials. This action is modelled by assessing individual renovation types and replacing mineral options with biobased alternatives. As some biobased material options have a reduced technical lifespan, this will also have an influence on the total number of renovations. Some renovations will have to take place more frequently, because biobased materials deteriorate quicker than their mineral counterparts, see tables 1.21 and 1.22 for an example.

Table 1.21 Changing components influencing technical lifespan

Selected renovations	Apartment building / 1990	Technical lifespan
Façade renovation without applying insulation	Brick cladding	1000
	Concrete façade elements	75
	Internal woodwork	50
	Iron wall anchors	100
	Screws/nails	100

Table 1.22 Biobased components influencing technical lifespan

Selected renovations	Apartment building / 1990	Technical lifespan
Façade renovation without applying insulation	Wood Cladding	50
	Biobased façade elements	50
	Internal woodwork	50
	Iron wall anchors	100
	Screws/nails	100

The research has resulted in a set of mineral products being replaced. For this modelling exercise, only alternatives with a high technology readiness level which have been broadly applied are incorporated into the analysis. An overview of all the replaced building products can be found in Table 1.21.

Table 1.23 Mineral products replaced by biobased products

Building part	Main element	Element	Traditional product	Biobased product
Roof	Roof, flat	Roof covering	PVC/EPDM roofing	Vegetal membrane; single layer (3,0 mm); mechanically mounted
Façade	Façade, open	Frames	PVC/aluminium	Hardwood. (Meranti), frame+dual turn window; painted, sustainable forestry;NBvT
Façade	Façade, open	Doors	Exterior door, aluminium, coated	Wooden threshold, exterior door; trop. hardwood, sustainable forestry
Roof	Roof, flat	Insulation	Rock wool/glass wool/EPS/PUR	Flexible wood fibre insulation (55 kg/m3)
Roof	Roof, sloped	Insulation	Rock wool/glass wool	Flax insulation
Façade	Façade, closed	Insulation	Rock wool/glass wool/ EPS/PUR	Flexible wood fibre insulation (55 kg/m3)
Façade	Façade, closed	Insulation	Rock wool/glass wool/EPS/PUR	Cellulose
Interior walls	Interior walls	Plating	Gypsum	Plywood
Façade	Façade, closed	Cladding	Sandwich panel	Sandwich panel wood wool insulation
Interior	Interior openings	Interior frames	PVC/aluminium	Wood; painted (alkyd)

According to EU-regulations (NEN, 2019) storage of GHGs in biobased materials can not be taken into account when assessing the environmental impact of a building. This is because the entire lifespan of the product needs to be taken into account. In the current system, almost all biobased products will be burned at the end of their first use, which means the carbon will be released into the atmosphere again.

1.4.10 Use of nature based solutions (4.2)

This Circular Renovation Action focuses on the potential added value of nature-based solutions, specifically focusing on the application of green roofs and façades on existing façades and roofs when these are renovated. This environmental impact will be modelled both from a building phase (increased need for construction materials) and a use-phase perspective (capturing of CO_2 and removal of fine particulate matter).

Within the built environment the high levels of CO_2, particulate matter, and other compounds impact human health negatively. Vehicular traffic has a significant influence on particulate matter (PM) levels in urban areas; followed by combustion activities (biomass, industrial, and waste burning) and road dust. In the urban atmosphere, fine particles are mostly associated with different health effects on the elderly, pregnant women, and even more so, children being the most susceptible (Mukherjee, 2017). Green roofs and green façades play an important role in the capturing and removal of CO_2 and particulate matter (PM), making their direct living environment healthier.

Based on what renovation type (both energy and non-energy) deals with roofs and façades, a selection of relevant building typologies was made. Specific attention was given towards flat roofs. Based on existing building systems and desk research (NMD, n.d. and Ottelé, 2014) the material intensities of the renovation types were updated. These material intensities specifically focused on the most commonly applicable variant of green roofs and façades to make sure that the renovation type would be applicable for a vast majority of the typologies in Europe. Both variants implemented on the building stock are listed in Table 1.24. The green roof implemented is the sedum roof type. For the façade, the living wall system based on planter boxes filled with soil is implemented.

Table 1.24 Nature-based solutions for roof and façade

Building part	Main element	Element	Product	Profile production	Source
Roof	Roof, flat	Cover system	Green roof	- Filter fabric - Eaves - Drainage - Substrate - Vegetation	NMD2.3
Façade	Cladding	Cover system	Green façade	- Steel profile - HDPE boxes - Potting soil - PE pipes - Vegetation	Ottelé, 2014

Based on the annual increase of green façades and roofs based on the renovation intensities, which were updated with nature based solutions, the annual CO_2 sequestration and PM removal were modelled. The basis for the CO_2 sequestration are the key factors that Shafique (2019) set out for green roofs in several urban areas and countries. These factors are shown in Table 1.25, where the factors of Germany and Japan will result in a bandwidth of CO_2 sequestration. Table 1.25 also shows the factor for PM removal, which was estimated by US EPA (2018a), stating that a green roof can remove about 40 pounds of PM from the air in a year.

Table 1.25 CO_2 sequestration and PM removal of green roofs

Product	Country	CO_2 sequestration (kg CO_2/m2/year)	PM removal (kg PM/m2/year)	Source
Green roof	Germany	0.313		Heusinger, 2017
Green roof	Japan	1.890		Heusinger, 2017
Green roof			0.195	EPA, 2018

Table 1.26 Infobox Urban Heat Island

Urban Heat Island
With the development or expansion of cities and towns, significant vegetation is lost. Urban surfaces are paved or covered with buildings, resulting in less shade and moisture to keep urban areas cool. The amount of Urban Heat Island Effect is experienced based on properties of urban materials which consist of solar reflectance, thermal emissivity, and heat capacity along with the ability to reflect, emit, and absorb the sun's energy. These conceptual issues lead to greater warming of urban areas compared to their rural surroundings, a phenomenon known as the 'heat island effect' (Heaviside, 2017).

Higher temperatures on account of urban heat islands, particularly during the summer, can affect the environment and quality of life. These negative impacts include:

- Increased energy consumption
- Elevated emissions of air pollutants and greenhouse gases
- Compromised human health and comfort
- Impaired water quality
- Urban Heat Island has both direct and indirect impact including social, economic, and environment

Climate change, increasing urbanisation, and an ageing population in much of the world, is likely to increase the risks to health from the UHI, particularly from heat exposure. Studies have shown increased health risks in urban populations compared with rural or suburban populations in hot weather and a disproportionate impact on more vulnerable social groups (Bhargava, 2017).

1.4.11 Re-using secondary products (5.1)

This Circular Renovation Action focuses on maximising the reuse of secondary products that are coming out of the EU-27 building stock due to renovation activities. By re-applying these products in new renovation activities, the demand for virgin material and GHG emissions will both be reduced. This action differs from action 3.1 by the level at which material is being reused. When looking at the butterfly diagram, created by the Ellen McArthur foundation (2019), we can see that recycling materials is very important. This means that material is brought back to its original (raw) state and reapplied in new products. In this action (5.1) we are modelling the impact of the reuse of products without taking them apart. We are focusing on a 'smaller' loop in the butterfly cycle by reusing a building product as a product.

Based on a study from the Economic Institute of the Built Environment (EIB, 2018) a list of products with a high reuse potential are defined. Together, these products account for 23.8% off the mass of outflowing products from the built environment due to renovations. This study also defines five challenging factors which might decrease the likelihood of reuse (see Table 1.27).

- Standard sizing.
- Pollution risk.
- Customisation.
- Performance.
- Disassembly.

Table 1.27 High-reuse potential products with reuse obstacles

Product group	Standard sizes	Pollution risk	Customisation	Performance guarantee	Disassembly challenges
(Façade) Cladding	0	1	0	1	0
Cooling systems	0	1	1	1	0
Exterior doors	1	1	0	1	0
Exterior window frames	0	1	0	1	1
Handrails	1	0	0	0	0
Insulation panels	0	1	0	1	0
Interior doors	1	0	0	1	0

Interior window frames	0	0	0	0	0
Baseboards	0	0	1	0	1
Radiators	0	0	1	0	0
Railings	1	0	0	0	0
Roof tiles	0	0	0	0	0
Sinks	0	1	0	0	0
Skylight	0	1	0	1	1
Stairs	1	0	0	0	0
Steel roofing sheets	0	1	0	0	0
Suspended ceilings	0	0	0	0	1
Toilets	0	1	0	0	0
Ventilation systems	0	1	1	1	0
Wooden eaves	0	1	0	0	0
Wooden floors	0	0	0	0	0
Wooden roofs	0	1	0	0	0
Wooden walls	0	0	1	1	0

For each of the initial list of high-reuse potential products, the highest reuse barriers have been decided (multiple barriers might apply). This resulted in these top three reuse barriers:

- **Pollution:** 26% of all products (mass).
- **Performance:** 27% of all products (mass).
- **Disassembly:** 34% of all products (mass).

Pollution

When reusing materials in a circular or sustainable fashion, it is important to search for high value reuse opportunities. The one caveat that is important to understand is that toxic or hazardous materials should not be reused and separated from the 'clean' waste stream with the aim of decontamination. Toxic substances contained in end-of-life articles eventually reach the waste stage and may contaminate recycled material streams, enter into a second service life, and potentially occur in unsafe uses (Reihlen, 2017). In regards to building materials, there are three main polluting factors which might hamper with reuse:

- Asbestos:
    - A study by SGS Search (2012) found that the average amount of dwellings in the Netherlands with asbestos pollution was: 7% of housing, 22.5% of industrial and agricultural buildings, and 8% of 'other buildings'. This study also states that asbestos can only be found in buildings from before 1992.
    - The amount of products polluted by asbestos were modelled by multiplying the products which are indicated in Table 1.27 coming from buildings built before 1992, with the percentage of the specific typology they were coming from.

E.g. 7% of the façade cladding from housing built before 1992 is affected by asbestos pollution.

- Lead paint:
    - Lead poisoning occurs when lead builds up in the body, often over months or years. Even small amounts of lead can cause serious health problems. Children younger than six years of age are especially vulnerable to lead poisoning, which can severely affect mental and physical development. At very high levels, lead poisoning can be fatal.

    - Lead-based paint and lead-contaminated dust in older buildings are the most common sources of lead poisoning in children.
    - Based on research by the US EPA (2018b), we found that 87% of the houses before 1940 and 24% of the houses between 1960-1977 may contain lead paint to some extent.
    - The amount of products polluted by lead paint were modelled by multiplying the products indicated in Table 5.1.1 coming from buildings built before 1977, with the percentage of the specific era they were coming from.
        - E.g. 24% of the exterior window frames from housing built before 1977 is affected by lead paint pollution.
- Lead piping :
    - Based on a study done by the Dutch Government (RIVM, 2019) approximately 2.5% of all dutch housing has lead piping. Lead pipes have not been used in the construction of homes and indoor installations since 1960. Since then, all drinking water companies have replaced almost all lead pipes in the distribution network with other materials. Research has shown that excess lead can negatively affect brain and nervous system development in unborn and young children up to and including seven years of age. It can lead to a slightly lower IQ (2 to 5 points) and behavioural changes. Infants who are bottle-fed are especially vulnerable. In adults, too much lead can lead to higher blood pressure and kidney problems.
    - The amount of lead pipes were modelled by multiplying the products indicated in Table 5.1.1 coming from buildings built before 1960, with the percentage of housing that is affected by lead piping (2.5%).

These percentages were deducted from the overall outflow, as these would not have been fit for reuse.

Performance

27% of materials might not be reused because of performance issues. The majority of these materials are wood/biobased products. Almost all maintenance and housing corporations in the Netherlands apply the NEN 2767 (NEN, 2019) norm to assess if biobased products need maintenance. This norm classifies elements between classes 0 to 5. This division is made based on the severity (is it very bad damage, or light damage?) and the spread (is it in a minor part of the product, or all throughout?).

Products are only replaced if there is a medium to severe damage in up to 70% of the product. For this modelling exercise, it is assumed that the residual 30% can be reused.

Disassembly

No good data is available on the recovery rate of products based on their assembly. These products were selected on the basis of easy recoverability, as seen by experts. Therefore it is assumed that the recovery rate of these products will be 75%. This number accounted for some losses during the deconstruction process.

2. Data projections & results

2.1. Modelling scenarios outputs

The first part of this chapter presents the results of the three different scenarios, described in Chapter 1.3. These analyses are based on in- and outflow projections of material needed to renovate the EU-27 building stock. The ‘inflow’ of these modelling exercises focuses on the materials needed to perform the execution of the described renovation types (energy or non-energy, see Chapter 1.3). The ‘outflow’ in this analysis focuses on the material that will be taken out of the building stock if renovations take place. The emission of GHGs focuses either on the embedded impact of the material needed (inflow) or the embedded impact of materials coming out of the buildingstock (outflow). The modelling of these three scenarios do not yet take into account the impact of Circular Renovation Actions. The impact of these actions will be modelled in Chapter 2.2.

2.1.1. Scenario 1 - Business as Usual (BAU)

2.1.1.1. Expected outputs

Scenario 1, Business as Usual, models the impact current renovation rates have on both virgin material consumption and GHG emissions. This is done based on a variety of renovation activities according to current practices, without any policy interference. The results for each of these actions are divided over the four geographic regions of the EU-27, the inflowing material, the building type (housing or utility) and outflow of materials. This analysis is visualised in a sankey diagram below (Figure 2.1).

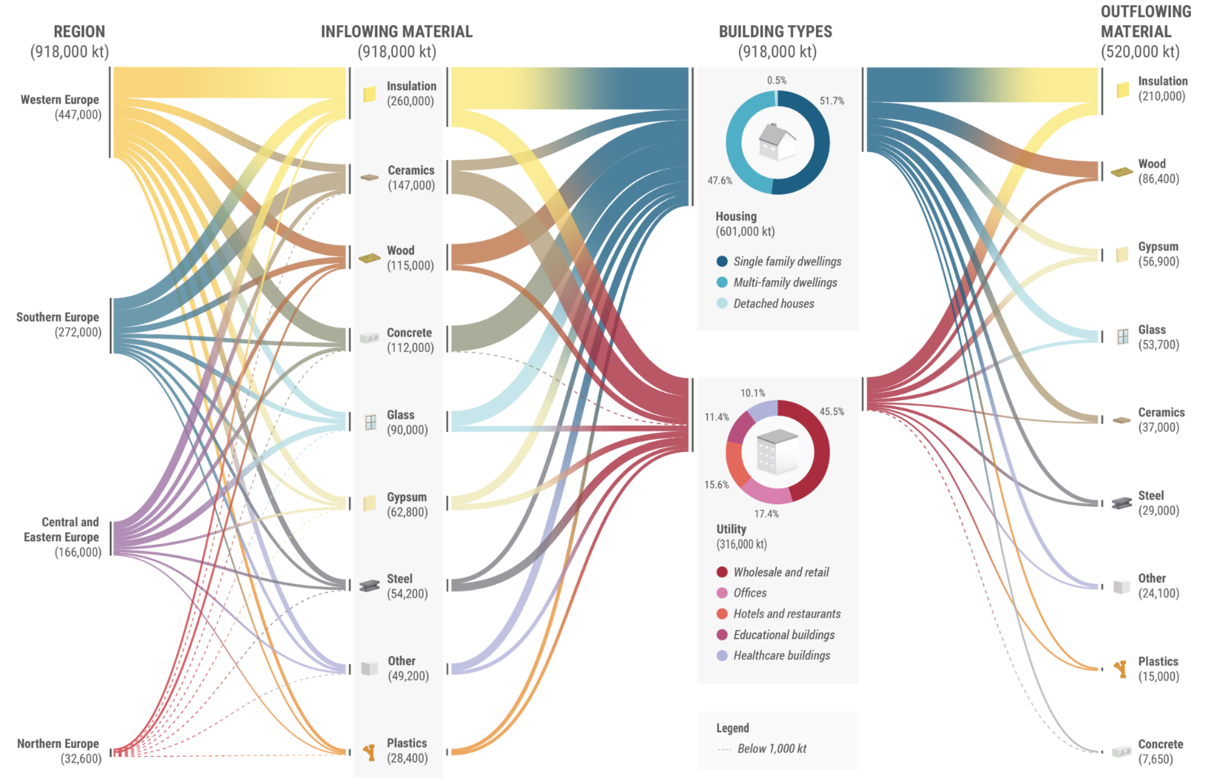


Figure 2.1 Material Flow Analysis geographic regions for business-as-usual scenario

2.1.1.2. Results

If current renovation practices in the EU-27 continue, the energy and non-energy related renovation activities will consume 918,000 kt of virgin materials from 2022 until 2050. The embedded impact connected to the consumption of these materials is the emission of 978,000 kt of embedded GHGs. The following insights based on the MFA in Figure 2.1 above are discussed in this section.

Geographic region

The majority of material demand will come from countries within Western Europe. Together they will demand 447,000 kt of all material consumption related to renovation activities in the EU-27 from 2022 until 2050. This translates to 48.6% of all material consumption. This comes as no surprise, since the majority of buildings are also located in this specific region (see the Executive Summary).

Material quantity versus impact

The top three materials entering the EU-27 building stock from 2022-2050 are: insulation materials (28%), ceramics (16%), and wood (12.5%). Concrete is a close runner-up with 12.2 % of the total material demand. Together, these four materials make up 68.7% of all materials entering the building stock.

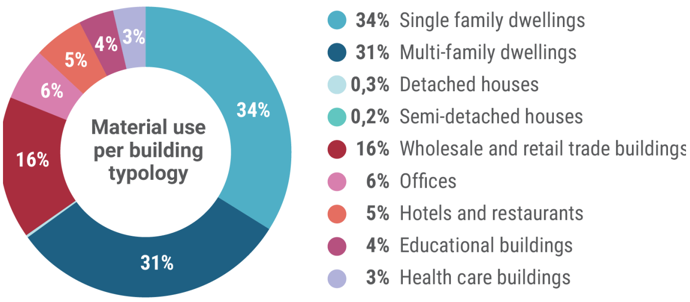


Figure 2.2 Material use, per building typology

From all GHG emissions related to the renovation of the EU-27 building stock (978,000 kt) these materials make up 38% of all GHG emissions. Other impactful materials which are not part of the top four most consumed materials, but which do have a large embedded GHG impact are: steel (5.9% of all the mass, but 23% of all embedded GHG emissions), glass (9.8% of all the mass, but 11% of all the impact), and plastics (3% of all the mass, but 14% of all the impact). Only 21% of all material consumption is related to energy related renovation activities. The other 79% is caused by non-energy renovations.

Building types

Different building types have different material consumption when it comes to renovation activities. What can be seen in the third column of the MFA is that a majority (65%) of all materials are used on renovation activities for housing. Figure 2.2 shows a further division of these two categories into building typologies. This chart shows that the majority of all material consumption for renovating activities are consumed by multi-family (31.2%) and single-family dwellings (33.9%).

Outflowing materials

Based on the fourth column of the MFA it can be assumed that less material is leaving the EU-27 building stock due to renovation than there is entering. In total 386,000 kt of mass is added to the EU-27 building stock during the timescope of this research. The materials flowing out of the building stock because of renovation are: insulation (39%), wood (16%), gypsum 10.6%), and glass (10.1%).

2.1.2. Scenario 2 - Policy compliant

2.1.2.1. Expected outputs

In Scenario 2, Policy Compliant, the impact of renovation practices have on virgin material consumption and GHG emissions is modelled for when renovation activities would increase to meet policy targets. Chapter 1.3 elaborates on the increase of certain renovation rates of both energy and non-energy related activities based on reviewed policy documents.

2.1.2.2. Results

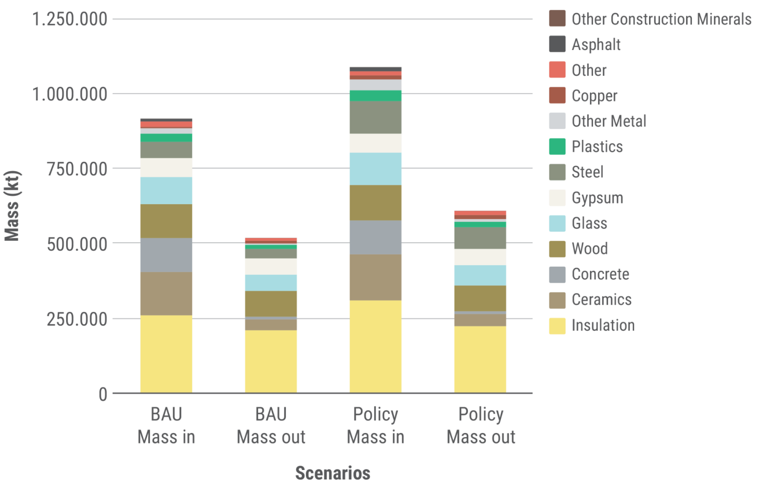


Figure 2.3 Comparison of BAU and Policy compliant scenario based on mass

If current renovation practices were increased to meet targets set by the EU, the energy and non-energy related renovation activities in the EU-27 will consume 1,090,000 kt of virgin materials. This is an increase of 18.7% in regards to the BAU scenario. The biggest absolute increase can be seen in the consumption of steel (with an increase of 51,000 kt), insulation (with an increase of 50,100 kt) and glass (with an increase of 20,100 kt).

Relative to their initial mass, the biggest increase can be seen in the consumption of 'other metals' (increases 106% compared to its original weight), steel (increases 96% to its original weight) and copper (increases 86% compared to its original weight). These increases can be explained by the increased rate of energy renovation activities. These will mainly focus on the replacement of windows, installation of climate installations, and increasing the thermal performances of façades by adding insulation material (Figure 2.3).

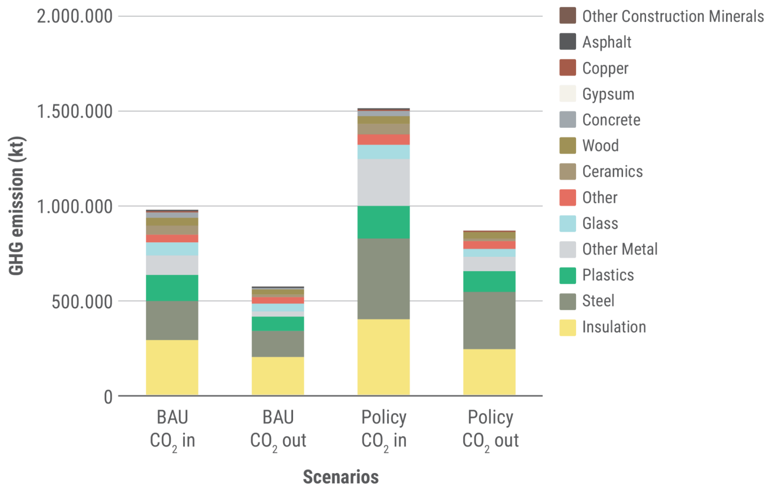


Figure 2.4 Comparison of BAU and Policy Compliant scenarios, based on embedded GHG emissions

Connected to the consumption of these materials are 1,520,000 kt of embedded GHG emissions. This is an increase of 47% in regards to the BAU scenario. The biggest absolute increase of GHG emissions can be found in the consumption of steel, 'other metals', and insulation. The relative increase in impact in regards to their initial GHG emissions is the biggest with 'other metals', steel, and copper (Figure 2.4).

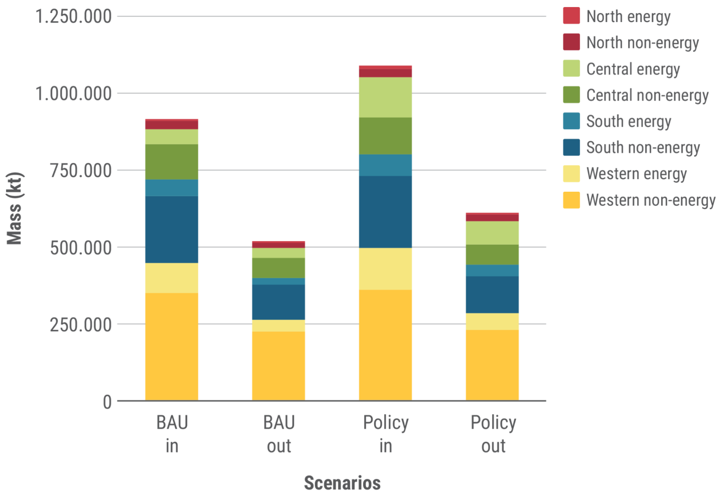


Figure 2.5 Comparison of BAU and Policy Compliant scenarios, based on energy and non-energy renovation types, divided over geographic regions

Based on this scenario, the quantity in which certain renovation types are taking place have changed. The overarching amount of renovation activities increases by 18%. The overarching amount of energy renovation increases by 75%, whereas the amount of non-energy renovations only increases by 3%. Because of this increase, the division between materials affected by energy and non-energy renovations shifts from 21% of materials used for energy renovations in the BAU scenario, to 32% of all materials used for energy renovations in the Policy compliant scenario.

The amount of material affected by certain renovation activities is plotted based on their geographic location (see Figure 2.5). For each region a light and darker bar per geographic region represent the increase in non-energy (light) and energy (dark) related renovations.

The biggest absolute and relative increase in material consumption for renovations takes place in Central Europe (81,700 kt of material, which represents an increase of 50%). The majority of this rise in material consumption is caused by energy-related renovation types, which increase by 162%. The other regions all increase their material consumption related to energy renovation types by +/- 49%. Across all four regions the non-energy renovation types increase by roughly 3% (similar to the overarching increase).

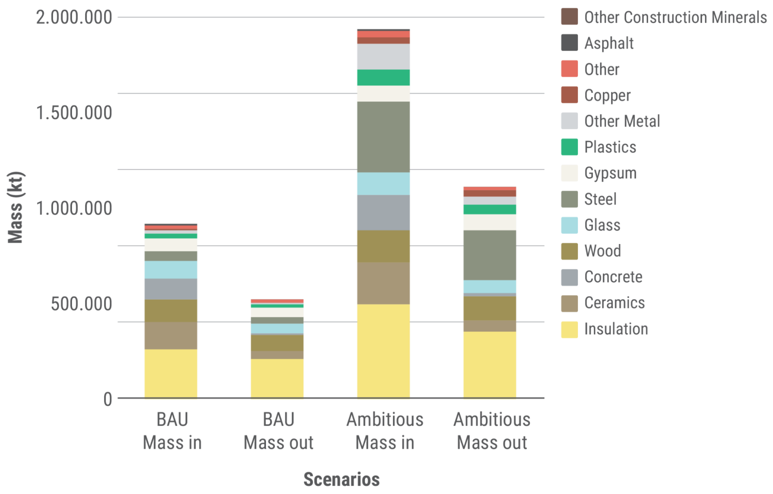
2.1.3. Scenario 3 - Ambitious

2.1.3.1. Expected outputs

In Scenario 3, Ambitious, the impact renovation practices have on virgin material and GHG emission is modelled if renovation activities were increased to renovate all buildings in the EU-27. Chapter 1.3 explains the increase of certain renovation rates of both energy and non-energy related activities based on this ambition.

2.1.3.2. Results

Figure 2.6 Comparison of BAU and Ambitious scenarios, based on mass



If current renovation practices were increased to have all buildings undergo a deep energy renovation before 2050, the energy and non-energy related renovation activities in the EU-27 will consume 1,940,000 kt of virgin materials. This is an increase of 112% in regards to the BAU scenario.

The biggest absolute increase compared to the BAU scenario is caused by steel (with an increase of 31,000 kt of material consumption), insulation (with an increase of 24,000 kt of material consumption) and 'other metals' (with an increase of 11,000 kt of materials) (figure 2.6). The relative increase of material consumption is the biggest for 'other metals' (with an increase of 636% of material consumption increase), steel (with an increase of 574% of material consumption increase), and copper (401% of material consumption increase). The last material increase is (for the majority) caused by the replacement of copper roofing in Central and Eastern Europe. High value reuse of this material consumption can potentially significantly reduce the impact of this renovation increase.

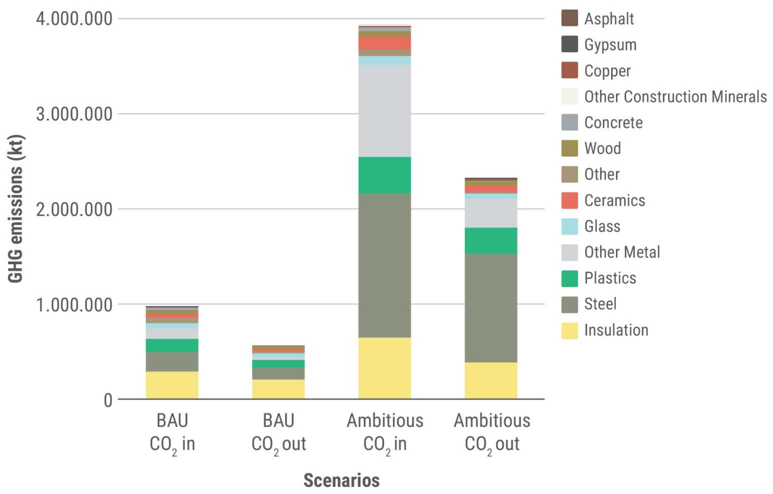


Figure 2.7 Comparison of BAU and Ambitious scenarios, based on embedded GHG emissions

Connected to the consumption of these materials are 3,950,000 kt of embedded GHG emissions. This is an increase of 304%. See Figure 2.7 for a split of the different materials consumed and GHG intensity of these materials. This big rise in GHG emission is mainly caused by steel (increases emissions by 131,000 kt), 'other metals' (86,000 kt), and insulation material (36,600 kt).

Based on the Ambitious scenario, the materials used for renovation of the European building stock has increased by 112%. This increase is mainly caused by a significant increase of energy-related renovation types. These will increase 321% according to the Ambitious scenario. Non-energy related renovation activities will increase by 54%.

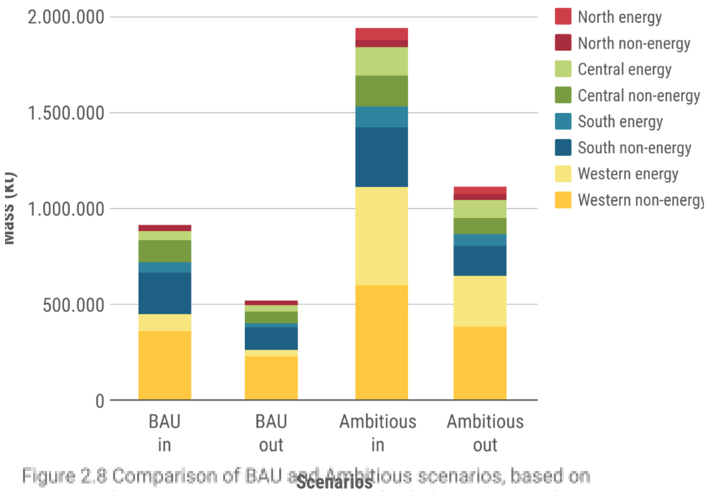


Figure 2.8 Comparison of BAU and Ambitious scenarios, based on energy and non-energy renovation types, divided over geographic regions

The majority of this increase is caused by a big influx of renovation in both Western energy (an increase of 450%) and non-energy renovation types (an increase of 70%).

Theoretical coverage of secondary materials

Based on mapped outflows, it can be assumed that a certain part of the materials coming out of the building stock can be reused in renovation activities (see Figure 2.8). Based on the in- and outflow of materials in the EU-27 countries during the timescope of this research (2022-2050) the theoretical coverage of secondary materials is shown in Table 2.1. This table does not take into account the exchange of materials with other types of building activities (demolition and construction) and does not account for any technical feasibility.

Based on this table, a few trends can be observed:

- None of the materials have a 100% coverage for any of the renovation scenarios.
- Many materials have a constant level of theoretical coverage throughout the three different scenarios. The highest constant materials are copper (between 94-99%) and gypsum (roughly 91%).
- Insulation material starts off high in the BAU scenario (80%) but is reduced in theoretical coverage to 70.78%.
- Steel and 'other metals' both significantly increase in theoretical coverage if the renovation rates go up.

Table 2.1 Theoretical coverage of secondary materials, per scenario

Material	Theoretical coverage BAU	Theoretical coverage Policy	Theoretical coverage Ambitious
Asphalt	21.61%	21.42%	21.38%
Ceramics	25.21%	24.70%	25.40%
Concrete	6.82%	6.82%	6.71%
Copper	99.00%	97.21%	94.19%
Glass	59.64%	59.90%	59.03%
Gypsum	90.56%	90.61%	90.72%
Insulation	81.03%	72.61%	70.78%
Other	69.18%	63.26%	56.28%

Other construction minerals	63.62%	64.14%	64.89%
Other metal	23.36%	28.12%	32.57%
Plastics	52.63%	54.77%	56.43%
Steel	53.50%	64.89%	71.23%
Wood	75.44%	75.94%	75.87%

2.2. Impact of Circular renovation actions

2.2.1. Increasing intensity of use (1.1)

Introduction

This Circular Renovation Action focuses on the reduction of virgin material consumption by preventing the need for additional buildings. This is done by transforming existing spaces into multipurpose spaces. Combining functions operating at different times, within a so-called mixed-use space. This creates optimal use of the available space and reduces the need for additional building space or buildings, which in turn reduces virgin material consumption and the emission of GHGs.

Figure 2.9 Material saved in construction, compared to An increase in renovation flows, of action 1.1 Increasing intensity of use

BAU scenario impacts

These renovations will result in a material saving of 203,900 kt of material and 135,600 kt of GHG emissions in the EU-27 for the entire forecast. This reduction of virgin material consumption (and related GHG emissions) will take place due to the prevented construction of new buildings. (see Figure 2.9) In comparison to the total material inflow for construction, the saving of materials is relatively low. Only 1.4% of all virgin material consumption is reduced, and 2.1% of all GHG emissions. However, in comparison to the environmental impact related to renovation activities, the Circular renovation action is quite impactful. The prevented kt of construction material are the equivalent of 20% of all materials needed for renovation and 15% of all GHG emissions related to renovation activities in the BAU scenario (see Figure 2.10).

Figure 2.10 Material saved in construction, compared to total renovation flows, of action 1.2 Increasing intensity of use

Impact Policy / Impact Ambitious

When scaling up the renovation rates in the Policy Compliant and Ambitious scenarios, the environmental impact does not change, as it focuses on the transformation of existing and available space. This will not increase if renovation rates are increased. Therefore the different scenarios do not cause an increase in material consumption for this action.

2.2.2. *Adaptive reuse of buildings (1.2)*

Introduction

This Circular Renovation Action focuses on preventing the consumption of (virgin) materials by applying the principles of adaptive reuse. According to the Metropolitan Research Institute (2019), adaptive reuse is the process of converting a building to a new use that is different from its original design.

BAU scenario impacts

During the time scope of this research (2022-2050), this Circular renovation action will demand an additional 6,957 kt of material and corresponding 6,515 kt of GHG emissions to transform existing buildings to different functions. These renovations will result in a material saving of 189,298 kt of material and 104,714 kt of GHG emissions in the EU-27. This reduction of virgin material consumption (and related GHG emissions) will take place due to preventing construction of new buildings. In comparison to the total material inflow for construction, the saving of materials is relatively low. Only 1.2% of all virgin material consumption is reduced, and 1.2% of all GHG emissions (see Figure 1.2.1). However, in comparison to the environmental impact related to renovation activities, the Circular renovation action is quite impactful. The prevented kt of construction material are the equivalent of 17% of all materials needed for renovation and 12% of all GHG emissions related to renovation activities (see Figure 2.11).

Impacts of Policy Compliant and Ambitious scenarios

When scaling up the renovation rates in the Policy Compliant and Ambitious scenarios, the environmental impact does not change, as it focuses on the transformation of existing and available space.

Figure 2.11 Material saved in construction compared to total renovation flows, of action 1.2, the adaptive reuse of buildings

2.2.3. *Choice of material and products with a long lifespan (1.3)*

Introduction

This Circular Renovation Action focuses on using components and/or elements with a longer technical lifespan for the renovation of the European building stock. This will lengthen the renovation cycle, which will reduce the need for virgin material (and embedded GHG emissions) in the future.

BAU scenario impacts

The reduction from the extended lifetime will start outweighing the additional material required from 2035 onwards. Until 2050, the total savings will amount to 4,119 kt of GHG emissions (0.45%). The total extra mass required will still outweigh the reductions because of extended lifetime, due to the higher mass of the products with extended lifetime, as compared to their BAU counterparts. This leads to an increase in mass of 8,337 kt until 2050 (0.96%). The initial saving of environmental impact by lengthening of the renovation cycle will start in the year 2032, when the initial saving is mainly due to the reduced need for new wood products (see Figure 2.12).

Since the benefits of this action will accumulate beyond 2050, results until the year 2070 are also shown. When taking into consideration the total reduction until 2070, an additional mass of 13,902 kt is required, while a savings of 32,880 kt GHG emissions takes place.

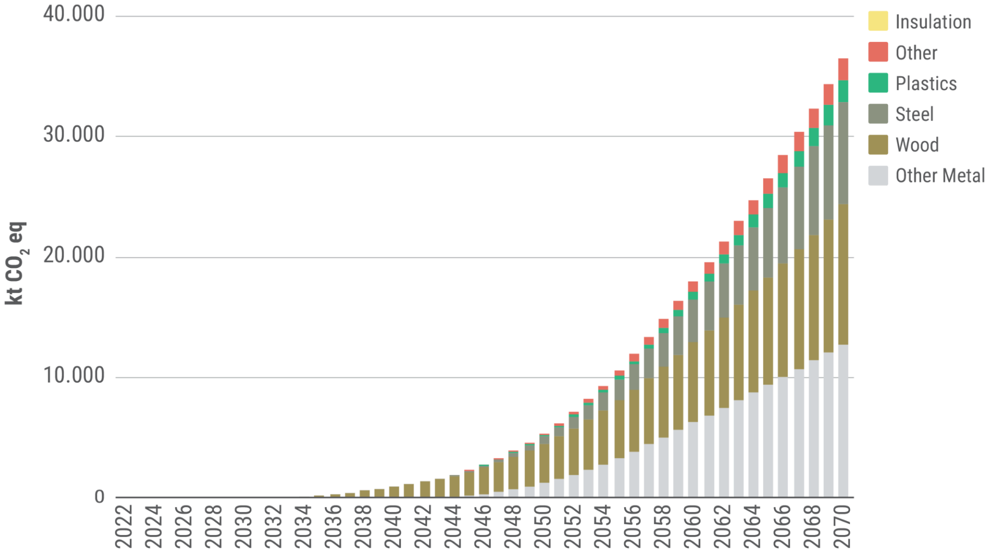


Figure 2.12 Cumulative GHG emission reduction, due to extended lifetime of building products

Scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy Compliant, or Ambitious) the environmental impact of lengthening the lifespan starts to create significant differences.

Policy Compliant

This action will require additional material mass, a total of 10,175 kt until 2050. The overall prevented GHG emissions from 2022-2050 is 3,163 kt. This is an increase of 0.93% of total material consumption and a decrease of 0.21% of total GHG emission related to renovation, in this scenario. Until 2070, the increase of mass will be 15,599 kt; the reduction in GHG emissions will be 38,174 kt.

Ambitious

This action will require additional material mass, a total of 22,057 kt until 2050. In contrast with the other two scenarios, the overall GHG emissions from 2022-2050 will actually increase with 4,508 kt. This is an increase of 1.14% of total material consumption and an increase of 0.11% of total GHG emissions related to renovation, in this scenario. Until 2070, the increase of mass will be 33,896 kt, the reduction in GHG emissions will be 19,842 kt.

Table 2.2 Prevented material consumption and GHG emissions per scenario, for action1.3 Choice of Material/product with a long lifespan

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO_2 eq)	GHG impact (%)
BAU	-8,337	-0.96%	14,820	0.45%
Policy Compliant	-10,175	-0.93%	3,163	0.21%
Ambitious	-22,057	-1.14%	-4,508	-0.11%

2.2.4. The saving of materials in production (1.4)

Introduction

This Circular Renovation Action focuses on the reduction of virgin material consumption and GHG emissions via the reduction of material needs during the production of building products.

BAU scenario impacts

During the timescope of this research (2022-2050) this Circular renovation action will reduce the environmental impact of renovation activities in the EU-27 by 19,103 kt of virgin material consumption and 28,524 kt of GHG emissions (see Table 2.3). In comparison to the total environmental impact of renovation activities in the EU-27 this will result in a reduction of 2.26% of virgin material consumption and 3.47% of GHG emissions. The majority of this virgin material consumption is created by the reduction of insulation (59.2%) and wood (37.7%). The majority of GHG emission reduction is caused by the reduction of insulation (85%).

Scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy compliant, or Ambitious) the environmental impact of lengthening the lifespan starts to create significant differences.

Policy Compliant

The overall prevented virgin material consumption and GHG emissions from 2022-2050 is 22,007 kt of material and 50,424 kt of GHG emissions. This is 2.84% of total material consumption and 4.84% of total GHG emissions related to renovation, in this scenario.

Ambitious

The overall prevented virgin material consumption and GHG emission from 2022-2050 is 44,188 kt of material and 83,479 kt of GHG emissions. This is 3.01% of total material consumption and 4.52% of total GHG emissions related to renovation, in this scenario.

Table 2.3 Prevented material consumption and GHG emissions per scenario, for action 1.4 Saving of materials in production

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO2 eq)	GHG impact (%)
BAU	19,103	2.26%	28,524	3.47%
Policy Compliant	27,007	2.84%	50,424	4.84%
Ambitious	44,188	3.01%	83,479	4.52%

2.2.5. Increased lifespan of buildings (2.1+2.2)

Introduction

This Circular Renovation Action focuses on the reduction of virgin material consumption by reducing the need for new buildings by increasing the lifespan of existing buildings.

BAU scenario impacts

During the time scope of this research (2022-2050) this Circular renovation action will result in a material saving of 277,407 kt of material and 150,776 kt of GHG emissions in the EU-27. This reduction of virgin material consumption (and related GHG emissions) will mainly take place due to the prevented demolition and construction of new buildings (see Figure 2.1.1). In comparison to the total material inflow for construction, the consumption of virgin materials is reduced by 1.90%. These materials are responsible for 1.83% of all GHG emissions (see Figure 2.13).

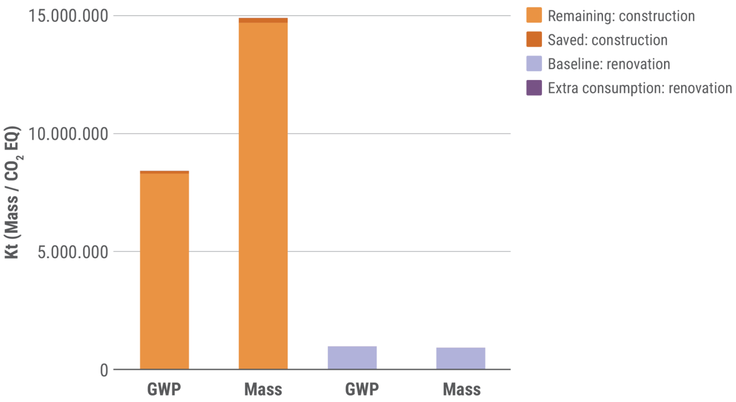


Figure 2.13 Material saved in construction compared to increase in renovation flows, of action 2.1 Increased lifespan of buildings

However, in comparison to the environmental impact related to renovation activities, the Circular renovation action is quite impactful. The prevented kt of construction material are the equivalent of 31.99% of all materials needed for renovation and 16.30% of all GHG emissions related to renovation activities (see Figure 2.14).

Figure 2.14 Material saved in construction compared to total renovation flows, of action 2.1 Increased lifespan of buildings

Impacts of Policy Compliant and Ambitious scenarios

When scaling up the renovation rates in the Policy Compliant and Ambitious scenarios, the environmental impact does not change, as it focuses on extending the life of buildings via repairing their construction and façade. These are modelled on demolition practices and will therefore not increase if renovation rates are increased.

2.2.6. Use of demountable products enabling reuse (2.3)

Introduction

This Circular Renovation Action focuses on the use of demountable products to enable reuse after their first lifecycle. As these products will be reused in other building and/or renovation projects, they will replace new products and therefore reduce the need for virgin materials and prevent GHG emissions.

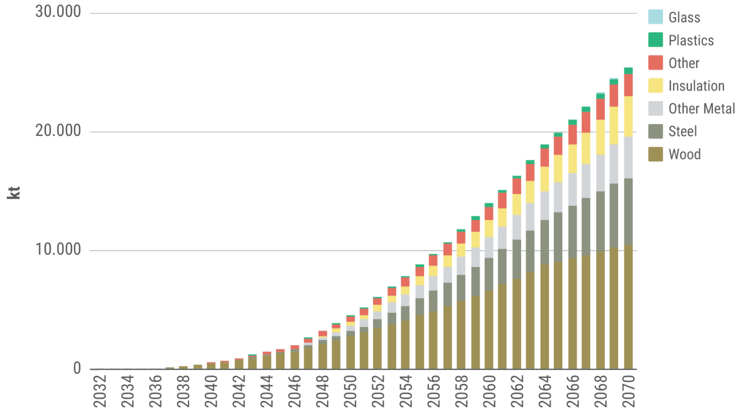


Figure 2.15 Cumulative potential mass reduction from reusing DfD products

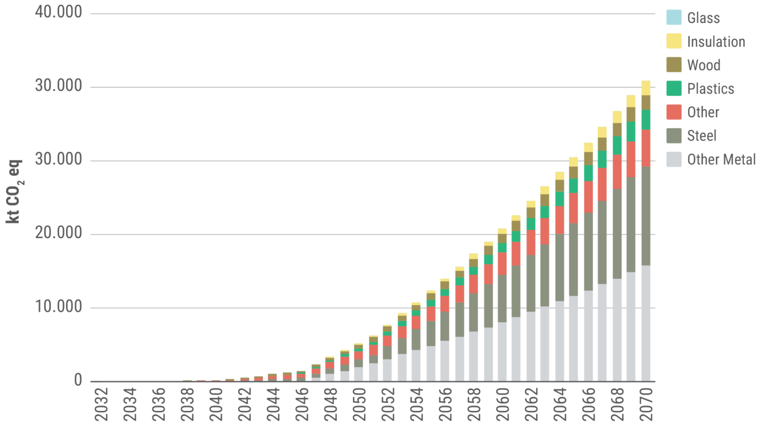


Figure 2.16 Cumulative potential GWP reduction from reusing DfD products

BAU scenario impacts

During the time scope of this research (2022-2050) this Circular Renovation Action will reduce the need for virgin material consumption by 3,556 kt for the EU-27 (see Table 2.4). Because of this reduced virgin material consumption, there will also be a reduction of 4,250 kt of GHGs. Relative to the total need for virgin materials and GHG emissions there is a respective reduction of 0.43% and 0.51%. As can be seen in Figures 2.15 and 2.16, the majority of the impact of this Circular Renovation Action takes place after the year 2050.

Impact scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy Compliant, or Ambitious) the environmental impact of using demountable building products changes significantly.

Policy Compliant

The overall prevented virgin material consumption and GHG emissions from 2022-2050 is 7,905 kt of material and 31,278 kt of GHG emissions. This is 0.83% of total material consumption and 3.01% of total GHG emissions related to renovation, in this scenario.

Ambitious

The overall prevented virgin material consumption and GHG emissions from 2022-2050 is 26,616 kt of material and 142,565 kt of GHG emissions. This is 1.81% of total material consumption and 7.71% of total GHG emissions related to renovation, in this scenario.

Table 2.4 Prevented material consumption and GHG emissions per scenario, for action 2.3 Use of demountable products enabling reuse

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO_2 eq)	GHG impact (%)
BAU	3,556	0.43%	4,250	0.51%
Policy Compliant	7,905	0.83%	31,278	3.01%
Ambitious	26,616	1.81%	142,565	7.71%

2.2.7. Use of materials with high recycled content (3.1)

Introduction

This Circular Renovation Action focuses on the prevention of virgin material consumption by increasing the percentage of secondary material in new building products. In the current system, some secondary materials are already applied and will be deducted from the overall percentage of secondary material use.

BAU scenario impacts

During the timescope of this research (2022-2050) this Circular renovation action will reduce the environmental impact of renovation activities in the EU-27 by 278,579 kt of virgin material consumption and 100,992 kt of GHG emissions. In comparison to the total environmental impact of renovation activities in the EU-27 this will result in a saving of 32.1% in virgin material consumption and 10.9% in GHG emissions. The majority of GHG savings will be created by using secondary materials in the production of insulation (37.1% of savings), glass (32.6% of savings), and plastics (22.7% of savings). Together these materials are responsible for 92.5% of the saved GHG emissions.

Impact scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy Compliant, or Ambitious) the absolute quantity of secondary material use and saved GHG emissions goes up (see Figure 2.17). However, in terms of percentage, the impact decreases.

Policy compliant

The overall prevented virgin material consumption and GHG emissions from 2022-2050 is 322,758 kt of material and 132,342 kt of GHG emissions (Table 2.5). This is 29.6% of total material consumption and 9.2% of total GHG emissions related to renovation in this scenario. The majority of this reduction is caused by the recycling of insulation material (39.8% of the GHG emissions reduction) and glass (29.7% of the GHG emissions reduction).

Ambitious

The overall prevented virgin material consumption and GHG emissions from 2022-2050 is 479,402 kt of material and 231,587 kt of GHG emissions. This is 24.7% of total material consumption and 6.2% of total GHG emissions related to renovation in this scenario. The majority of this reduction is caused by the recycling of insulation material (36.9% of the GHG emissions reduction) and plastics (27.4% of the GHG emissions reduction).

Table 2.5 Prevented material consumption and GHG emissions per scenario, for action 3.1 Use of high recycled materials

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO2 eq)	GHG impact (%)
BAU	278,579 kt	32.1	100,992 kt	10.9
Policy Compliant	322,758 kt	29.6	132,342 kt	9.2
Ambitious	729,532 kt	24.7	231,587 kt	6.2

2.2.8. Choice of biobased material (4.1)

Introduction

This Circular Renovation Action focuses on the reduction of GHG emissions via the use of biobased materials to replace mineral materials used for renovation activities.

BAU scenario impacts

Based on the methodology described in Chapter 1.4, it is assumed that 45,044 kt (6.6%) of all materials needed for renovation activities in the EU-27 can be replaced with biobased alternatives. This will cause a weight increase of 39,609 kt (5.8%), as some of the biobased alternatives (mainly insulation) are heavier than their 'mineral' counterparts.

When only non-biogenic carbon reduction is taken into consideration, this Circular Renovation Action will cause a reduction of 85,278 kt (10.1%) of GHG emissions related to renovation activities during the timescope of 2022-2050. If biogenic carbon storage is taken into account, then this Circular Renovation Action will cause a further reduction of 66,426 kt (7.18%) of GHG emissions (see Figure 2.18) related to renovation activities from 2022-2050.

Impact scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy Compliant, or Ambitious) the environmental impact of using biobased materials increases significantly.

Policy compliant

The overall prevented mineral material consumption and GHG emission from 2022-2050 is 55,272 kt of material and 115,750 kt of GHG emissions. This is 7.5% of total material consumption and 11.4% of total GHG emissions related to renovation, in this scenario. If biogenic carbon storage is taken into account, a further reduction of 101,074 kt of GHG emissions is achieved.

Ambitious

The overall prevented mineral material consumption and GHG emissions from 2022-2050 is 84,794 kt of material and 174,617 kt of GHG emissions. This is 7.4% of total material consumption and 9.6% of total GHG emissions related to renovation, in this scenario. If biogenic carbon storage is taken into account, a further reduction of 166,427 kt of GHG emissions is achieved.

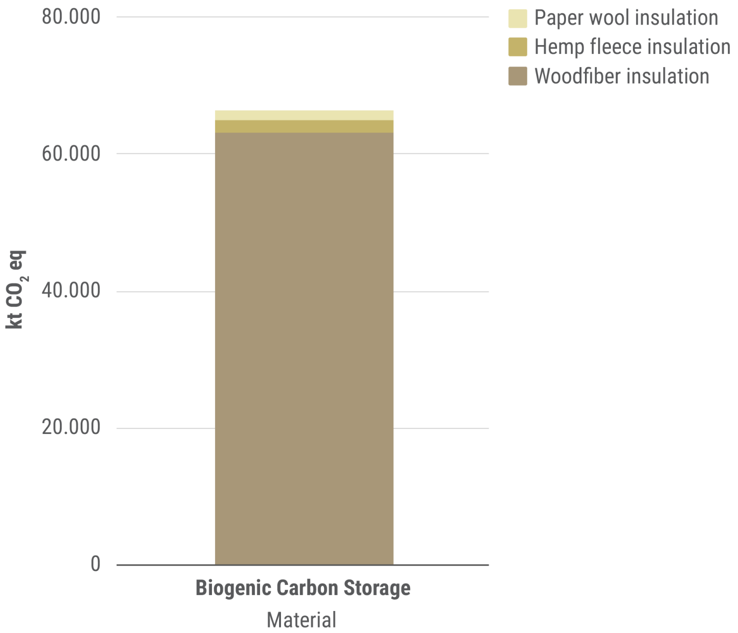


Figure 2.18 Biogenic carbon storage per biobased material

Table 2.6 Prevented material consumption and GHG emissions per scenario, for action 4.1 Choice of biobased material

Scenario	Mass impact (kt)*	Mass impact (%)*	GHG impact (kt CO_2 eq)**	GHG impact (%)**
BAU	-39,609	-4.5%	85,278 (66,426)	9.2% (7.1%)
Policy Compliant	-65,301	-6.0%	115,750 (101,074)	7.6% (6.6%)
Ambitious	-110,328	-5.6%	174,617 (166,428)	4.4% (4.2%)

* Negative number indicates an increase in total material mass consumption
** Number between parentheses indicates GHG emissions stored in biobased materials

Table 2.7 Infobox: Carbon storage in biobased materials

Carbon storage in biobased materials

When using biobased materials, it is important to understand that a (sudden) increase of demand for biobased material can lead to unsustainable overexploitation of natural resources within the EU. Currently, Europe's forests generate an annual surplus, which is generally underutilised. There are studies which estimated that the large-scale biobased renovation of the building stock in Europe until 2050 would not pose an unsustainable pressure on lands. All these results must be cautiously interpreted because the topic is very complex, and the studies are hardly able to address all the facets of the issues.

For example, the cross-sectoral competition for the resource biomass from the different sectors is hardly considered. The sole study trying to address the competition for biomass between the biomaterial and bioenergy sectors in Europe, found that the current expectations can lead to a demand of biomass that is 50–100% more than what can be considered realistically available.

Although the increase in circular practices and the valorisation of the bio-waste can increase the supply of usable biomass, the competition between the two sectors is and will probably remain high, contributing to limit the potentiality of biobased materials to play a leading role in the context of renovations. (Cardellini, 2021)

Concerning the environmental impact, biobased renovation materials have, on average, a better profile than the fossil-based, with results that are obviously highly dependent on the product and the environmental impact considered. Speaking specifically about greenhouse gas emissions, it is known that biobased materials have, on average, a lower carbon footprint than their fossil-based counterparts. The order of magnitude of these benefits highly depends not only on the specific product considered, but also on how and if the temporary carbon storage benefits of biobased products are accounted for.

At this moment there is no scientific consensus on the method to be used to assess this environmental impact, because it will be highly dependent on the scope of the research. According to EU regulations (NEN-EN 15804) storage of GHG emissions in biobased materials cannot be taken into account when assessing the environmental impact of a building. This is because the entire lifespan of the product needs to be considered. In the current system, almost all biobased products will be burned at the end of their life, which means the carbon will be released into the atmosphere again (NEN, n.d.).

For that reason the biogenic storage of GHG emissions will not be taken into account for the overall scoring of Circular Renovation Action 4.1. To create insight into the potential impact of this action, if we did take it into account, a rough estimate has been given below.

2.2.9. Use of nature-based solutions (4.2)

Introduction

This Circular Renovation Action focuses on the potential added value of nature-based solutions. Specifically focusing on the application of green roofs and façades on existing façades, and roofs when these are renovated.

BAU scenario impacts

Based on the methodology described in Chapter 1.4, it is assumed that an additional 224,064 kt of material is needed to install green roofs and façades on existing buildings during the time scope of this research (2022-2050). The majority of the added material are soil (54.6%), vegetation (14.2%), substrate (13.5%), and plastics (13.13%). The majority of the added GHG emissions is caused by the plastic components (13.3% of weight, 27.81% of GHG emissions) and steel frame components for green façades (3.34% of weight, 70.6% of GHG emissions) of the nature-based solutions .

As described in Chapter 1.4, the nature based solutions will also store carbon and fine particulate matter (PM) during the use phase of this Circular Renovation Action. The cumulative storage of GHGs during the time scope of this research does not compensate for the embedded GHG emissions during the production of the plastic and steel components of the nature-based solution (see Figure 2.19). In tha PM on an annual basis. This roughly corresponds to the annual emission of 363 million cars.

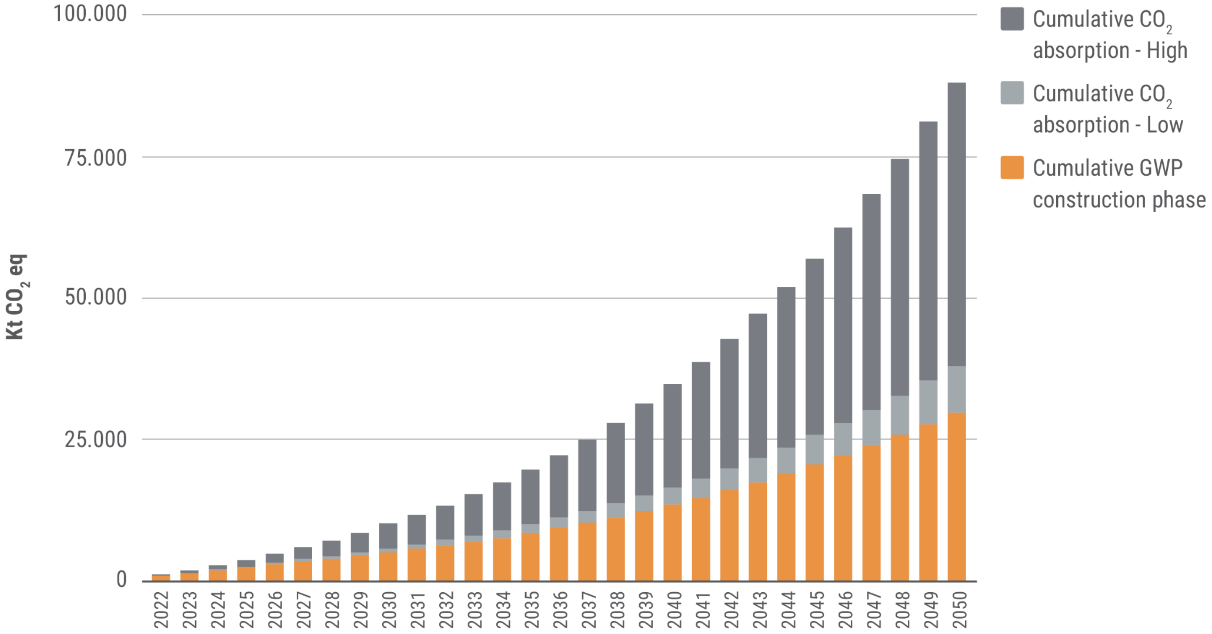


Figure 2.19 Cumulative CO_2 eq. emitted during production of green roofs and facades and CO_2 eq. absorbed

Impact scenarios

When this Circular Renovation Action is projected on the different renovation scenarios (Business as Usual, Policy Compliant, or Ambitious) the environmental impact of this action does not change drastically.

Policy compliant

In this scenario, this Circular Renovation Action creates an increase of 230,805 kt of material consumption and an increase of 30,773 kt of GHG emissions (Table 2.8). At the same time 453 kt of PM will be stored on an annual basis from the year 2050 onward. This is roughly the same as 374 million cars. Also, a total of 8,524-51,472 kt biogenic carbon is being stored within the green roofs and façades if this is taken into account.

Ambitious

In this scenario, this Circular Renovation Action creates an increase of 299,850 kt of material consumption and an increase of 33,013 kt of GHG emissions. At the same time 683 kt of PM will be stored on an annual basis from the year 2050 onward. This is roughly the same as 564 million cars. Also a total of 12,869 - 77,705 kt of biogenic carbon is being stored within the green roofs and façades if this is taken into account.

Table 2.8 Prevented material consumption and GHG emissions per scenario, for action 4.2 Use of nature based solutions

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO2 eq)	GHG impact (%)
BAU	-224,064	-25.8%	-29,777 (8,280 - 49,995*)	-3.3% (0.9% - 5.4%*)
Policy Compliant	-230,805	-21.2%	-30,773 (8,524 - 51,472*)	-2.0% (0.6% - 3.3%*)
Ambitious	-299,850	-15.5%	-33,013 (12,869 - 77,705*)	-0.8% (0.3% - 2.0%*)

* Carbon storage in green roofs and façades

Table 2.9 Infobox: Positive ecological effect of nature-based solutions

The positive ecological effect of nature-based solutions
Building level On a building level, nature-based solutions can positively impact the following areas: ● Energy savings (Besir & Cuce, 2018) ● Reduced sound transmission into buildings (Ascione et al., 2020) ● Increase a façade's longevity (Radic et al., 2019) ● Increase performance of photovoltaic panels (PV-panels) (Schindler et al., 2016) ● Reduce the surface and air temperature of buildings (Cameron et al., 2014) The effectivity and performance of the nature-based solutions is strongly dependent on characteristics of the system, such as leaf area, geometry, substrate type, connection to the building, the characteristics of the building (height, insulation, construction materials, building

envelope, glazing area, solar orientation, shading), and to local climate conditions (seasons, heating or cooling needs) (Wong et al., 2010).

Based on research done by Manso et al. (2021) green roofs are more energy efficient than black roofs in all climates relevant for the EU-27. In warm mediterranean climates, up to 84% of energy savings can be reached in cooling seasons and 48% in heating seasons (this is for non-insulated buildings).

In cold climates (marine, west coast climate and warm, summer, humid continental climates), where winters require more heating loads, all types of green roofs have proven to be more effective than traditional black roofs. In summer, green roofs demonstrate to reduce energy loads when compared to black roofs but not as much as in warmer climates (Manso et al., 2021).

Green walls can potentially increase the energy efficiency in buildings, due to surface temperature reduction and shade provided by plants (Mazzuli et al., 2012) . Studies demonstrate that, in hot, summer Mediterranean climate, when compared to a conventional wall, green façades can have an energy efficiency of 34% (Perez et al., 2017) during the cooling season.

Urban Level
If applied in a significant urban scale, green roofs and green walls have the potential to provide ecosystem services, contributing to the mitigation of the Urban Heat Island Effect, water management, urban noise attenuation and air quality improvement (Berardi et al., 2014). The Urban Heat Island Effect (UHIE) is influenced by surface temperature, air pollution, wind speed, a building's height, limited green and open areas, and lack of water evaporation. By implementing nature-based solutions and reducing the UHIE, the public's comfort will improve and a potential reduction in energy consumption for the cooling of buildings can be created.

The implementation has other impacts as well. This includes contributing to the aesthetic enhancement and recreational use of public spaces, allowing, for instance, their use for urban agriculture, fostering biodiversity (Mayrand & Clergeau, 2018), while promoting citizens health and well-being (Kabish et al., 2017).

2.2.10. Re-using secondary products (5.1)

Introduction
This Circular Renovation Action focuses on maximising the reuse of secondary products that are coming out of the EU-27 building stock due to renovation activities. By re-applying these products in new renovation activities the demand for virgin material and emission of GHGs will be reduced.

BAU scenario impacts
Based on the methodology described in Chapter 1.4, it is assumed that a reduction of 99,049 kt (11.4%) of virgin material consumption is created by reusing existing components for renovation activities (2022-2050). This will subsequently create a reduction of 103,085 kt of GHG emissions (11.1%). In this calculation, no impact has been calculated for transporting or repairing elements.

Impact scenarios
When this Circular Renovation Action is projected on the different renovation scenarios (Policy, Compliant. or Ambitious) the environmental impact of using reused components for renovation activities increases significantly.

Policy compliant

In this scenario, this Circular Renovation Action reduces the virgin material consumption by 106,000 kt of material (Table 2.10). This is a reduction of 10.3%. This reduction of virgin material consumption will consequently reduce the emission of GHGs by 125,100 kt. This is a reduction of 8.7%.

Ambitious

In this scenario, this Circular Renovation Action reduces the virgin material consumption by 170,900 kt of material. This is a reduction of 9.3%. This reduction of virgin material consumption will consequently reduce the emission of GHGs by 229,100 kt. This is a reduction of 6.13%.

Table 2.10 Prevented material consumption and GHG emissions per scenario, for action 5.1 Recycling secondary products

Scenario	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO_2 eq)	GHG impact (%)
BAU	99,049	11.4%	103,085	11.1%
Policy Compliant	106,000	10.3%	125,100	8.7%
Ambitious	170,900	9.3%	229,100	6.1%

3. Overview of the Circular Renovation Actions

Table 3.1 Overview of Circular Renovation Actions and scenarios

Action category	Action	BAU		Policy		Ambitious		Feasibility
		Reduction virgin material use (kt)	Reduction emission GHGs (kt)	Reduction virgin material use (kt)	Reduction emission GHGs (kt)	Reduction virgin material use (kt)	Reduction emission GHGs (kt)	
Reducing use of resources	1.1 Renovating instead of building	203,900	135,600	203,900	135,600	203,900	135,600	Medium
	1.2 Adaptive reuse	182,341	98,199	182,341	98,199	182,341	98,199	Medium
	1.3 Choice of material/product with a long lifespan*	-8,337	14,820	-10,175	3,163	-22,057	-4,508	High
	1.4 Saving of material in production	19,103	28,524	27,007	50,424	44,188	83,479	High
Waste prevention	2.1+2.2 Increased lifespan of a building	277,407	150,776	277,407	150,776	277,407	150,776	Medium
	2.3 Use of demountable products	3,556	4,250	7,905	31,278	26,616	142,565	Medium
Use of recyclable materials	3.1 Use of materials with high recycled content	278,579	100,992	322,758	132,342	479,402	231,587	Low
Use of biobased materials	4.1 Choice of biobased material**	-39,609	85,278	-65,301	115,750	-110,328	174,617	Medium
	4.2 Nature-based solutions***	-224,064	-29,777	-230,805	-30,773	-299,850	-33,013	Low
Increased recycling rates	5.1 Reusing secondary products	99,049	103,085	106,000	125,100	170,900	229,100	Low

* 1.3: Benefits of extended lifetime of building products will not occur before 2050
** 4.1: The total mass of used products will increase
*** 4.2: Installation of green roofs and façades requires additional material and GHG emissions, GHG absorption is not taken into account

4. A European Roadmap: Combining Circular Renovation Actions

4.1 Introduction

The transition towards a sustainable built environment and building sector can never be achieved by focusing on one Circular Renovation Action alone. A diverse range of activities and interventions are needed to reduce the environmental impact of renovating the building stock across the EU-27. By combining several Circular Renovation Actions into clusters, a clear roadmap and focus on impactful renovating activities can be generated. For this modelling exercise, two major policy targets are defined that can be achieved by any of the individual actions or clusters. These targets are as follows:

- **Reduction of virgin material consumption.** This target can either be achieved by reducing the need for virgin material by reducing the overall demand for materials or by replacing virgin materials with secondary materials.
- **Reduction of GHG emissions.** This target can either be achieved by reducing the consumption of virgin materials following the strategies described above or by replacing the virgin materials with less impactful alternatives.

The impact and ranking of these Circular Renovation Actions has been done solely on environmental impact and reduction of virgin material consumption. The potential financial impact, conflicting policy goals, availability of material, and (lack of) technical infrastructure has not been taken into account.

4.2 Strategy: Action prioritisation and timeline

The Circular Renovation Actions have been grouped into three clusters based on the overall target that they are trying to achieve (see Figure 4.1). The next chapter expands upon the three clusters.

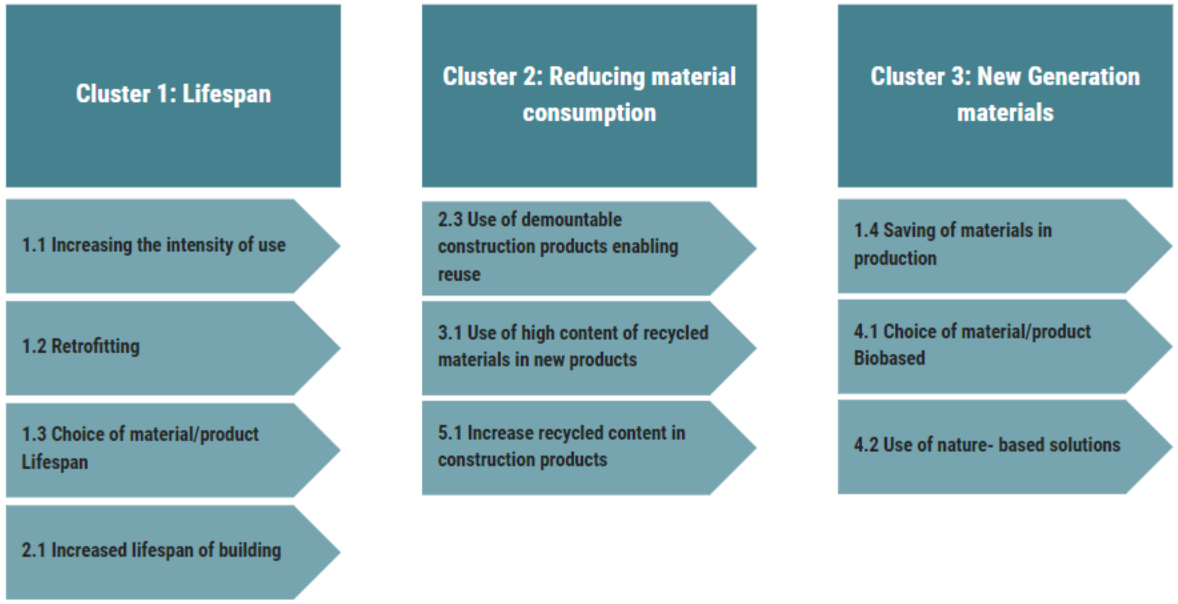


Figure 4.1 Three circular renovation clusters, based on overall circular targets

4.3 Cluster 1: Increased Lifespan

4.3.1. Strategy

The construction sector provides an irrefutable and critical service to human beings: it provides shelter. Subsequently the manufacturing, use, and disposal of buildings and building materials happen on a massive scale, causing increased consumption of national resources.

In the European Union, the built environment consumes over 50% of all natural resources (EC, n.d.b). At the same time, many buildings are demolished before their technological lifespan has been completed. On average, buildings in the EU-27 only 'last' between 50-75 years (W/E Adviseurs, 2013). By demolishing these existing buildings and constructing new ones, the value stored in the original stock is lost and additional need for virgin construction material is created. Cluster 1, Increased Lifespan, is a combination of four Circular Renovation Actions which all focus on extending the lifespan of existing buildings (or parts of them) to reduce the need for virgin material consumption. By doing so, the environmental impact from the building sector will also be reduced. Included Circular Renovation Actions are:

- Action 1.1: Increasing intensity of use.
- Action 1.2: Adaptive reuse of existing buildings.
- Action 1.3: Choice of materials with a long lifespan: choosing materials with a longer lifespan that will reduce the need for regular renovation.
- Action 2.1+2.2: Increased lifespan of buildings through renovation.

In combining these Circular Renovation Actions, the overlap between creation of multipurpose spaces within (mainly) office buildings (Action 1.1) does not interfere with the transformation of office buildings into dwellings via adaptive reuse practices (Action 1.2). The transformation of office spaces to dwellings is modelled based on empty office buildings which have a high potential for transformation. For Action 1.1, it has been assumed that the creation of multipurpose spaces can only happen in 'busy/urban' areas which would create a high demand for office buildings which would therefore not be empty. This means there is no overlap between the individual actions in this cluster.

4.3.2. Main Circular Economy target

This cluster of Circular Renovation Actions specifically focuses on the reduction of the need for virgin materials. Specifically in the construction of new buildings. By doing so, this action will also reduce the demolition of existing buildings, reducing the amount of demolition waste. Since building materials are inherently linked to the emission of GHGs, the reduction of consumption of virgin materials will also reduce the overall emission of GHGs.

4.3.3. Result

Summary

Based on the combination of Circular Renovation Actions 1.1, 1.2, 1.3 and 2.1, a reduction of 655,311 kt (75.6%) of virgin material consumption is created by extending and intensifying the use of buildings via renovation activities (from 2022-2050). This means that the total reduction of construction materials will be more than the materials needed for renovation during the same timespan. This will subsequently create a reduction of 399,395 kt of GHG emissions (43.17%).

BAU scenario impacts

During the time scope of this research (2022-2050), this cluster of Circular Renovation Actions (1.1, 1.2, 1.3 and 2.1) will ask for an additional 6,957 kt of material and 6,515 kt of GHG emissions. These renovations will result in a material saving of 655,311 kt of material and 399,395 kt of GHG emissions in the EU-27. This reduction of virgin material consumption (and related GHG emissions) will take place due to the prevented construction of new buildings. In comparison to the total material inflow for construction the saving of materials is relatively low. Around 4.4% of all virgin material consumption is reduced, and 4.6% of all GHG emissions (see Figure 4.2)

However, in comparison to the environmental impact related to renovation activities, this cluster is quite impactful. The prevented kt of construction material are the equivalent of 75.6% of all materials and 43.17% of all GHG emissions related to renovation activities.

Policy Compliant and Ambitious scenarios impacts
Actions 1.1, 1.2, and 2.1 will not change based on an increase in renovation rates, as they are all modelled based on available space or buildings in the current EU-27 building stock. Since the results of Action 1.3 will largely only become visible after 2050, this impact is very minimal in relation to the other actions. For the Ambitious scenario, this action has no impact at all.

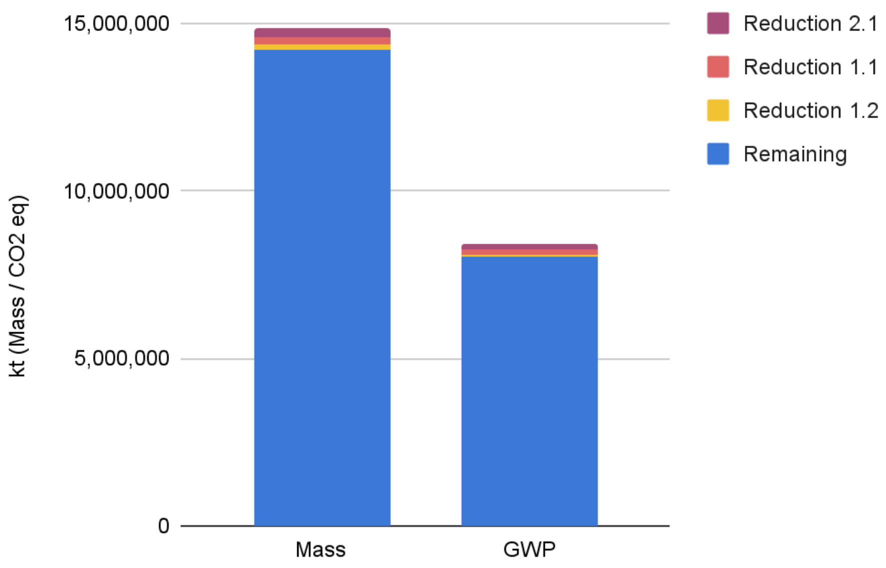


Figure 4.2 Construction flows reduced and remaining, Cluster 1

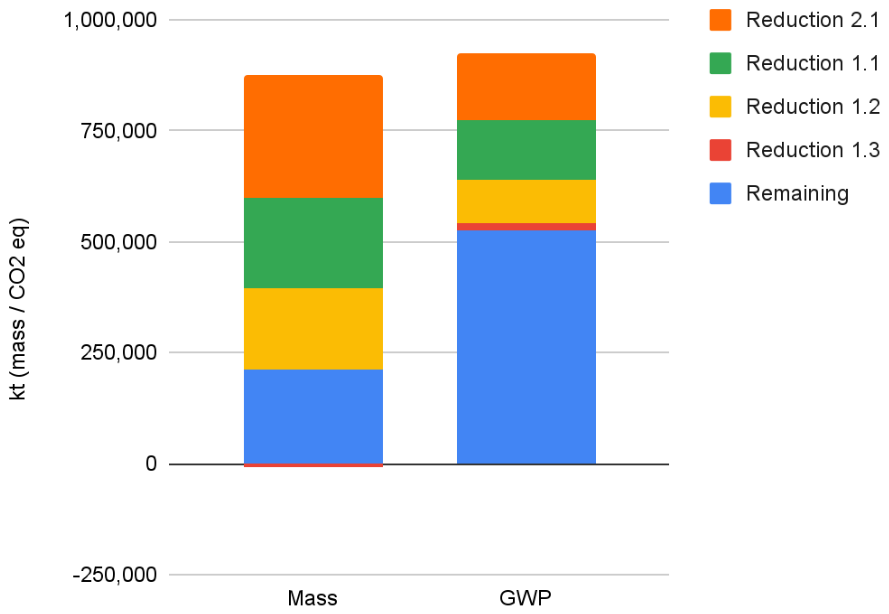


Figure 4.3 Reduction from Cluster 1 as compared to total renovation flows

4.3.4. Timeline

If implementation of the Circular Renovation Actions in this cluster were to have started near the beginning of 2022, there would be immediate results in relation to Actions 1.1, 1.2, and 2.1. These actions focus on the reduction of construction and demolition of buildings. This impact will mainly show in the consumption of virgin building materials. As discussed above, the positive impact of Action 1.3 will only start to become visible after the year 2050. The negative impact (increased use of materials with high embodied GHG emissions) would start immediately.

4.4. Cluster 2: Reducing material consumption

4.4.1. Strategy

On average, 90% of the construction and demolition waste is being reused in the EU-27 (Eurostat, 2022). Usually this means that materials are crushed and used as underlayment for infrastructure projects which would be defined as being downcycled. This destruction of (environmental and financial) value happens even though the technical life cycle of the product has not been reached. Based on the Ellen McArthur Foundation butterfly model (Kottaridou, 2019) we see that in the 'technical cycle', different strategies are possible. Extending the life cycle of a product can significantly reduce the emission of GHGs caused by the building sector. Cluster 2, Reducing material consumption, focuses on the reuse of secondary products and/or materials to reduce the consumption of virgin materials and therefore the emission of GHGs. Included in this Circular Renovation Action are:

- Action 2.3: Use of demountable products: the use of new products that can be disassembled in future renovation or deconstruction projects.
- Action 3.1: Use of materials with high recycled content: the application of secondary materials in the production of new products.
- Action 5.1: Reusing secondary products: the reuse of products that are 'freed' from the Urban mine because of renovation processes.

As the availability of secondary materials are not taken into account for this study, there is no overlap between the different Circular Renovation Actions.

4.4.2. Main Circular Economy target

This cluster focuses on the reduction of virgin material consumption by replacing virgin materials with recycled materials (now) or design disassemblable products which can be reused (in future cycles).

4.4.3. Result

BAU scenario impacts

Based on the combination of Circular Renovation Actions 2.3, 3.1, and 5.1, a reduction of 346,348 kt of virgin material use (39.93% of the total virgin material consumption) is created by extending the use of building components and intensifying the use of secondary materials in producing new components during renovation activities (2022-2050). This will subsequently create a reduction of 195,452 kt of GHG emissions (21.13%) (see figure 4.4).

Policy and Ambitious scenarios impacts

By scaling this cluster to the Policy Compliant and Ambitious scenarios, we can see an immediate effect on the increased use of secondary materials and the amount of secondary components available. The reuse of the new 'disassemblable' materials will only start to have an impact after the year 2050. In the modelling of these scenarios it was assumed that materials can only be reused once. This to prevent accumulation of secondary materials towards 2050.

- **Policy Compliant**
  - Reduced virgin material consumption 2022-2050: 401,829
  - Reduced emission of GHG 2022-2050: 280,602
- **Ambitious**
  - Reduced virgin material consumption 2022-2050: 642,082
  - Reduced emission of GHG 2022-2050: 595,134

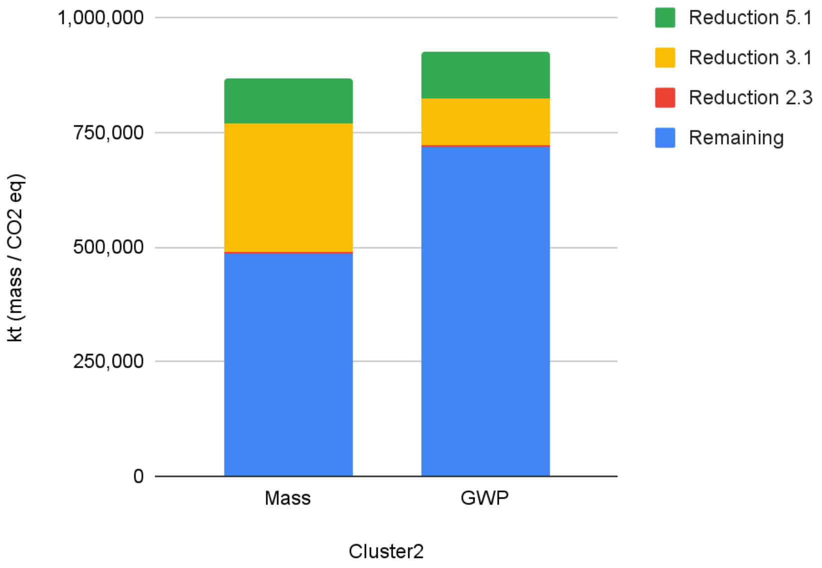


Figure 4.4 Renovation flows reduced and remaining, Cluster 2

4.4.4. Timeline

If the right (physical and digital) infrastructure for recycling materials and re-using secondary building products was in place, the environmental impact of Actions 3.1 and 5.1 would already be seen from 2022 onward, as they can be applied to replace virgin materials now. The first impact of Action 2.3 can be seen after 10 years. However, the majority of this impact will be after the scope of this research (2050).

4.5. Cluster 3: New generation materials

4.5.1. Strategy

By looking at the in- and outflow of all materials from renovation activities, it is clear that the in- and outflow of materials will not balance itself out to create a system in which no primary materials are needed. In the theoretical optimum scenario, there is an overlap of 56% of in- and outflowing materials. This underscores the need for other sustainable materials to reduce the environmental impact of the renovation sector. Cluster 3, New generation materials, is focused on producing new types of components and materials which will significantly reduce the emission of GHGs whilst working with virgin materials. Included in this cluster are these actions:

- Action 1.4: Saving of material in production: using prefab production methods to reduce the consumption of primary materials.
- Action 4.1: Choice of biobased materials: replacing 'mineral' materials with biobased alternatives.

- Action 4.2: Nature-based solutions: application of green walls and roofs to existing buildings when renovating relevant elements of the building.

In modelling this cluster, the efficiency in production (Action 1.4) has been projected mainly on mineral materials in façade and roof construction which are not replaced by biobased alternatives (Action 4.1). As the nature-based solutions (Action 4.2) are mainly focused on adding green walls to the façade (and not replacing materials), there was no interference with the other actions. Since green walls are already prefabricated, it was decided not to put another efficiency factor over the materials needed to install these green walls.

4.5.2. Main Circular Economy target

The main circular economy target reached with this cluster is the reduction of virgin mineral materials. This reduction is either achieved through innovative production methods or the replacement of 'mineral' materials with biobased materials.

4.5.3. Result

BAU scenario impacts

In this cluster there are two Circular Renovation Actions that will increase the total mass of materials used: Actions 4.1 and 4.2 will require an additional 260,673 kt of material in terms of mass, of which 28.6% will be biobased/renewable and 71.4% virgin/non-renewable, of which the majority will be soil and substrate for green roofs and façades.

Based on the combination of Circular Renovation Actions 1.4, 4.1, and 4.2, a reduction of 45,044 kt (6.6%) of virgin material is created by replacing 'mineral' materials with biobased alternatives. An additional reduction of 19,103 kt (2.5%) is achieved by reducing materials used in production. This will subsequently create a reduction of 113,802 kt of GHG emissions (13.8%). If the storage of carbon in biobased products was taken into account, this would result in an additional reduction of 66,426 kt of GHG emissions.

While the construction of green roofs and façades requires extra material, there are also considerable benefits in terms of CO_2-equivalent absorption (8,280 - 49,995 kt of GHG emissions) and particulate matter (PM) absorption: 440 kt per year, equivalent to the annual emission of 363 million cars. To put matters into perspective, there were 292 million registered cars in Europe in 2019 (Statista, n.d.) (see figure 4.5).

Policy Compliant and Ambitious scenarios impacts

By scaling this cluster to the Policy Compliant and Ambitious scenarios, we can see an immediate effect on the increased use of biobased materials.

- Policy compliant:
    - Reduced virgin material consumption 2022-2050: 55,272 kt.
    - Reduced emission of GHGs 2022-2050: 166,174 kt.
    - Biogenic carbon storage in biobased materials: 101,074 kt.
    - Carbon absorbed by green roofs/façades: 8,524 - 51,472 kt.
    - Particulate matter absorbed by green roofs/façades: 453 kt.
- Ambitious:
    - Reduced virgin material consumption 2022-2050: 84,794 kt.
    - Reduced emission of GHGs 2022-2050: 259,096 kt.
    - Biogenic carbon storage in biobased materials: 166,428 kt.
    - Carbon absorbed by green roofs/façades: 12,869 - 77,705 kt.

  - Particulate matter absorbed by green roofs/façades: 683 kt.

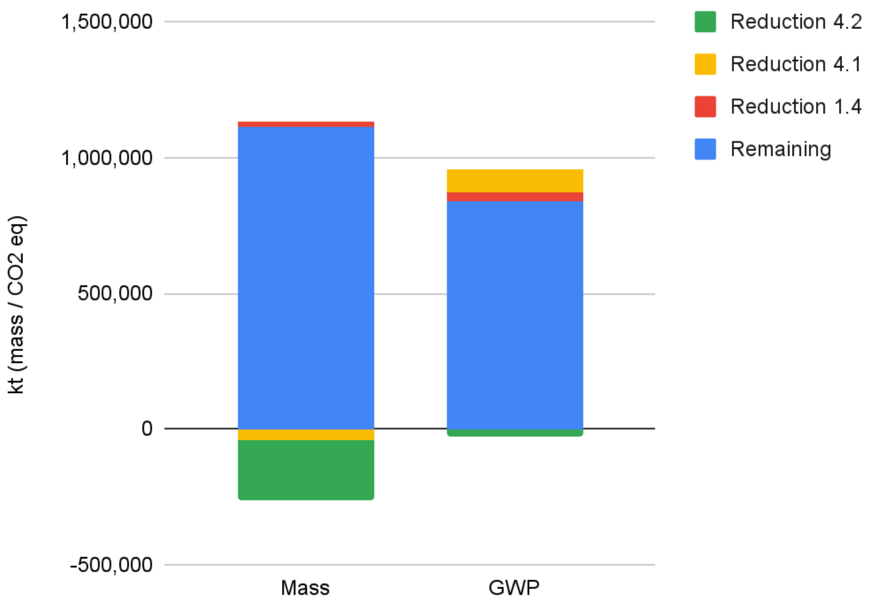


Figure 4.5 Renovation flows reduced and remaining, Cluster 3

4.5.4. Timeline

The impact of this action will be immediate. As Action 4.2 focuses on adding new green roofs and façades to the building stock every year, the results will also cumulatively increase. It is important to note that sustainable forestry practices (Action 4.1), innovative production techniques (Action 1.4), and nature-based solution care regimes (Action 4.2) must be widespread throughout the EU-27. This is to make sure that the big increase in the application of these actions does not result in negative impacts along the production or use chain.

5. Conclusions and Recommendations

5.1. Overview of Circular Renovation Actions

This research assesses the impact of a set of Circular Renovation Actions on predetermined renovation scenarios.The research creates a baseline based on the following scheme:

- Make use of an existing model or develop one that simulates the European building stock
- Conduct modelling of specific renovation actions based on the current status.
- Create a baseline understanding of the impact of the different renovation actions in order to help to the effective implementation of the circular economy in the built environment.
- Assess the benefits of each renovation action and identify optimal synergies among them to optimise the benefits of circular economy and climate.

As described in Chapter 1.4, the Circular Renovation Actions are a set of processes, interventions, or upgrades of the urban environment that have been developed by the EEA in previous research projects. The main goal of these actions is to cover most of the possible renovation options that pertain to a circular economy in the built environment. The intention behind providing such a big range of actions is to get to a full understanding of the real potential of different options, to establish how the built environment can contribute to achieving the European climate targets for 2050.

The results of the modelling activities assess the impact that these Circular Renovation Actions have on both virgin material consumption and GHG emissions until the year 2050. Table 5.1 gives an overview of the impact of these actions, per scenario: *Business as Usual, Policy Compliant,* or *Ambitious*.

Table 5.1 Overview of Circular Renovation Actions and scenarios

Action category	Action	BAU		Policy Compliant		Ambitious	
		Reduction virgin material use (kt)	Reduction of GHG emissions (kt)	Reduction of virgin material use (kt)	Reduction of GHG emissions (kt)	Reduction of virgin material use (kt)	Reduction of GHG emissions (kt)
Reducing use of resources	1.1 Renovating instead of building	203,900	135,600	203,900	135,600	203,900	135,600
	1.2 Adaptive reuse	182,341	98,199	182,341	98,199	182,341	98,199
	1.3 Choice of material/product with a long lifespan*	-8,337	14,820	-10,175	3,163	-22,057	-4,508
	1.4 Saving of material in production	19,103	28,524	27,007	50,424	44,188	83,479
Waste prevention	2.1+2.2 Increased lifespan of a building	277,407	150,776	277,407	150,776	277,407	150,776
	2.3 Use of demountable products	3,556	4,250	7,905	31,278	26,616	142,565
Use of recyclable materials	3.1 Use of materials with high recycled content	278,579	100,992	322,758	132,342	479,402	231,587
Use of biobased	4.1 Choice of biobased material**	-39,609	85,278	-65,301	115,750	-110,328	174,617

materials	4.2 Nature-based solution***	-224,064	-29,777	-230,805	-30,773	-299,850	-33,013
Increased recycling rates	5.1 Reusing secondary products	99,049	103,085	106,000	125,100	170,900	229,100

* 1.3: Benefits of extended lifetime of building products will not occur before 2050
** 4.1: The total mass of used products will increase
*** 4.2: Installation of green roofs and façades requires additional material and GHG emissions; GHG absorption is not taken into account

Further analysis of these results provide the following insights:

In the Business as Usual scenario, preventing new construction has the largest influence on reduction of virgin material consumption.
The Business as Usual scenario demonstrates that three of the top four actions with the highest reduction of virgin material consumption are related to the extension of existing buildings' useful life:

- The highest reduction of GHG emissions can be generated by increasing the lifespan of existing buildings (Action 2.1+2.2) via the renovation of faulty foundations.
- Renovating buildings instead of building (Action 1.1) generates the second-highest impact and the third-highest in saving virgin material consumption.
- Reusing building components (Action 5.1) has the third-highest impact, which is not in the top four of saved virgin material consumption.
- The fourth largest impact is generated by increasing the use of secondary materials in the production of new products (Action 3.1). This action has the highest impact on virgin material consumption among all the Circular Renovation Actions. Here, only technical feasibility and not availability of secondary materials has been taken into account. Therefore, this action might decrease in potential impact if availability is indeed taken into account.

The recycling of materials can lead to a large increase of saved virgin material consumption and GHG emissions across different scenarios.
Even though the recycling of secondary materials during the production of new building products (Action 3.1) ranks fourth in reduction of GHG emissions during the BAU scenario, it will surpass all other actions if the renovation rate goes up to the Ambitious scenario. It is remarkable that even though Action 5.1's potential to save virgin material consumption does not increase at the same rate as Action 3.1, the saved GHG emissions are similar.

Not all actions result in a reduction of material consumption.
The analysis indicates that Actions 1.3, 4.1, and 4.2 do not lead to a reduction in virgin material consumption. There are two reasons for this. First, for Action 1.3 (lengthening the lifespan of products), the environmental impact of the alternatives chosen have a higher mass compared to the original products. As the lengthened lifespan of these products will mostly reap GHG emission benefits after the year 2050, the environmental impact is relatively small within the time scope of this research. Second, for Action 4.1, there is a reduction in mineral material consumption. This reduction is nullified by the increased consumption of heavy materials such as soil or biobased insulation material. The overall consumption emission does go down, especially when taking into account the biogenic carbon storing qualities of materials in insulation, green walls, and roofs.

5.2 Overview of clusters

Combining several Circular Renovation Actions into clusters provides the foundation for a clear roadmap and focus. The impact and ranking of these Circular Renovation Actions is solely based on environmental impact and reduction of virgin material consumption. The potential financial impact, conflicting policy goals, availability of material, and (lack of) technical infrastructure have not been taken into account. Table 5.2 provides an overview of the impact of these clusters, per scenario: *Business as Usual, Policy Compliant,* or *Ambitious*.

5.2.1. Overview table

Table 5.2 Overview of table cluster results

Action category	**Action**	**BAU**		**Policy Compliant**		**Ambitious**	
		Reduction of virgin material use (kt)	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**	**Reduction of virgin material use (kt)**	**Reduction of GHG emissions (kt)**
Cluster 1	1.1 Renovating instead of building	655,311	399,395	NA	NA	NA	NA
	1.2 Adaptive reuse						
	1.3 Choice of material/product with a long lifespan						
	2.1+2.2 Increased lifespan of a building						
Cluster 2	2.3 Use of demountable products	346,348	195,452	401,829	280,602	642,082	595,134
	3.1 Use of materials with high recycled content						
	5.1 Reusing secondary products						
Cluster 3	1.4 Saving of material in production	64,147	113,802*/ 180,228**/ 230,223***	55,272	166,174*/ 267,248** / 318,720***	84,794	259,096*/ 425,524**/ 425,601***
	4.1 Choice of biobased material						
	4.2 Nature-based solutions						

* Saving of GHG emissions due to reduced virgin material consumption

** Saving of GHG emissions due to reduced virgin material consumption, if biogenic carbon storage is taken into account

*** Saving of GHG emissions due to reduced virgin material consumption, if biogenic carbon storage and storage of carbon during lifecycle are taken into account

5.2.2. Cluster 1: The largest prevention of virgin material consumption in the BAU scenario

The biggest saving of virgin material consumption can be generated by extending the lifespan of existing buildings with the Circular Renovation Actions in Cluster 1. The combination of these four Circular Renovation Actions provide a material savings of 655,311 kt and 399,395 kt of embedded GHG emissions. This represents 75.6% of all materials needed for renovating the EU-27 building stock and 43.2% of all embedded GHG emissions related to the inflow of material demand, or as high as the annual CO_2 emissions of France and Spain combined (Our World in Data, .d.).

Since the Circular Renovation Actions are dependent on the availability of buildings fit for renovation or transformation (or those that are suitably located), the impact does not increase if the renovation rates are increased in the Policy Compliant or Ambitious scenarios. For example, increasing the amount of buildings that will be renovated to increase their energy performance does not increase the amount of vacant office spaces fit for adaptive reuse. Table 5.2.1 indicates that Cluster 1 will always outperform Cluster 3, based on both reduction of virgin material consumption and reduction of GHG emissions. However, the results also demonstrate that in the Policy Compliant scenario, even though Cluster 1 reduces the virgin material consumption more than the combined actions of Cluster 2, the reduction of embedded GHG emissions is still higher in Cluster 2.

5.2.3. Cluster 2: An exponential increase in the saved environmental impact based on renovation scenarios

Based on the combination of the three Circular Renovation Actions in Cluster 2, up to 346,348 kt of virgin material consumption can be reduced in the BAU scenario, along with 195,452 kt of GHG emissions. This represents roughly 39.9% of all material consumption related to renovation activities in the BAU scenario and 21.1% of all GHG emissions. Based on the increase of renovation rates through the different scenarios, a big differentiation can be seen between the prevented material consumption of Cluster 2 and the saved emission of GHGs. Based on the increased renovation rates, 1.8 times more virgin material consumption is prevented in the Ambitious scenario, compared to the BAU scenario. When comparing the prevented emission, almost three times more GHG emissions are prevented in the Ambitious scenario compared to the BAU scenario. This indicates that when the consumption of GHG-intensive material increases, a lot of impact can be saved by using these materials from a secondary source.

5.2.4. Cluster 3: A significant environmental impact both inside and outside the scope of the project

Based on the combination of the three Circular Renovation Actions in Cluster 3, up to 64,146 kt of mineral material consumption can be reduced. This decrease is nullified by the increased consumption of biobased materials (mainly soil for the green roofs and façades). Even though the overall consumption of materials increases, results show a significant reduction of GHG emissions. This impact even surpasses the saved GHG emissions from Cluster 2, if biogenic carbon storage in both production and use-phase are taken into account. As other environmental impacts—the capturing of PM, reduction of the Urban Heat Island Effect, and increase of healthy living environments—are not taken into account, the impact of this cluster will most likely be a lot higher if assessed through a more holistic set of indicators.

5.3 Model limitations and uncertainties

Static modelling
The modelling in this research was done based on the Urban Mining Model developed by Metabolic in collaboration with both the Economisch Insituut van de Bouw (EIB) and the Joint Research Commission (JRC). In this research, the material intensities of buildings are considered static. The material intensities differ per region, building type, and age category, but the latest reference buildings used are from the year 2014. This means that new regulations, especially ones considering energy efficiency standards of buildings, are not considered. For this reason, some material flows might be underestimated, i.e. the insulation material required for renovation. This is especially relevant if we consider renovation cycles which have a short cycle (less than 30 years to remain within the 2022-2050 timeframe of this research). Since this is only a minority of all actions, the result will not be hugely affected.

Availability of data
As many Circular Renovation Actions are hugely dependent on scarcely available data, it was not always possible to find plausible data sources to map the impact of certain renovation actions based on different geographic regions. If this was the case, the regions for which data could not be found were assumed to be an average of regions for which data was accessible. This will most likely influence the outcome of the differentiation per region. More research needs to be done on finding data entries for the different Circular Renovation Actions per region to enhance the quality of this analysis.

Over the horizon
The scope of this research is focused on the materials used for renovation activities in the EU-27 from 2022-2050. As some of the proposed Circular Renovation Actions create positive environmental impact only after the year 2050, they might seem irrelevant to clustering or the roadmap. By lengthening the timescope of this research to beyond 2050, assumptions have been made regarding the development of the EU building stock, since no data is available at the moment. This means that results regarding these Circular Renovation Actions have less scientific backing.

Decarbonization
During the same timeframe as this research, other major transitions regarding sustainability are taking place. Two major ones are the decarbonization of the grid and the reduced need for energy because of increased thermal performance of the EU-27 building stock. Both have a major impact on overall GHG emissions, both directly via the reduced consumption of energy which can largely be attributed to the renovation of the EU-27 building stock, and indirectly via the reduced emission of GHGs if energy is used. The second topic is especially relevant for the assumptions made in this research, because decarbonization of the grid will cause a reduction of GHG emissions related to the production of building materials.

Circular Economy
For all EU-27 countries, a fully circular metabolism for renovation and construction materials seems highly unlikely before 2050. Slow population growth and continued GDP growth result in a steady growth of the materials stored in the building stock towards 2050. The amount of construction and input through renovation far exceeds the material outflow. This dynamic is exacerbated due to the potential longer lifespans of buildings, which means that the outflow catches up only slowly with the inflow. Since the inflow is expected to exceed the outflow, it means that the availability of materials ‘mined‘ from the built environment will not be sufficient to supply the demand for new construction and renovation materials before 2050. Therefore, similar to Deetman, et al. (2020), this study shows substantial challenges for achieving a global circular economy in the coming decades.

Additionally, instead of only focusing on material quantities, from an ‘urban mining‘ perspective, the quality of materials is of equal importance. While the material quantity provides insight into the maximum potential, the material quality eventually determines the possibilities for reuse and recycling. Further research should focus on identifying the potential for contamination of certain materials, as well as the quality (and losses) of materials both during and after disassembly. Additionally, it is important to consider that every country in the EU-27 has their own regulations and legal frameworks that influence the potential for reuse and recycling. The same holds for renovation actions that focus on extending the lifespan of buildings. Right now these are only modelled based on technical feasibility, but social and economical factors might also be very important to consider.

From a circular economy perspective, material reuse should be prioritised instead of recycling (to keep materials as high in the value chain as possible). To facilitate reuse, future research should focus on financial feasibility, skill development in the building sector, and on the right digital and physical infrastructure to allow for the reuse of components instead of downcycling. A key element in this transition will be the use of ‘Urban Mining Hubs‘ in which these components can be tested, repaired, and redistributed to new building sites.

Closing remarks

In conclusion, the results of the research show that, despite the rather limited information on material intensities, as well as uncertainties regarding future construction, demolition, and renovation rates, we have been able to calculate the potential material stocks and flows. On a EU-27-level, the results provide insight into the orders of magnitude of materials stocks and flows and can help identify opportunities for material reuse/recycling and facilitate the development of pathways for environmental impact reduction.

Discussion and final remarks

This study is based on previous research from both the EEA regarding Circular Renovation Actions and Metabolic modelling systems. It aims to bridge the outputs of this research and the development of a series of policies and roadmaps at the European level, which will serve to address climate challenges and achieve the goals set for 2050. Therefore, the best way to understand the results is viewing them as part of a larger context, amidst a large number of uncertainties and a high level of complexity.

Nevertheless, the results of the research show that, despite the rather limited information on many levels, as well as uncertainties regarding future renovation rates, we have been able to calculate the potential material stocks and flows in line with other studies. On a EU-27-level, the results provide insight into the orders of magnitude of material stocks and flows. It can help identify opportunities for material reuse/recycling and facilitate the development of pathways for environmental impact reduction.

One of the most interesting outcomes of this study is the constatation that some of the planned actions for the built environment will not have influenced the results of our built environment until well past 2050, a reminder of the importance of planning Circular Renovation Actions for immediate results but also for the long term. In many cases, the actions with almost no influence before 2050 have the biggest long-term impact for the built environment, so it is important to remember that the problem can only be addressed with a combination of short and long term actions.

Another important remark that must be made is the granularity at which results are shown in this report. Due to the complexity of the modelling exercise and the description of many circular renovation actions some of the more granular insights that are possible to extract from the created model are not incorporated into the report. The geographical spread and the moment at which materials are released from the building stock will have a great impact on the potential implementation of the circular renovation actions.

6. Addendum: Combined Action Results

Introduction

This document is an addendum to the report *Modeling the Renovation of Buildings in Europe from a Circular Economy and Climate Perspective (2022)*. Combined results from the modeling exercises in the report are presented below for the Business as Usual (BAU) scenario.

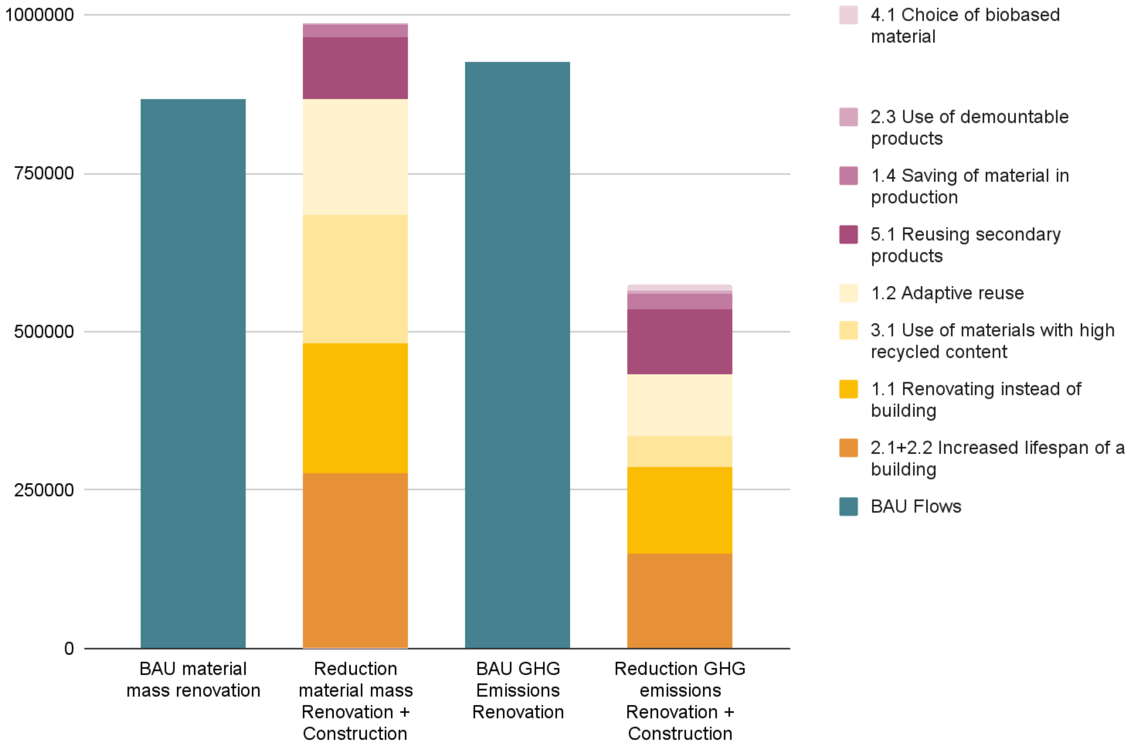
Results overview

The total impact of all renovation actions combined comes to a reduction of **974,645** kt in primary material mass (112.38% of renovation flows*) and **602,208** kt of GHG emissions (65.09% of renovation flows) between the years 2022 - 2050. The percentage is higher than 100% due to the fact that the Circular Renovation Actions together achieve not only a reduction in the primary materials used for renovation but also prevent the use of a certain amount of material in new construction.

Of the total reduction in primary material mass, 67.31% comes from preventing construction and 32.69% from altering renovation flows. For GHG emissions, 68.22% comes from preventing construction and 31.78% comes from altering renovation flows.

When comparing the impact of all circular renovation actions combined to the entire construction & renovation flows, the reduction in primary material usage is 6.20% and in GHG emissions reduction 6.45%.

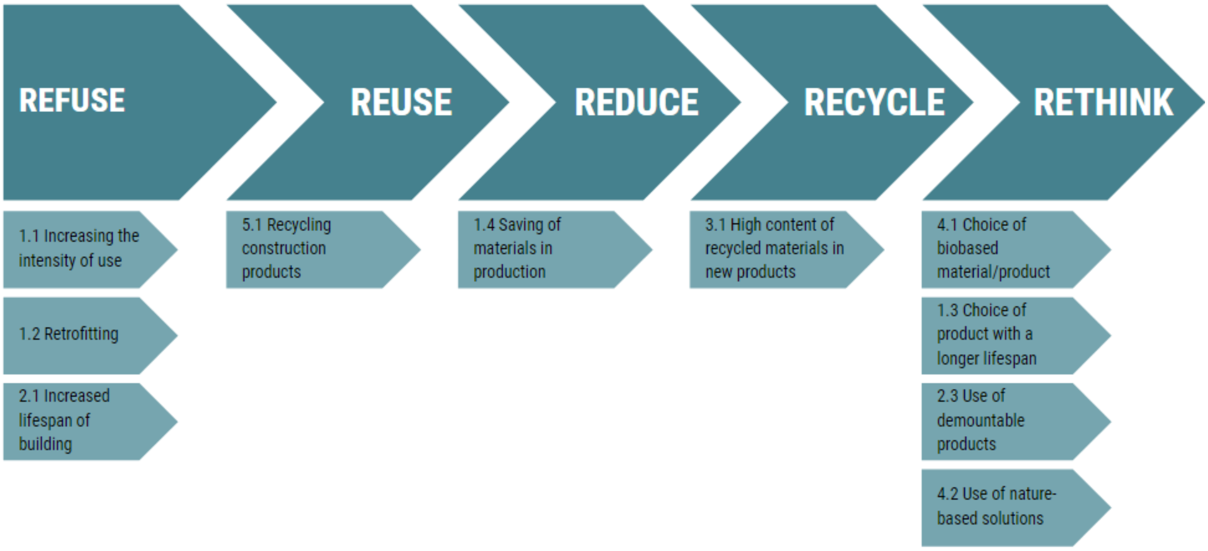
The total impacts are distributed over the different actions as visible in Figure 1.1 from this addendum.



Addendum figure 1.1: Impacts of all renovation actions combined

Precedence of modeling actions

The renovation actions have been modeled to avoid double counting of impacts. For this reason an order in which the actions take precedence over one another has been chosen. The order of the actions has been chosen with the R-ladder framework in mind (Rood, T. & Kishna, M. 2019, Outline of the Circular Economy). Preferring reduction of material use, then reuse of products and recycling of materials, and lastly rethinking the materials and production methods used for new building products.



Addendum figure 1.2: Overview of order of renovation actions for modeling of total impact

Methodology

The order used for modeling the results of all actions combined is visible in the overview above. First, the total reduction from preventing construction of new buildings was calculated (Actions 1.1, 1.2 and 1.2). Next, the total product flows required for renovation were calculated. From this result, the potential of recycled products was deducted (Action 5.1). From the remaining products, the potential savings from materials in production were deducted (Action 1.4). For the remaining products, the number of products that could be manufactured from secondary materials were deducted (Action 3.1). The remaining products were replaced with biobased alternatives (Action 4.1) and longer lifetime alternatives (Action 1.3) where possible. For all newly manufactured products (all products except those from action 5.1) it was assumed that they are installed using DfD principles where possible. Based on this it was calculated what the impact was of using DfD techniques (action 2.3), taking into account that the climate benefits from recovering a DfD product to prevent the production of a product made from secondary materials are less high than preventing the production of a product made from primary materials.

Results

The impact of each action by the modeling method described above can be seen below in table 1.3.

Action	Mass impact (kt)	Mass impact (%)	GHG impact (kt CO2 eq)	GHG impact (%)
2.1 Increased lifespan of a building	277,407	31.99%	150,776	16.30%
1.1 Renovating instead of building	203,900	23.51%	135,600	14.66%
3.1 Use of materials with high recycled content	203,288	23.44%	48,021	5.19%
1.2 Adaptive reuse	182,341	21.02%	98,199	10.61%
5.1 Reusing secondary products	99,049	11.42%	103,085	11.14%

1.4 Saving of material in production	17,703	2.04%	25,172	2.72%
2.3 Use of demountable products	2,297	0.26%	2,853	0.31%
4.1 Choice of biobased material	-4,881	-0.56%	10,616	1.15%
1.3 Choice of material/product with a long lifespan	-1,025	-0.12%	1,839	0.20%
4.2 Nature based solutions*	-224,064	-24.22%	-27,354	-2.96%

Addendum table 1.3: Primary material usage and GHG emission impacts per action.

**Action 4.2: Use of nature based solutions*

Overall this action would have a negative impact on primary material usage and GHG emissions of production, for this reason it has been excluded from the full results describing the potential for primary material use and GHG emission reductions. The interaction between using secondary materials and the production of green roofs / facades was deemed minimal, since the largest part of the GHG emissions in these products arise from the steel frame elements for the green facades and the recycling of steel is already considered to be at the theoretical maximum in the current market. Only the plastic elements in the green roofs / facades would benefit from the increased recycled content of action 3.1, reducing the overall GHG emissions of production with about 5%. Of course the benefits of this action extend beyond the production of the building products themselves. When taking into account carbon sequestration, particulate matter absorption and benefits for local biodiversity of green roofs / facades there is a strong case to be made for implementing these nature based solutions. Green roofs are an especially attractive option, with their lower GHG emissions from production.

Annexes

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Model (manual)

To give the reader insight into the modelling exercises performed for this research, a data model has been provided. There are several files connected to the modelling exercises, which are provided in Excel format and the modelling exercises itself that were done in Python notebooks. There are various files provided, which are described here.

Microsoft Excel file containing raw data used for graphs in report
Visual Sheets - Renovation In Europe CE & Climate.xlsx

This Excel file contains all raw data used for generating the graphs in the report. All sheets are labelled according to the graph in the report they correspond to.

Microsoft Excel file containing input data sources for modelling work
Input Sheets - Renovation In Europe CE & Climate.xlsx

This Excel file contains the data sheets used for both the generation of the baseline material flows as the Circular Renovation Actions described in the report.

Several of the input sheets were generated by combining various data sources described in the report methodology section. To prevent clutter in the data files these intermediate data sources have not been included, but only the relevant combined input data used directly in the modelling exercise.

Microsoft Excel file containing baseline material flows for all three scenarios presented
Output Material Flows - Renovation In Europe CE & Climate.xlsx

This Excel file contains the material flows of the renovation types for the three different scenarios.

Microsoft Excel file containing output data of modelling the renovation actions
Output Sheets - Renovation In Europe CE & Climate.xlsx

This Excel file contains the modelling output data from the Python files described below. For some Circular Renovation Actions additional calculations are done in this Excel file.

Several Python notebook files used to transform the input files into the material flows and output data files
1a - Building stock EU per year.ipynb
1b - Translate renovation rates to intensities - buildings.ipynb
2a - Integrating Circular Actions Part 1.ipynb
2b - 2.3 DfD Products.ipynb

Most of the modelling work has been done within these Python notebook files. It is believed that the files are sufficiently commented using Markdown cells for the reader to follow along without further instruction in this document. For the modelling exercises the data infrastructure was different than is presented in these files. For this reason, not every notebook file is functional out of the box and might require changing input data sources to the Excel files provided.