Embodied carbon regulation in the European construction sector

An analysis of the economic impact

shifting paradigms

Colophon

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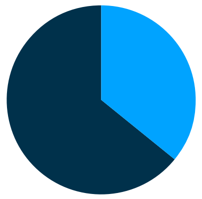
‘Establishing embodied carbon as a design criterion makes it possible to combine the most favourable combination of individual strategies.’

Executive summary

0.1. Buildings in the EU are responsible for 36% of greenhouse gas emissions

This report presents 72 case studies on how reducing embodied carbon in construction will impact the investment costs of buildings and infrastructure. The analysis focusses on the European Union (EU) and the United Kingdom (UK).

Buildings and infrastructure require energy to operate, which contributes to greenhouse gas (GHG) emissions. In buildings, this involves primarily heating, cooling and lighting. For infrastructure, it is associated with the movement of cargo, people, data, water, electricity or fuels, and materials. However, the construction, maintenance, renovation and eventual decommissioning of buildings and infrastructure also contribute to GHG emissions. They include those related to the extraction, processing, production, recycling or disposal of construction materials, as well as those from energy use when buildings are assembled, maintained, renovated, demolished or disassembled.



36%
Building construction and operation in the EU are responsible for at least 36% of GHG emissions

When we consider GHG emissions associated with a building’s construction materials and its full life cycle (excluding operational emissions from its use phase), they are referred to as embodied carbon.

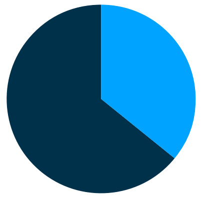
Buildings and the construction sector in the EU are responsible for:

- at least 36% of GHG emissions,
- around 50% of all extracted materials, and
- over 35% of EU waste generation.[1]

GHG emissions from the life cycle of construction materials are estimated at between 5% and 12% of total EU GHG emissions. To achieve the goal of net-zero emissions by 2050, these emissions must be reduced. This will affect both renovation of the existing building stock and new construction. To reduce the EU’s operational emissions will require renovating and retrofitting an estimated 75% of the building stock.[1] This will involve returning buildings to good condition, while also retrofitting[2] them to improve their energy performance. Renovation and retrofits should be implemented using techniques that involve the least amount of embodied carbon.[3]

The European Commission (EC) already regulates building energy efficiency through EU-level policy frameworks, such as the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED),[4] which target operational emissions. Regulating the embodied carbon of buildings is a logical next step to ensure that the entire life cycle of a building or piece of infrastructure meets the net-zero goal by 2050.

0.2. Ample potential exists for cost-effective embodied carbon emission reduction



41%

across all design case studies, embodied carbon reductions of 41% could cut costs by 9% compared to the business-as-usual case (BaU)

The literature review has identified over 100 quantitative and qualitative data points on reducing embodied carbon for new construction and renovation. The data are categorised into six interventions to reduce embodied carbon emissions. They are inspired by circular economy principles on the use of regenerative resources, recycling, lifetime extension, circular design and business models.[5] Figure 1 shows the insights drawn from 72 publications, providing quantitative data on the impact of these interventions on embodied carbon and/or investment costs.

1. Make the best use of existing and future construction

The potential for GHG mitigation is greatest at the planning stage, where the approaches chosen can seek to avoid or, at least, minimise new construction. Although that is not always possible, particularly given growing demand for housing, strategies to minimise vacant floor space or even regulate floor space per capita can help reduce demand for new housing construction.[6] For infrastructure, continuously expanding the road network can be avoided if research concludes that changing commuter habits is a more effective way to solve congestion issues in the long run.[7] Renovation, rather than demolition and replacement, offers another approach. For example, avoiding demolition in the United Kingdom would reduce the construction sector's annual embodied carbon emissions by 16%.[8]

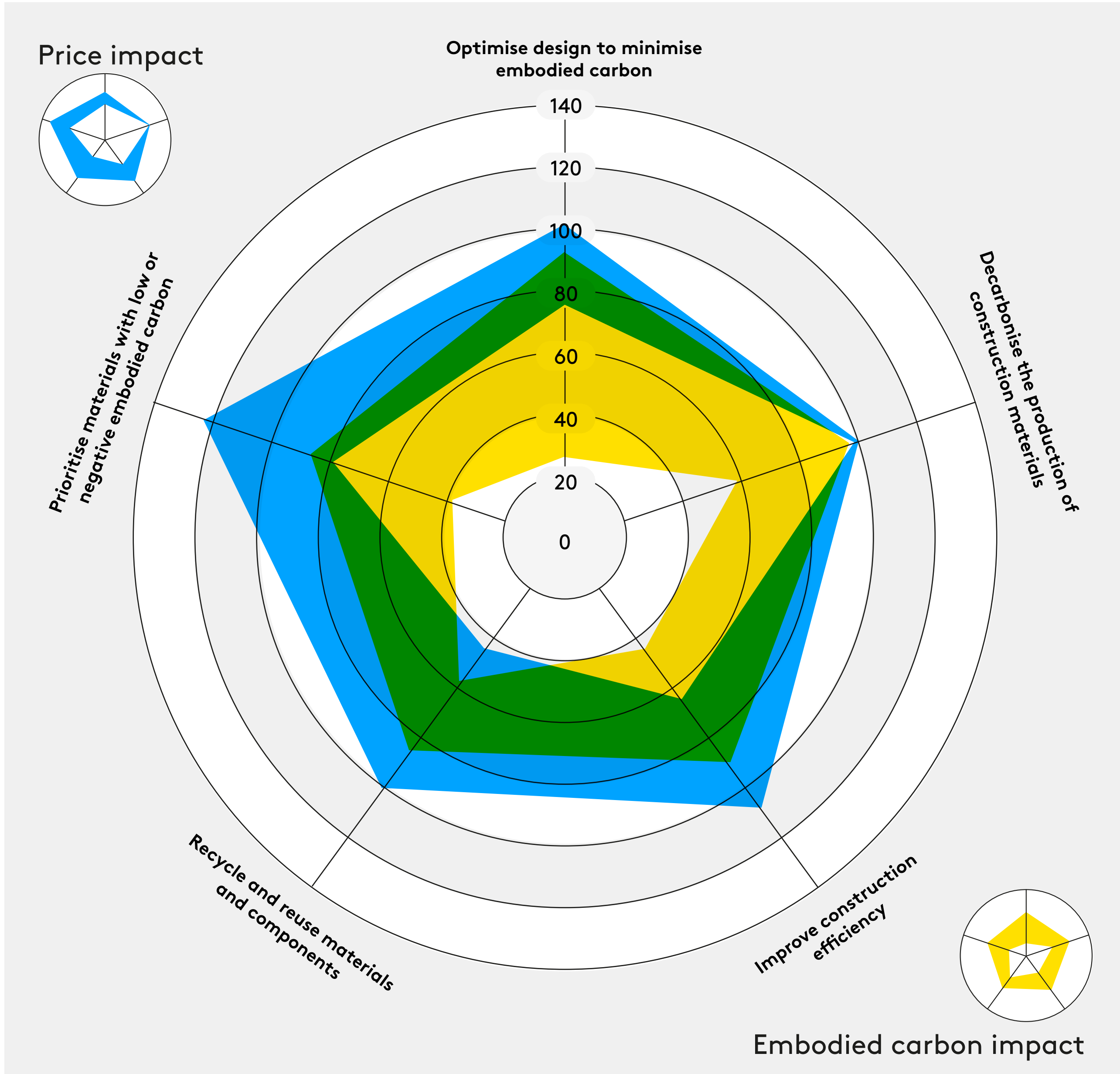
2. Optimise design to minimise embodied carbon

Defining embodied carbon reduction as an objective in the building design phase is effective. Most of the technical options for embodied carbon are within reach at that point and the option offering the least amount of embodied carbon can be selected for each material or functional unit. Thus, establishing embodied carbon as a design criterion makes it possible to design the most favourable combination of individual strategies, by material or functional unit, as described in the remaining four interventions. Case studies indicate that tailored design can reduce both embodied carbon and costs for both buildings and infrastructure. On average, across all design case studies, embodied carbon reductions of 41% could cut costs by 9% compared to the business-as-usual case (BaU) (→ Figure 1).

Embodied carbon was reduced by 15% in buildings in the EU without additional cost, while in the United States (US), reductions of 19% (houses) and 45% (office buildings) were achieved with an increase in overall project costs of only 1%. Dedicated design software from Australia that allows architects to minimise embodied carbon helped to achieve similar climate impact reductions at 5% to 10% lower costs.

The infrastructure case studies reported even more convincing results, with embodied carbon reductions of between 48% and 64% at wastewater treatment plants and 15% to 25% lower costs.[9] A 40% reduction in embodied carbon appears quite high, but comparative case studies of sport stadia and bridges confirm that figure. The large variation in embodied carbon expressed as tCO_2e per square meter[10] suggests that ample potential exists for peer-to-peer learning on low embodied carbon design.

Figure 1 Cost and climate impact of the five embodied carbon reduction interventions



In this figure, 100 represents no change. Thus, reducing embodied carbon would have no impact on price. Values below 100 indicate that carbon reduction or cost savings are realistic. All sources of quantitative data on embodied carbon come from historic real life or hypothetical case studies (primarily 2017-2022). Projections towards 2050 have been left out.

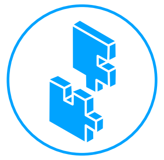
3. Decarbonise the production of construction materials

Capital investments in the heavy industries that supply traditionally carbon-intensive construction materials can also reduce embodied carbon. For most industrial facilities, this requires switching fuels to hydrogen or electricity, both produced from renewable energy sources. Such fuel switches would also require further capital investments in expanding renewable energy generation and distribution capacity beyond that required with the continued use of existing technology. The sources consulted do not include the embodied carbon impact of these capital investments.

However, those investments, combined with those needed in heavy industry, will total between 6 and 13 billion EUR per year.[11] Investments of that magnitude require significant carbon-intensive materials, which will entail substantial upfront embodied carbon emissions. When considering these emissions and the limited global carbon budget which remains,[12] is this indeed an effective intervention and can we still afford it?

Figure 1 shows that intervening in heavy industry could reduce embodied carbon by between 3% and 42%. This could be implemented without any impact on the investment costs of a new building or piece of infrastructure. However, most of the data sources reported on individual materials, which reduce the embodied carbon of only part of a building, thus distorting the average figure. Combining the potential to mitigate embodied carbon in the production of cement, steel and glass with available technologies could achieve a 42% reduction for a reference house.[13] Decreasing embodied carbon beyond 50% is possible only in the long run and would require a combination of major capital investments, new technologies and design optimisation.

4. Improve construction efficiency

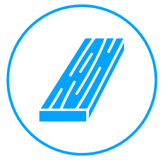


This fourth strategy focusses on improving the construction process, primarily by moving construction off-site to a factory setting and assembling the construction modules on-site. Waste avoidance and an average of 25% embodied carbon reduction represent most of the mitigation impact. Cost reductions of 15% were also reported, together with improved working conditions. Off-site construction can also improve the efficiency of renovation and retrofitting.

5. Recycle and reuse materials and components

Both recycling and reuse can reduce the embodied carbon of new construction by an average of 32%, with a 19% cost reduction on average. Emission reductions of over 95% were recorded for individual construction materials. However, most results refer to individual materials; this distorts the average when trying to understand the impact in terms of a structure that contains multiple materials. The University of Manchester found that the emission reduction potential of recycling building materials in the EU could reach 43%.[14]

6. Prioritise materials with low or negative embodied carbon



Finally, material substitution may offer the greatest opportunity to make deep reductions in embodied carbon, with an average reduction of 37%. However, the cost case is less convincing. Based on all sources, cost savings and increases average out to be neutral. However, Figure 1 includes a single outlier from a report for the American Concrete Institute,[15] which finds wood-based construction to be 23% more expensive than cast-in-place reinforced concrete. Those findings contradict academic sources, which indicate that the cost of material substitution, including wood-based construction, may be between 4% more expensive and 22% less expensive.

Overall, the cost effectiveness of wood-based construction appears to be very case specific, as the Forest Service of the US Department of Agriculture also concluded when analysing the carbon benefits of wood-based construction.[16]

The results of the six interventions examined make a compelling case that ample opportunities exist for cost-effective embodied carbon reductions. This conclusion echoes the UK Green Building Council, which stated that "embodied carbon management may be seen as a proxy for cost management."[17] The variation in the results supports the conclusion that the climate and cost effectiveness of the options are case specific, but the many options available indicate that one or more cost-effective embodied carbon mitigation measures are likely available for each case.

Only a few of the sources consulted referred to new technologies that require major capital investments. Most compared recent real-life cases of new construction, relying on readily available technologies. This is encouraging because these options can be deployed in the short run and primarily involve reducing the use of carbon-intensive materials.[18] In the long run, capital investments can also reduce the embodied carbon of carbon-intensive construction materials such as steel, cement, aluminium and glass. Thus, in the long run, a 91% reduction in embodied carbon is realistic and will increase the investment costs of a house by less than 0.4%. When carbon capture and storage are included to avoid the remaining 9% of emissions, the costs of a house will increase by 0.4%.[19]

The cost savings may have increased over recent months. Russia's escalation of its invasion of Ukraine in early 2022 aggravated supply constraints and inflation and increased energy prices across the European continent.[20] This gave a competitive advantage to less energy-intensive products and production methods with a low carbon footprint.

0.3. Policies to avoid a 'rebound effect' and ensure absolute emission reductions

It is encouraging that embodied carbon reduction can reduce investments costs for new construction, renovations and retrofits. However, it creates the risk of a rebound effect, whereby efficiency gains lead to cost savings, which in turn lead to increased consumption or use. For example, consumers might use those cost savings to enlarge floor area. Such rebound effects would prevent absolute emission reductions across construction value chains and should be considered when designing effective emission reduction policies.

Avoiding or minimising new construction altogether remains the most effective way to reduce embodied carbon emissions in the construction sector. Strategies based on that objective optimise the utilization rate of existing buildings and avoid vacancies, ensure that new construction reflects actually need, and involve renovating rather than replacing buildings. They should be part of any effort to reduce and avoid emissions from this sector. When new construction is unavoidable, most of the GHG mitigation and sequestration potential lies in the design stage. The stakeholders who design buildings or define the design criteria should be an important policy target.

To avoid stranded assets,[21] the EU needs to right-size large capital investments in construction sector value chains, particularly when the investments themselves involve a substantial amount of embodied carbon. For example, decarbonising the heavy industries that produce construction materials requires switching from fossil fuels to low-carbon alternatives, such as hydrogen or electricity from renewable energy sources.[22] This requires substantial capital investments in those industries, as well as in increased renewable energy generation and distribution capacity.

All these investments in heavy industry and the energy sector have their own embodied carbon impact. This should be considered when scaling and prioritising the options to reduce the embodied carbon impact of the construction sector. However, it is often ignored in long-term models of roadmaps intended to reduce the GHG footprint of industrial products. Understanding cross-sectoral impacts and properly tying interventions in material flows to GHG emissions across sectors requires a systems approach[23] and closer collaboration between the energy system and material analysis communities.[24]

Finally, the use of wood, flax, hemp, cellulose, wood fibre or cork-based insulation materials may help to transform the construction sector into a net carbon sink if emissions along the value chains of these natural construction products are managed properly. Although forestry stakeholders indicate that forest production can be expanded while strengthening biodiversity, competing land use activities, as well as relevant planetary boundaries, should be considered when planning to use forestry- or agriculture-based construction materials at scale.

'Greening the value chains of traditionally carbon-intensive construction materials requires major capital investments, which have their own embodied carbon impact. However, this downside is often ignored.'

chapter 1

Embodied carbon in EU construction

1.1. Understanding the cost implications of embodied carbon reductions

Embodied carbon refers to the GHG emissions of a product related to its material content and extraction, production, manufacturing, assembly and construction, and to maintenance, renovation, demolition and disposal or recycling (→ Figure 2). It excludes the operational greenhouse emissions of a building associated with to heating, cooling, ventilation, lighting and running equipment.[25]

Embodied carbon can also work in a positive manner. Some materials absorb CO_2 during their production or recover some of those production-related emissions during their use and demolition.[27] When emissions from other life cycle stages do not exceed the amount of carbon that has been absorbed, a product can be net carbon negative. The construction sector, with its long-term use of materials in the building stock, could lock the carbon stored in these materials away safely for decades and, perhaps, even centuries.[28]

The EC is considering whether to regulate GHG emissions related to the entire life

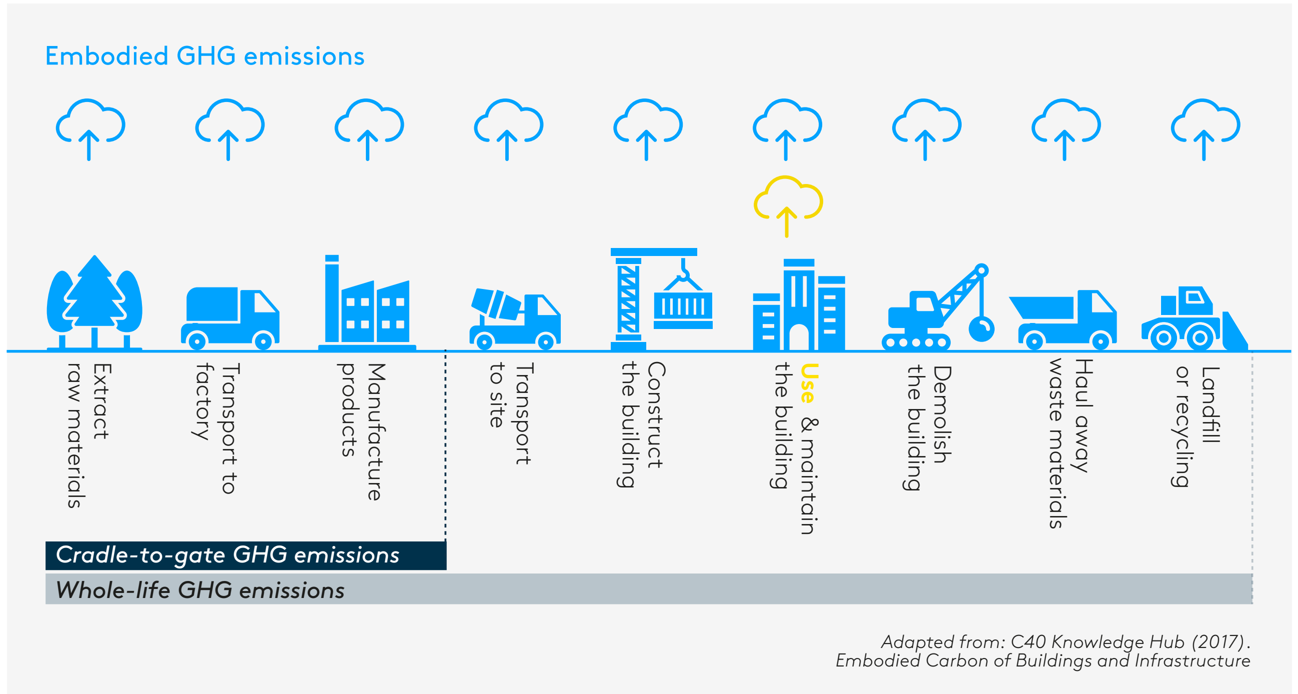


Figure 2 Cost and climate impact of the four embodied carbon reduction strategies[26]

cycle of materials used in the construction sector. This would involve the planned revision of the EPBD, which aims to address "'carbon emissions over the full lifecycle of a building"[29] and of the Ecodesign of Sustainable Product Regulation (ESPR), which would include products' carbon and environmental footprints.[30]

Efforts to reduce operational emissions — by both improving building efficiency and increasing the share of renewable energy — have begun to bear fruit. Thanks to improving building energy efficiency, the focus on building life cycle emissions can now gradually shift to their material footprint and the GHG emissions associated with the production, transport, application, maintenance and eventual end-of-life phase of these materials.

To assess the consequences of these regulations on the costs of new construction and building renovation and retrofits, this briefing report addresses this question:

What is the cost impact on new construction and renovation of reducing embodied carbon in the construction sector in the European Union?

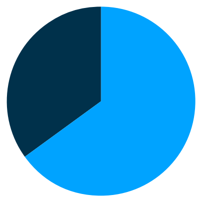
1.2. The importance of embodied carbon

Historically, EU climate action in the built environment focused primarily on improving building energy efficiency in the use phase, prioritising renewable energy development and reducing energy demand. This focus on energy has left a major opportunity untapped: the ability to drive deeper cuts in GHG emissions by reducing material use and demand, switching to materials with a lower carbon footprint and, perhaps, even using materials that sequester, rather than emit, carbon during their production and use.[31]

With an estimated 67 percent of global GHG emissions associated with material management rather than operational energy use,[32] reducing the carbon footprint of materials is a sensible target along a pathway to net zero by 2050. It incorporates embodied carbon emissions that are still too often overlooked when taking purchase, investment or design decisions.[33] Understanding and quantifying embodied carbon allows decision-makers in the construction sector to take a life cycle perspective on the carbon footprint of construction materials.

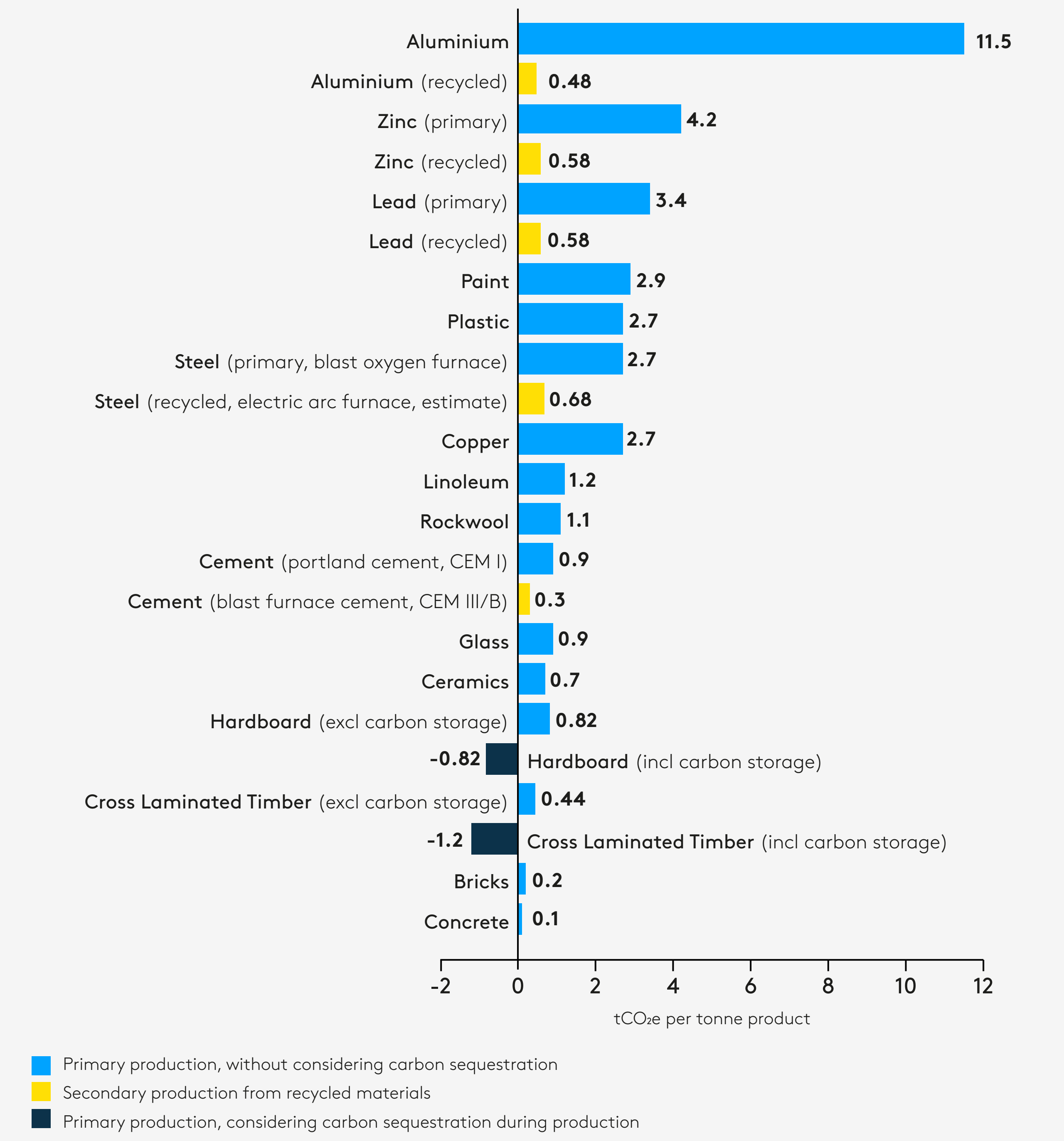
1.3. The carbon footprint of construction materials

Figure 3 shows that the embodied carbon of different construction materials varies significantly. It shows that material substitution can reduce embodied carbon. Figure 3 presents data from the from the Inventory of Carbon and Energy (also known as the ICE database), supplemented by data from academic articles. Such information should play an important role in the design stage and the selection of construction materials. The figure also confirms that recycling building materials can reduce embodied carbon. All the examples show that the embodied carbon of primary materials is higher than that of their secondary equivalents. (→ Figure 3)



65%
In the EU, buildings account for 65% of cement use

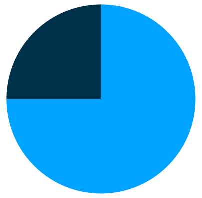
Figure 3 Embodied carbon of construction materials[34]



1.4. The EU construction sector

Building construction and operation in the EU are responsible for 36% of GHG emissions.[1] Fifty percent of all extracted materials are used in the building sector and the building sector generates more than 35% of waste. GHG emissions from material extraction, construction products manufacturing, and building construction and renovation are estimated to generate between 5% and 12% of total EU GHG emissions. According to the EC, greater material efficiency could avoid up to 80% of these emissions.[35]

In the EU, buildings account for 33% of steel, 20% of plastics, 25% of aluminium



75%
Investments in improving the energy efficiency of existing buildings are important. According to the EC, around 75% of EU building stock is energy inefficient

and 65% of cement use. If infrastructure construction were included, these values would probably be significantly higher. Without major change, 2050 GHG emissions from steel, chemicals and cement would increase well beyond the 2015 level as continued increases in production volumes would surpass efficiency gains.[36]

Investments in improving the energy efficiency of existing buildings are important. According to the EC, around 75% of EU building stock is energy inefficient and 5% of the EU's carbon dioxide emissions could be avoided by improving the efficiency of the existing building stock. Today, approximately 1% of the building stock is renovated and retrofitted annually, but the pace of renovation should be accelerated.[1] These renovations and retrofits should also be implemented with the least amount of embodied carbon as possible.[3] The encouraging news is that renovation, in general, is more carbon effective than building new[37] and can be completed much more quickly.[38]

The EU committed to net carbon neutrality by 2050. That goal must also apply to the construction sector and the production of construction materials. The Commission is thus strengthening its regulation on monitoring the embodied carbon footprint of construction products by harmonising embodied carbon metrics and disclosure requirements in its proposal for a revised Construction Products Regulation. This regulation aims to provide reliable information on the environmental performance of products from different manufacturers in different countries. In addition, the revision of the EPBD addresses carbon emissions over a building's full life cycle. The EPBD is a suitable framework to introduce the mandatory assessment and information disclosure related to both embodied and operational emissions for buildings.

This briefing paper explains the impact of efforts to reduce the embodied carbon of a building or piece of infrastructure on costs. The UK was included in the focus area as substantial research on embodied carbon reductions in the built environment was conducted there when the country was still part of the EU.

> 'Embodied carbon management may be seen as a proxy for cost management.'
> UK Green Building Council

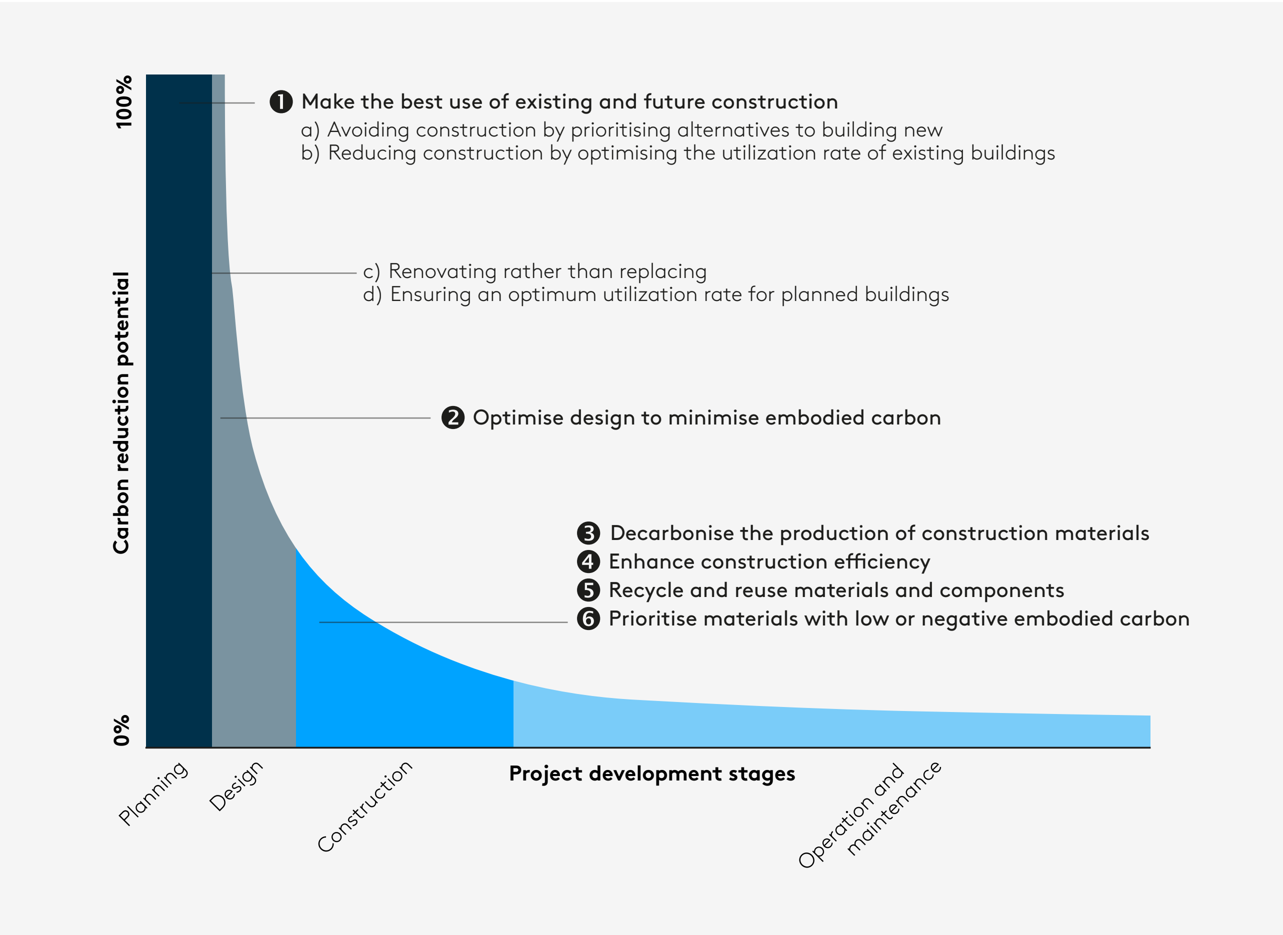
chapter 2

Embodied carbon reduction and investment costs

This section examines the effects of reducing the embodied carbon of new construction, renovations and retrofits on the investment costs of a new building, piece of infrastructure or building renovation and retrofit project. The results are presented in the form of an eco-efficiency index,[39] which shows how different measures related to process and production efficiency, building design, and material use affect both a structure's costs and its embodied carbon.

The literature on embodied carbon and costs impacts can be categorised into six main interventions to reduce embodied

Figure 4 Embodied carbon reduction potential at different project development stages[40]



carbon. These interventions correspond well to circular economy principles to prioritise regenerative resources, extend the lifetime of existing assets, use waste as a resource, design for the future, and rethink the business model.[5]

Each intervention emphasises a different stage in a building's life cycle and involves different stakeholders in the construction materials value chain. The first — 'Make the best use of existing and future construction' — was added to provide a full overview of the mitigation options, However, the cost of interventions that seek to avoid or minimise new construction has not been analysed because they do not compare well with approaches to minimise embodied carbon in the construction of new buildings or infrastructure. (→ Figure 4)

Figure 4 shows how the potential to reduce GHG declines at different project development stages. While many opportunities exist to reduce the embodied carbon footprint of new construction (interventions 2-6), efforts to minimise the need for new construction have the greatest impact per square metre (interventions 1a-1d).

2.1. Make the best use of existing and future construction

Until construction practices have advanced such that the construction sector sequesters carbon in the built environment, regenerates ecosystems, restores biodiversity, and emits no waste, re-suspended dust particles or bituminous aerosols,[41] efforts to avoid and reduce construction should receive priority over minimising its impact. This can be achieved by avoiding vacancies and low use rates through strategies such as:

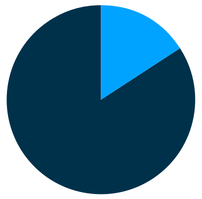
a. Avoiding construction by prioritising alternatives to building new

Avoiding construction altogether is not always possible, particularly when population growth, an ageing population4[2] and decreasing household size[43] require more residential units. On the other hand, new construction can result in more vacant floor space. When KPMG commissioned a new office building in Amsterdam, it left 50,000 m² vacant office space behind. The owner of the firm's former office struggled to find new tenants for several years.[44]

Considerations are different for infrastructure. Research from the Netherlands points out, for example, that building more highways is a less effective strategy to reduce congestion than incentivising people to work partly from home if they can.[7] Other strategies that reduce the need for motorised transport infrastructure are to create compact neighbourhoods with mixed use buildings. This allows people to live close to their work and services, such as grocery shops, and favours walking and bicycling over driving.[45] Research in Canada and the Netherlands also suggests that while wider roads solve congestion in the short run, behaviours adjust and traffic jams return. However, because road capacity has increased, traffic jams involve even more cars.[46]

b. Reducing construction by optimising the utilization rate of existing buildings

Some new construction can be avoided by optimising the utilization of the existing building stock. Milan is documenting the city's vacant and underused spaces, while Portland's Residential Infill Project has eased regulations for 'adaptive reuse' projects that repurpose buildings for new uses. Other options are to introduce or increase taxes on unoccupied or unused properties or to reduce them on shared



16%
Avoiding demolition in the UK would reduce the total embodied carbon in the country's construction sector by 16%

spaces within buildings.[6] Starting in 2022, Amsterdam has sought to reduce vacant space by requiring building owners to report vacancies that last for several months. A penalty on vacant floor space encourages owners to ensure that the building is used.[47] The city of Birmingham, England adopted a similar approach in 2021, imposing a graduated council tax rate for unoccupied properties. The rate reaches 100% for properties that have remained vacant for two years and 400% for those that have been empty for more than 10.[48]

Evidence from the US finds that the construction sector can contribute to meeting the goal of limiting global warming to 2°C only if floor space per capita is reduced by 20%.[49] In the EU, efforts to reduce absolute embodied carbon from new construction will likely also require regulating the size of new buildings based on floor space per capita, as rising land prices are not likely to provide a sufficient incentive. Such regulations could ensure that reductions in embodied carbon are not offset by gradual increases in per capita floor space. The tiny house movement also draws attention to the material and carbon footprint of large homes. It aims to inspire people to reduce their per capita floor space as an effective way to reduce an individual's footprint.[50]

c. Renovating rather than replacing

Efforts to renovate existing buildings in the EU fit well within a circular economy strategy to extend the life of existing assets and avoid demolition.[51] For example, estimates for the United Kingdom indicate that avoiding demolition would reduce annual carbon emissions by 16% of the total embodied carbon in the country's construction sector.[8] This argument supports strategies to prioritise renovation over demolition and new construction. These statistics were confirmed by data from Hong Kong, where mean embodied carbon for refurbished buildings is 33% to 39% less than for new-build projects and the cost of renovated buildings is 22% to 50% less than for new-build projects (per square metre of floor area). However, in Australia, renovation was found to increase costs while reducing embodied carbon only marginally.[52]

The value of life-cycle extension as a way to reduce embodied carbon emissions is already part of the public debate. In London, the Marks & Spencer retail company faced public opposition to plans to demolish and replace warehouses. Stakeholders who favoured renovation and retrofitting cited climate change as their primary argument.[53]

d. Ensuring an optimum utilization rate for new buildings

Embodied carbon metrics often fail to consider a building's utilization rate. However, the expected use intensity of a building or piece of infrastructure should be considered when taking an investment decision and assessing its environmental impact. A new building with very low embodied carbon that remains vacant still makes an excessive contribution to climate change. An example is floor space sharing which refers to options such as communal arrangements in residential settings and co-working offices. It is the most cost-effective abatement option in the construction sector, saving around 100 EUR per tCO_2e mitigated.[54]

2.2. Optimise design to minimise embodied carbon

Description: The second intervention is to optimise the design of the building or piece of infrastructure to achieve an embodied carbon minimum. As shown in Figure 4, interventions at the early project development stages include a range of measures and the most effective combination can be chosen: recycling; re-use; prioritising low-carbon construction materials; design for disassembly; and avoiding overspecification that leads to designing structures for higher loads than necessary.

Construction projects may use between 30% and 50% more cement and steel than would be necessary if value chains were optimised, for example by substituting materials, reducing overspecification, and using high- strength steel and techniques, such as post-tensioning.[55] 'Design for disassembly' offers another design option, enabling recycling and reuse. It prepares the building for the circular economy and extends the life of construction elements.

Embodied carbon and operational emissions can inform design decisions but may pose trade-offs. The 'embodied energy payback period' concept links them. It calculates the time required, for example, for an insulation material to offset the emissions from its production, with savings in the use phase.[56] This calculation can support an informed choice to minimise a building's overall (operational and embodied) emissions. In that regard, a World Wildlife Fund case study showed that triple glazing would reduce operational energy use, but that its higher embodied emissions would offset the gains compared to double glazing.[17]

Design also incorporates optimising a building's context and positioning. Because this is very case specific, it has not been included in the results. Nonetheless, passive design and natural elements, such as trees, shading5[7] and green roofs,[58] can improve building thermal conditions and comfort, while avoiding both the operational and embodied carbon impact of technical solutions such as air conditioning.

Example: The circular viaduct in the Netherlands has been successfully assembled and disassembled for a second life at a different location. Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Water Management, made circular economy criteria an important element of the viaduct procurement process. By sharing knowledge and experience, Rijkswaterstaat aims to make circular procurement a common practice in the Netherlands.[59]

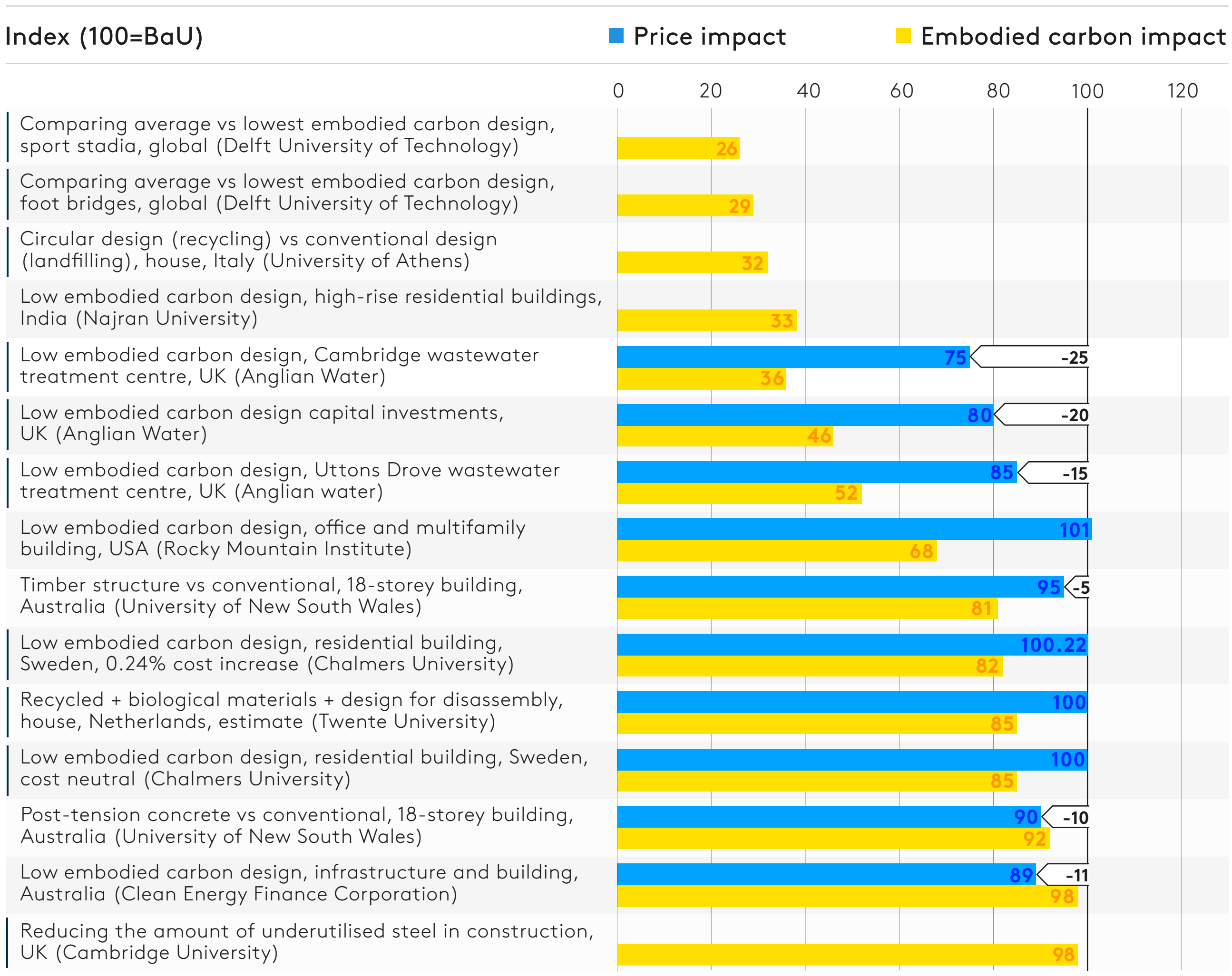
Results: Research from the Netherlands[60] and Sweden shows that the embodied carbon of residential buildings can be reduced by 15% without additional cost (→ Figure 4). This reduction was achieved by using recycled and biological materials and through design for disassembly. Deeper cuts in embodied carbon, reaching 18%, might increase costs by 0.22% over those of a conventional house.[61] Another case study from the Netherlands found that the circularity of a standard one-family house can be doubled by replacing traditional materials with circular alternatives without impacting life cycle costs.[60] However, no information linked this data to an embodied carbon impact.

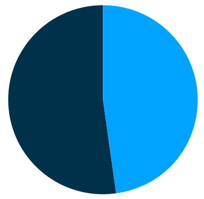
A case study from Italy suggests possible embodied carbon reductions of over 70%, but does not specify the cost implications. Large, cost-neutral reductions are also reported in the US. In a study of mid-rise commercial office and multifamily buildings, the Rocky Mountain Institute found that design can reduce embodied carbon by between 19% and 45%, with an overall project cost increase of 1%.[62]

Embodied carbon reductions in infrastructure investments can also be cost effective. The UK's Anglian Water and its subcontractors estimated the impacts of capital investments in wastewater treatment facilities. They recorded embodied carbon reductions of between 48% and 64% and cost reductions of between 15% and 25%.[63] In Australia, research showed that low-carbon infrastructure design can reduce emissions by an average of 12%, while reducing investment costs by 2%.[64]

The University of New South Wales in Australia explored how 'carbon value engineering' can help reduce embodied carbon and capital cost by substituting building materials, systems or design strategies without a negative impact on functionality. It found that design choices informed by their embodied carbon reduction potential can reduce embodied carbon by between 8% and 26%, while reducing costs by 5% to 10%.[65] (→ Figure 5)

Figure 5 Costs and embodied carbon impact of optimising building design to minimise embodied carbon[66]



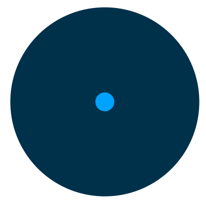


48%
Anglian Water recorded embodied carbon reductions of between 48% and 64% and cost reductions of between 15% and 25%

Research has found that the embodied carbon of sport stadia built between 2000 and 2011 ranges from 250 $kgCO_2e$ per seat (London Olympic Stadium) to 3500 $kgCO_2e$ per seat (Beijing Olympic Stadium). For pedestrian bridges, the differences are even larger, reaching a factor of 10.[67] These differences are mainly attributed to the volume of carbon-intensive materials used, since the materials' emission coefficients did not vary substantially by geography.[10] Given those large differences, significant emissions could have been avoided if all stadia, pedestrian bridges and buildings were designed with minimal embodied carbon.

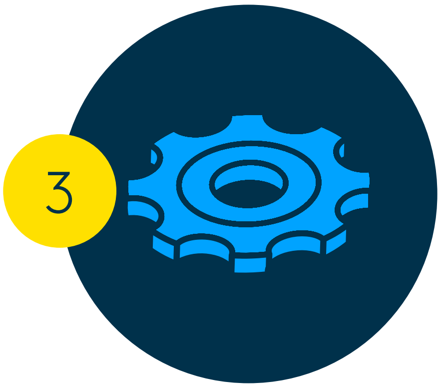
Low-carbon design can reduce expenditures on materials but may increase the cost of design and time needed to select the most appropriate building materials. When Microsoft invested in reducing emissions related to the construction of new buildings and data centres, it found many construction materials available at comparable cost and performance levels. However, the materials' level of embodied carbon differed. The company concluded that reducing embodied carbon requires comparing materials and selecting the manufacturer that offers the lowest embodied carbon. This effort only increases the 'soft costs' associated with brainstorming sessions, meetings and the coordination required to create and implement a plan to minimise embodied carbon.[68] This echoes a similar finding from Material Economics, which concluded that optimising concrete elements or steel beams to reduce total materials use often increases complexity and coordination.[54]

A study published by Finland's Tampere University also argues that design-for-disassembly could be a climate protection strategy that is as effective as building wooden structures. However, accounting for the impact of design-for-disassembly components requires expanding the system boundaries by incorporating the entire next use cycle in the assessment or adjusting a component's impact to take account of the number of use cycles. In this context, low embodied carbon design strategies must sometimes strike a balance between using low-carbon materials with a shorter lifetime or durable materials and components with a longer lifetime. This means trading short-term emission reductions for long-term ones.[69]



The embodied carbon of sport stadia built between 2000 and 2011 ranges from 250 $kgCO_2e$ per seat (London Olympic Stadium) to 3500 $kgCO_2e$ per seat (Beijing Olympic Stadium)

2.3. Decarbonise the production of construction materials



Description: The third intervention focuses on the heavy industries that produce construction materials. It seeks to reduce the carbon footprint of construction materials by changing production methods, switching fuels and improving energy efficiency.

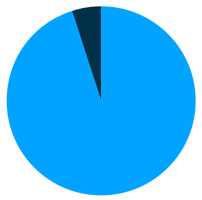
Example: The Swedish company, H2 Green Steel, is investing in hydrogen-based steel production. Using hydrogen from renewable energy sources, it aims to produce 5 million tonnes per year with a 95% reduction in carbon footprint.[70]

Results: Most sources that target the production of construction materials report on costs or embodied carbon impact by tonne or functional unit.[71] For this analysis, the information has been translated into the impact at the level of a house by combining it with information on the contribution of each construction material to the embodied carbon footprint of a reference house (Annex 1).[13] Similarly, a breakdown of investment costs by construction material was used to estimate the impact on investment costs, given that materials make up only approximately 58% of real estate investment costs.[72] For example, switching fuels in glass production can reduce emissions at production by around 80%.[73] However, because glass represents only 4% of the embodied carbon of the reference house, this intervention alone reduces its embodied carbon by only 3%.

The datapoint in Figure 6, 'Combined application of process emission reductions (cement, steel, bricks, glass)' applies the combined embodied carbon reduction potentials of four major construction materials to the reference house, generating a 42% reduction.

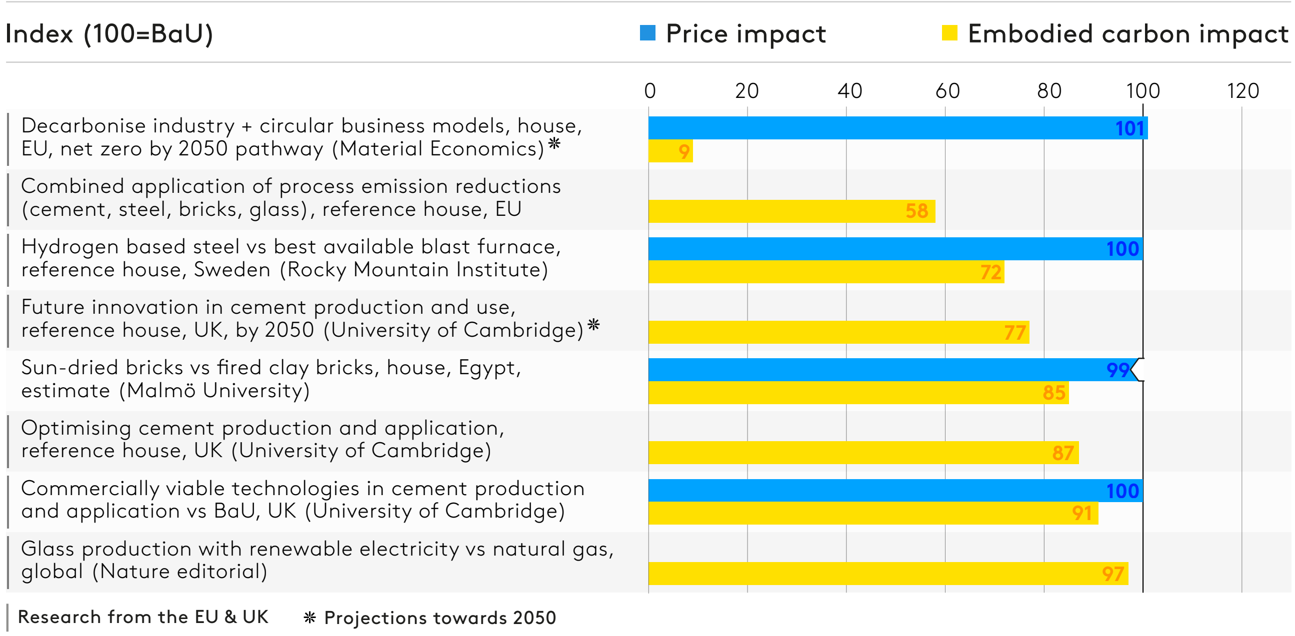
Over the long run, deeper reductions in the carbon footprint of construction materials will be possible as new technologies mature and can replace old assets. This will require large-scale capital investments in greening the value chains of traditionally carbon-intensive construction materials,[74] such as cement, steel, glass and aluminium, to be achieved by switching from fossil fuels to hydrogen or electricity from renewable energy sources. These investments will all have their own embodied carbon impact. For example, expanding the capacity of renewable energy to power steel mills requires substantial amounts of materials, each with its own carbon footprint. These figures do not include the embodied carbon impact of such investments. (→ Figure 6)

Researchers at Cambridge University analysed cement use and concluded that up to 37% of current cement industry emissions could be mitigated relying only on technologies that are both available and commercially viable. In the long run, high-potential technologies across all life cycle stages could unlock emissions reduction of up to 93%.[75] The case of H2 Green Steel suggests that 95% of GHG emissions from steel can be mitigated during production[70] and the rational use of steel can reduce demand for this material by 35%.[76]



95%
H2 Green Steel suggests that 95% of GHG emissions from steel production can be mitigated

Figure 6 Costs and embodied carbon impact of decarbonising the production of construction materials[77]



Other building materials are also reported to have high GHG mitigation potential. For example, emissions can be reduced by 75% by producing glass with electricity from renewable energy sources, reducing the embodied carbon footprint of a reference house by 4%.[78] The GHG footprint of sun-dried bricks is 99% lower than that of fired clay bricks and can reduce costs by at least 50%.[79] Although this research was conducted in Egypt, it may have potential for southern Europe.

Cementitious materials make up around 66% of all embodied emissions associated with building and infrastructure construction.[8] The potential for efficiency improvements in current production methods is limited, estimated at 24% for steel and 13% for cement.[80] Increasing those numbers would require large capital investments. Alternatively, substitutes for conventional clinker (beyond metallurgical slag and fly ash) can offer a lower GHG footprint. Those substitutes include mechanically activated pozzolans or calcined clays.

Aluminium also raises concerns because it is one of the most carbon-intensive construction materials on a per tonne basis (Figure 3). Industry stakeholders have pledged to reduce emissions by 80% by 2050, despite an anticipated 40% increase in capacity and demand.[81]

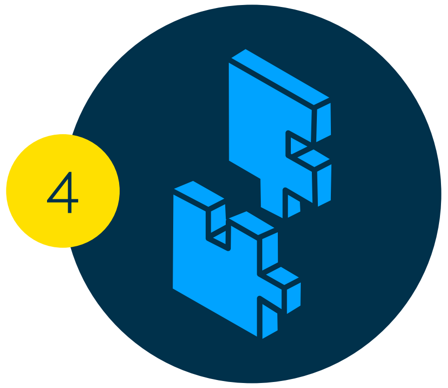
Two studies examined investments in low-carbon solutions for heavy industries and the long-run cost impact. The additional cost of net-zero cement and steel in the construction sector is estimated at EUR 40 billion to 50 billion per year by 2050, or around 0.2% of the EU's projected GDP at that time.[82] Even so, reducing the embodied carbon of construction materials has only a small impact on the cost of the final product. The estimated total product cost increase of a house with reduced embodied carbon is only 0.4%.[83] This is explained by the fact that carbon-intensive products such as cement make up a small part of a building's final cost.[84]

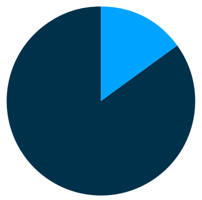
2.4. Enhance construction efficiency

Description: The fourth intervention focusses on improving the construction process. Off-site and modular construction are typical methods; they involve completing part of the construction in a factory setting and assembling the finished modules onsite. This strategy abates GHG by reducing both material waste and transport movements.

Example: The Dutch construction company, Ursem Modulair Bouwen, has adopted modular and off-site construction techniques. The company reports that this approach enables it to reduce construction time by 50% and waste production to less than 1% of total materials used. This is in comparison to traditional construction methods, where waste volumes can reach 10% to 15% of total material use.[85]

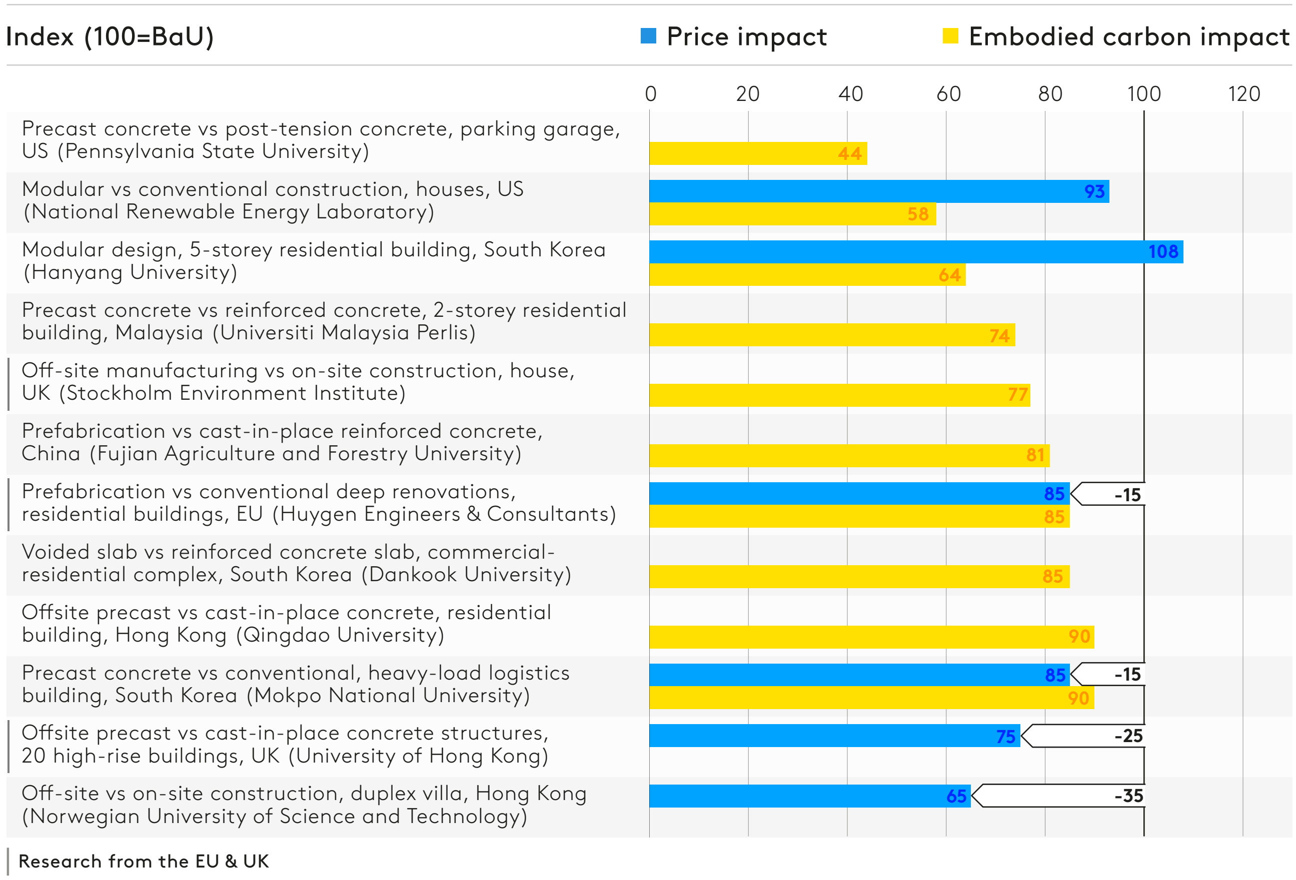
Results: Most of the sources consulted note that efficiency improvements reduce both embodied carbon and costs (→ Figure 7). Off-site construction can reduce emissions by 10% to 39%.[86] Prefabrication can also help reduce both embodied carbon and the cost of renovation and retrofitting by an estimated 15%.[87]





15%
Prefabrication can reduce both embodied carbon and the cost of renovation and retrofitting by an estimated 15%

Figure 7 Cost and embodied carbon impact of enhancing construction efficiency[88]

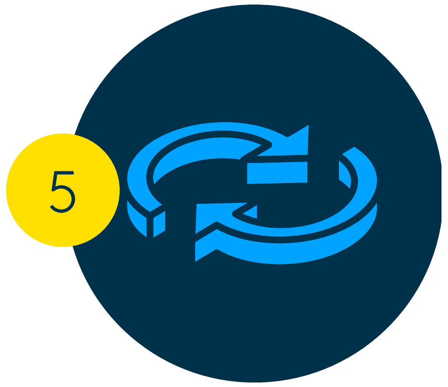


Industrial prefabrication or off-site construction allows for waste reduction and is already used widely in the EU for new buildings. Off-site construction also allows for increased automation or, even, the use of robots.[89] Labour shortages in some EU member states primarily affect manufacturing, construction and services,[90] but off-site construction can help meet future demand for construction even during periods of shortages.

The US-based independent National Renewable Energy Laboratory estimates that high-performance modular builders can drastically reduce both costs and GHG emissions. A 'net zero by 2050' ambition would then no longer increase the costs of a house by 8% but, rather, by only 1%. Total GHG emissions could also be reduced by 60% if modular design was combined with low-carbon construction materials and decarbonised electricity production.[91] Research from Canada found that off-site construction also offers workforce benefits, including "greater productivity, higher learning rate, better working conditions, enhanced worker quality, and improved safety and health."[92]

While off-site and modular construction is already used widely for new construction, it can also play a role in renovation and retrofitting. Initiatives such as P2Endure,[93] Energiesprong and More-Connect[94] aim to leverage the cost and environmental benefits of off-site construction to support renovation.[95] Such initiatives require some standardisation of the product or target building, for example, through row housing. In 2018, EU renovation initiatives using pre-fabricated solutions generated cost savings of at least 15% and reduced on-site construction time by 50%. In addition, it reduced both on-site disturbances during construction and waste.[96] The reported cost savings are due primarily to fewer mistakes, standardisation, lower labour costs, shorter construction time, reduced health and safety risks, and greater resource efficiency.[97] Higher investment costs for modular design were found only in Hong Kong.[96]

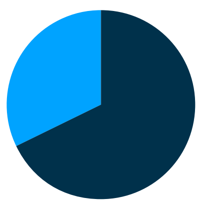
2.5. Recycle and reuse materials and components



Description: The fifth intervention strategy is to improve the building's end-of-life value and incorporate recycled materials and recovered construction elements in new buildings and renovation. (Renovation and retrofitting, which could be considered a reuse strategy, are not included but were addressed in section 2.1.)

Some of the interventions discussed previously can facilitate recycling and reuse. Circular business models for construction products and materials, such as take-back schemes, modular design and off-site construction (section 2.4), and design-for-disassembly (section 2.2), can help increase the end-of-life value of a building or piece of infrastructure.[98]

Example: The use of secondary building elements in new construction can help reduce primary sourcing, as demonstrated by Circl. This circular bank building in Amsterdam contains elements that were recovered from decommissioned branch offices and subsequently used in the building's interior as part of a broader strategy for circular design and building operation.[99] Durable building elements used on a building's exterior do not always meet modern standards for building insulation. When recovered, they can be reused on the inside of a new building. (→ Figure 8)



68%
Recycled cement or 'Freement' can reduce the embodied carbon in concrete by 68%, while reducing costs by 56%

Results: Nine sources that address recycling and reuse show that those approaches can reduce embodied carbon. Three sources also calculated the cost. The first involved the use of a SmartCrusher, a container-sized technology that can crush concrete from demolition sites, allowing for recovery of the heterogeneous composite elements of concrete, including unhydrated cement, hydrated cement, gravel and sand. They can be used immediately, with limited processing, as resources for new concrete onsite. Recycled cement is sold in the Netherlands as Freement.[101] According to a Dutch consultancy, this technology can reduce the embodied carbon in concrete by 68%, while reducing costs by 56%. Because these recycling technologies can be deployed on-site, they are cost effective. According to a Korean research institute found that they are 36% more cost effective and produce only 34% of the GHG emissions of off-site recycling.[102]

The second cost impact was provided by a Leeds Beckett University study on reclaiming bricks, which reduced their carbon footprint to close to zero. This nearly eliminated their embodied carbon contribution to a reference house (Annex 1) without increasing the costs.[103]

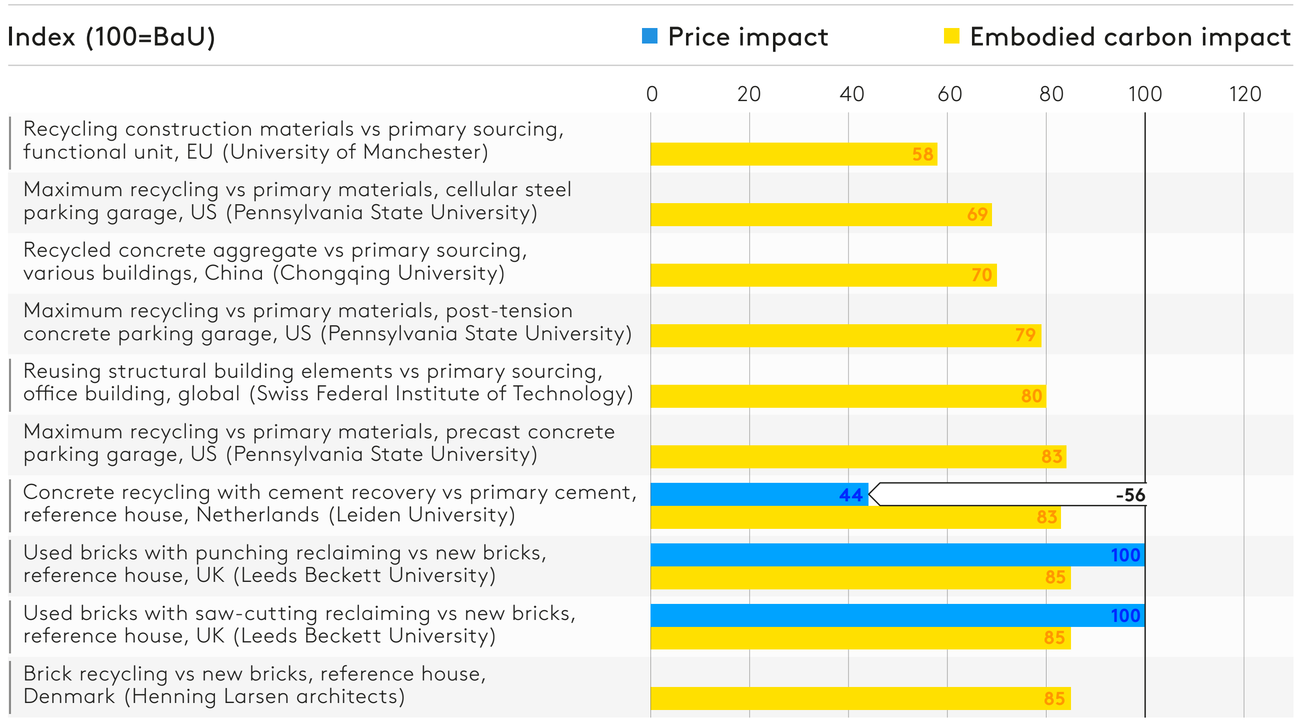
Recycling can reduce the carbon footprint of the most carbon-intensive materials. Figure 2 shows that primary aluminium has the highest embodied carbon, at between 11.5 tonnes and 16 tonnes CO_2e/tonne product.[104] This carbon footprint results from the fossil fuels used to produce the electricity used in aluminium smelters. That footprint can be reduced 24-fold when aluminium is produced from recycled materials.[105] Efforts to shrink the carbon footprint of aluminium focus on prioritising electricity from renewable energy sources and improving recycling rates.[104]

Recycling materials can avoid up to 95% of embodied carbon emissions compared to using virgin materials (Figure 3).[106] Even higher emission reductions — up to 99% — have been reported for reused bricks.[107] The availability of secondary resources and products constitutes the limitation on recycling and reuse. This is the case for glass, but its recycling rates can be improved. When considering availability in the UK context, the increased use of cullet can reduce GHG emissions from flat plate production by 18%.[108] According to industry sources, steel from the EU contains 59% recycled content.[109] The recirculation potential of metals could also be increased further if pollution, notably from copper, is reduced.

Considering the availability of secondary resources, enhanced material recirculation could reduce emissions within the EU by between 82 million tCO_2e/year and 183 million tCO_2e/year by 2050.[110]

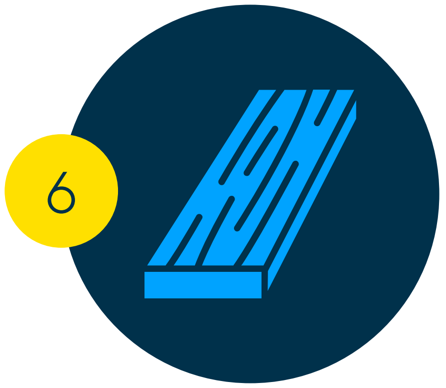
Sufficient information is available on recycling but few sources refer to reuse. Research by the Swiss Federal Institute of Technology finds that reusing structural building elements reduces embodied carbon emissions by 20%, even when they are transported 300 km and with 25% oversizing.[111] It is common practice to include the transport emissions of raw materials in that calculation and required under EN 15978, the European Committee for Standardisation (CEN) standard for measuring building environmental sustainability.[112]

Figure 8 Cost and embodied carbon impact of recycling and reusing materials and components[100]



2.6. Prioritise materials with low or negative embodied carbon

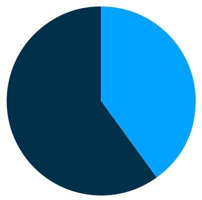
Description: Substituting conventional construction materials with alternatives with a low embodied carbon footprint or that can sequester CO_2 can help reduce the carbon footprint of construction. Bio-based construction materials — often referred to in European publications as 'wood-based construction' — offer such sequestration potential. Most life cycle scenarios assign lower CO_2 emissions to wood-based construction than to concrete or steel frame buildings.[113] Wood-based construction can also reduce the heat island effect by altering the buildings' thermal properties.[114]



Wood-based construction materials can be a net carbon sink only if certain conditions are met, tipping the entire life cycle balance to carbon negative. Those conditions are: sustainable plantation management; tree replanting after harvest; the use of renewable energy to process the wood; and wood reuse or recycling when the building reaches the end of its life. One consideration is that because wood production is a land use activity, it competes with other uses, such as agricultural production, food production, settlements and infrastructure. The use of wood at scale requires balancing these uses. It should, perhaps, be combined with strategies to reduce the land footprint of food systems by encouraging the use of plant-based food products rather than animal ones.[115]

Using roundwood for long-lived products is a more effective way to fight climate change than using woody material as a fuel.[116] One source provided estimates for Europe indicating that prioritizing wood in the construction of residential buildings could provide net carbon storage of 18 million tCO_2e/year to 46 million tCO_2e/year by 2030.[117] However, this assessment did not consider supply constraints for forestry products.

One requirement is that the wood be sustainably produced, re-grown and transported, preferably over short distances. This implies sourcing a substantial amount from within the EU itself. Forests and other wooded land cover more than 40% of total land surface in the 39 European Environment Agency countries, with forest cover and wood standing stock increasing.[118] In addition, plantation forests can be managed to contribute to biodiversity.[119] According to the European Forest Institute, "History shows that European forests can simultaneously increase the carbon sink, biodiversity and wood production."[120] Achieving those goals does require strong forest governance.



40%
Forests and other wooded land cover more than 40% of total land surface in the 39 European Environment Agency countries, with forest cover and wood standing stock increasing

Carbon sinks are important because they can compensate for hard-to-abate emissions. When deployed at scale, they could help reduce atmospheric concentrations of CO_2 in the future. Some sources describe emissions from heavy industry as difficult to abate.[121] Some construction materials, such as cement and glass, emit CO_2 from both fossil fuel use and the chemical processes that occur inside kilns and furnaces (calcination of calcium carbonate). Approximately 60% of CO_2 emissions from Portland cement[122] and one-third of emissions from glass production come from chemical processes.[123] These cannot be avoided by resorting to alternative fuels or production processes.

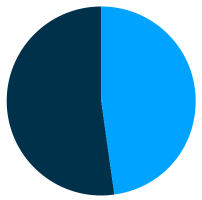
Results: Wood-based construction can reduce embodied carbon substantially. However, the results in terms of cost are mixed. Studies from the Netherlands,[60] UK[124] and US referenced in Figure 9 confirm that choosing materials with low embodied carbon is often cost-effective. Prioritizing bio-based materials can also reduce embodied carbon and may even sequester carbon. Industry players report that, together, wood-based and automated off-site construction can reduce embodied carbon by 80% and waste by 70%.[125] Most academic sources that compared steel or concrete with timber construction and the use of industrial timber products such as cross-laminated timber found large reductions in embodied carbon.

Case studies from Scotland find that timber use can reduce a building's embodied carbon by up to 48% compared to the baseline case of reinforced concrete and 58% compared to steel.[126] A Canadian study that compared a cast-in-place concrete building and a mass timber structure found that the latter reduced embodied carbon by 24%.[127]

But what about the costs of this substitution? Researchers from the Czech Republic analysed the investment cost of 1,520 contemporary catalogue houses and found that the investment costs of timber houses are 4% higher, on average, than those of brick houses.[128] The German Institute for Sustainable Constructions earlier confirmed the 4% higher investment cost[129] (→ Figure 9).

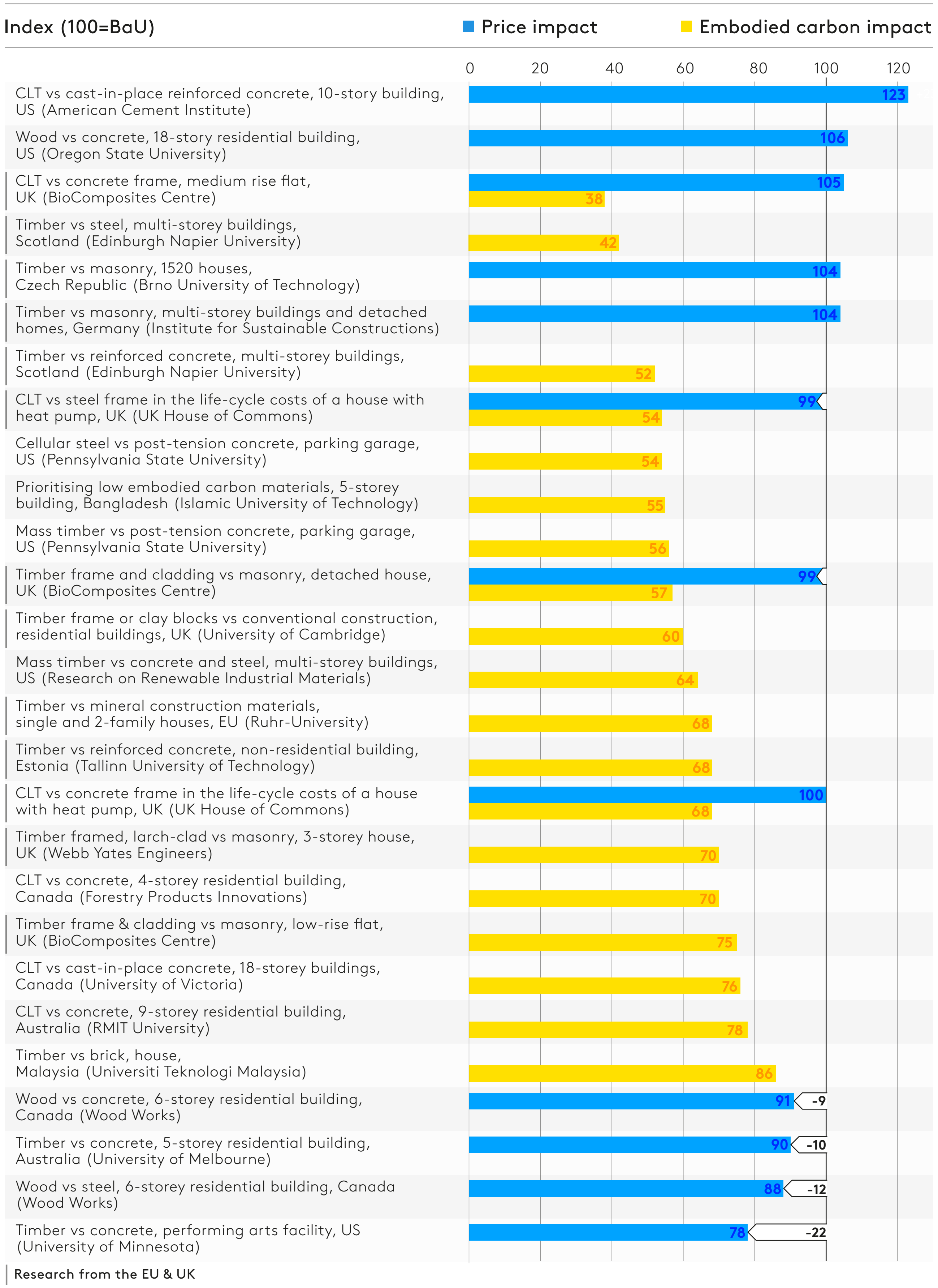
A study by the University of Minnesota, Twin Cities (US) found that cross-laminated timber construction is 22% less expensive than concrete, based on a 5-storey residential and commercial building. A report commissioned by the American Concrete Institute came to the opposite conclusion: it found that wood-based construction is 23% more expensive than cast-in-place reinforced concrete.[130]

In addition, actual cost savings may have increased over recent months. The Russian escalation of its invasion of Ukraine in early 2022 aggravated supply constraints and inflation and has increased energy prices across the European continent.[20] This puts energy-intensive products, which are often also carbon-intensive, at a disadvantage



48%
Case studies from Scotland find that timber use can reduce a building's embodied carbon by up to 48% compared to the baseline case of reinforced concrete and 58% compared to steel

Figure 9 Cost and embodied carbon impact of prioritising materials with low or negative embodied carbon[131]



and may have further increased the cost-benefit of strategies to reduce embodied carbon in construction.

Beyond costs, wood-based structures take less time to assemble on-site and require lighter equipment and foundations because the material is lighter.[132] Confirming this, a case study from Melbourne, Australia found that a wood-based structure is 10% less expensive and can be built in half the time required for a reinforced concrete structure.[133]

More carbon-intensive materials could be replaced through material substitution and the use of wood-based construction materials and flax, hemp, cellulose, wood fibre and cork-based insulation materials.[71] If emissions along the value chains of these natural construction products are managed carefully, they could transform the construction sector into a net carbon sink. However, they all need land to grow. Given the volume of materials that the construction sector uses, expanding the use of natural products at scale requires significant amounts of land (with the exception of agricultural residues). In addition, using land-based products to reduce the climate impact of construction must not impede progress on addressing other environmental concerns, as climate change is just one of the nine planetary boundaries that humanity must respect to avoid irreversible environmental changes.[134]

According to forestry stakeholders, the production of European forests can expand without pushing beyond other planetary boundaries. Competition over land use involves activities ranging from food production to urban area expansion and infrastructure development. Thus, understanding the role that forestry and agricultural products can play in the construction sector depends on other types of land use. Policies or shifts in consumer behaviour can affect the future availability of land to support the construction sector's transition towards net zero or, even, net negative GHG emissions. Examples of such shifts include reducing the consumption of animal-based food products and increasing the consumption of plant-based ones, which have a smaller land footprint. Other examples would include reducing average floor area per resident or shifting mobility priorities from privately-owned cars to more active, shared and public forms of transportation. Such changes could reduce the need for urban areas to expand.

‘Policies should support an absolute ceiling on the construction sector’s GHG emissions.’

chapter 3

Conclusions

Over 200 articles and publications identified six interventions that can help reduce the embodied carbon emissions of buildings and pieces of infrastructure. Sixty-nine of them included data on the cost and mitigation potential of one or several of the interventions.

3.1. Embodied carbon reduction potential and its costs

Most academic research finds that reducing costs and the carbon footprint of the construction sector go hand in hand, whether for individual interventions or combined ones. These results confirm the UK Green Building Council’s finding that “embodied carbon management may be seen as a proxy for cost management, providing an additional means of value engineering at early design stages.”[17] The case studies examined include information on villas, single-family houses, multi-storey apartment blocks, offices, sport stadia, bridges, wastewater treatment plants and heavily loaded long-span logistics buildings from a range of countries. This broad scope enables us to extend the conclusions to residential buildings, commercial buildings and infrastructure.

The studies on sport stadia[135] and bridges[136] are noteworthy as they show that differences of up to 10-fold in embodied carbon may exist within specific building categories. Because differences in functionality or geographical factors cannot explain differences in embodied carbon, the potential to reduce embodied carbon through peer-to-peer learning is substantial. This also seems to suggest that embodied carbon is not an important design criterion worldwide.

The impact of embodied carbon reductions on investment costs for design, recycling and reuse and improvements in construction efficiency is negative: costs will fall. The cost impact of investments in decarbonising the production of conventional carbon-intensive construction materials is close to neutral. Cost increases are observed only when substituting materials, specifically when using engineered wood products rather than concrete. However, this outcome is influenced by data from the Concrete Reinforcing Steel Institute. If this single outlier from a non-academic source is excluded, the cost impact of material substitution is between cost neutral and -1%.

One set of case studies focussed on low embodied carbon design, which makes it possible to combine several technical measures. Taking embodied carbon into account in the design stage is the most effective way to reduce both embodied carbon and costs.

A few sources provide several data points, rather than a single one, for a specific case study. This shows that there is an optimum balance at which substantial embodied carbon reductions are cost neutral. Reducing embodied carbon further would come at a cost premium. Thus, deeper cuts

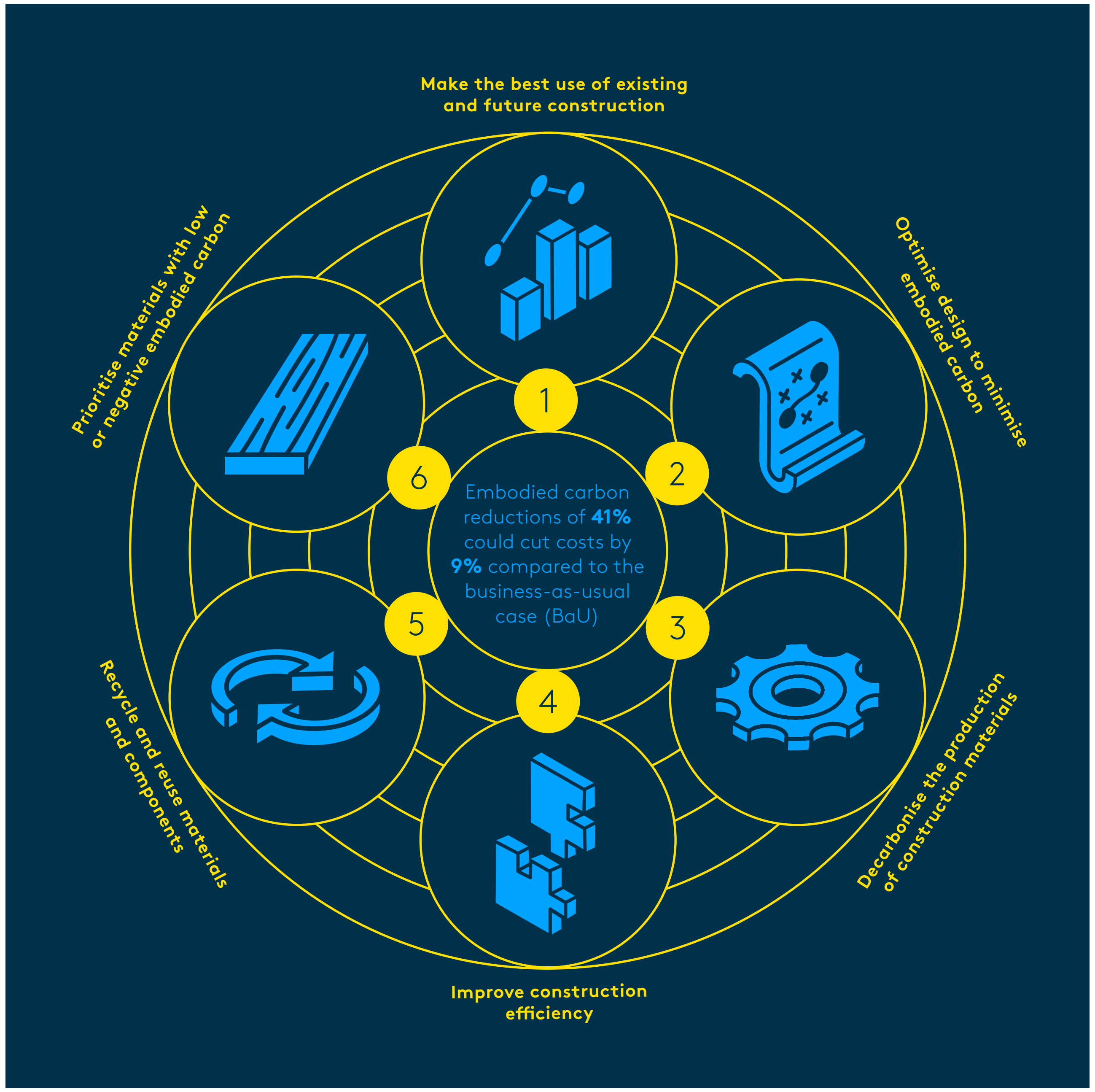


Figure 10 Six interventions to reduce embodied carbon emissions from construction

in embodied carbon emissions are possible with minor cost increases.

Two sources also project towards 2050. Reducing embodied carbon emissions in the building sector to meet the 2050 goal of net zero emissions will increase the cost of a house by between 0.4% and 1%, with the decarbonisation of the production of certain traditionally carbon-intensive materials increasing the cost substantially. Even so, this will have little impact on the cost of new construction because these materials' share of the cost of a new building, let alone of its sales price, is small.

Investments in producing steel and cement with a very low carbon footprint will dramatically increase the demand for renewable energy, thus also requiring large investments in renewable energy generation and distribution. All these capital investments will require significant carbon-intensive materials, which will entail substantial upfront embodied carbon emissions, before reducing the construction sector's embodied carbon footprint.

In addition to reducing GHG emissions, some of the proposed construction practices and building designs can also reduce costs, noise and dust nuisance, improve labour conditions, and reduce the time required for construction. If the construction sector continues to rely on steel and concrete, these benefits will not accrue even if these materials' embodied carbon footprint shrinks. On the other hand, steel and concrete do continue to outperform the alternatives for certain applications.

The use of wood-based construction and plant-based insulation materials could be expanded to replace more carbon-intensive materials. Doing so could transform the construction sector into a net carbon sink but would require significant amounts of land. This could create competition with other land uses, including forestry and agriculture. Thus, understanding the role that those two sectors' products can play in the construction sector requires understanding their interaction with other types of land use and how policies and trends will affect land use in future.

3.2. Policy recommendations

The results of this analysis of the mitigation potential and impact on investment costs of embodied carbon reductions in the construction sector suggest multiple policy implications that can guide the EU's policymaking process.

Prioritising interventions and setting targets

1 Policies should support an absolute ceiling on the construction sector's GHG emissions, rather than ceilings related to other parameters such as total floor space added per year, sector turnover, or the amount of construction materials used. That absolute ceiling should be lowered gradually as 2050 approaches, in line with the pace of the EU's international commitments to reduce its contribution to climate change.

2 Construction should be avoided and reduced to the extent possible by:
a) optimising the utilization rate of existing buildings and avoiding vacancies, for example, by requiring that buildings be occupied and used, particularly when floor space is scarce;[47]
b) building to meet actual need and ensuring that planned buildings have a high utilization rate;
c) encouraging stabilising or, even, reducing floor space per capita to avoid the rebound effect described above; and,
d) renovating, rather than replacing, buildings.

3 The design stage offers the greatest potential to reduce embodied carbon in new construction. Policies should create incentives for architects and construction companies to identify the most cost-effective ways to abate it and to perform energy efficiency upgrades of existing real estate. Minimising the use of carbon-intensive materials is crucial to enable deep cuts in emissions from the construction sector. There are plenty of alternatives as "a variety of alternative materials, technologies and practices are available."[18]

4 To avoid stranded assets, the EU should right-size investments to decarbonise centralised heavy industries that produce carbon-intensive products such as cement, steel, glass and aluminium.[21] Such investments should be designed to decarbonise only the production capacity remaining after other less carbon-intensive and, often, decentralised options — such as low-carbon design, material substitution, recycling and reuse - are deployed to their full potential.

5 Decisions to prioritise certain interventions should be based on an assessment of all GHG emissions involved. Decarbonising these heavy industries requires substantial capital investments and increased capacity to generate and distribute hydrogen or electricity from renewable sources. All these investments

have their own embodied carbon impact, which should be considered when scaling and prioritising the options to reduce the embodied carbon impact of the construction sector. However, long-term models and roadmaps to reduce the GHG footprint of industrial products often ignore this. Addressing it requires a systems approach and closer collaboration between the energy system and material analysis communities and, perhaps, adopting a concept such as embodied energy or carbon payback.[24]

Avoiding a rebound effect

1 Many of the options discussed in this briefing paper are commercially viable. This raises the question as to why they have not achieved broader market uptake, driven also by their competitive advantage. Further research may be needed to ensure that the main barriers to adopting strategies to reduce embodied carbon are addressed.

2 Policies should be designed to avoid a rebound effect[137] because it would hinder absolute reductions in GHG emissions. Because embodied carbon reductions often reduce costs, this creates the risk of rebound, whereby efficiency gains in embodied carbon also reduce costs. Those cost savings may increase demand or use, driving absolute emissions upwards.[138] For example, reduced construction costs could prompt users to invest in more floor space than they would otherwise. Encouraging efficiency gains with levies on energy and material use are an effective way to do so.

Policy framework and synergies

1 The design of policies to reduce the absolute embodied carbon footprint of the construction sector should take into account the lessons learned from existing initiatives to regulate embodied carbon within EU member states. It should also consider efforts to develop standardised methods to calculate the environmental impact of construction products and cost-efficient, transparent and robust carbon accounting processes.[139]

2 The revised methodology for life-cycle assessments in the revised European Standard for the sustainability of construction works (EN 15978)[140] should better reflect efforts to increase buildings' recycled content and end-of-life value.

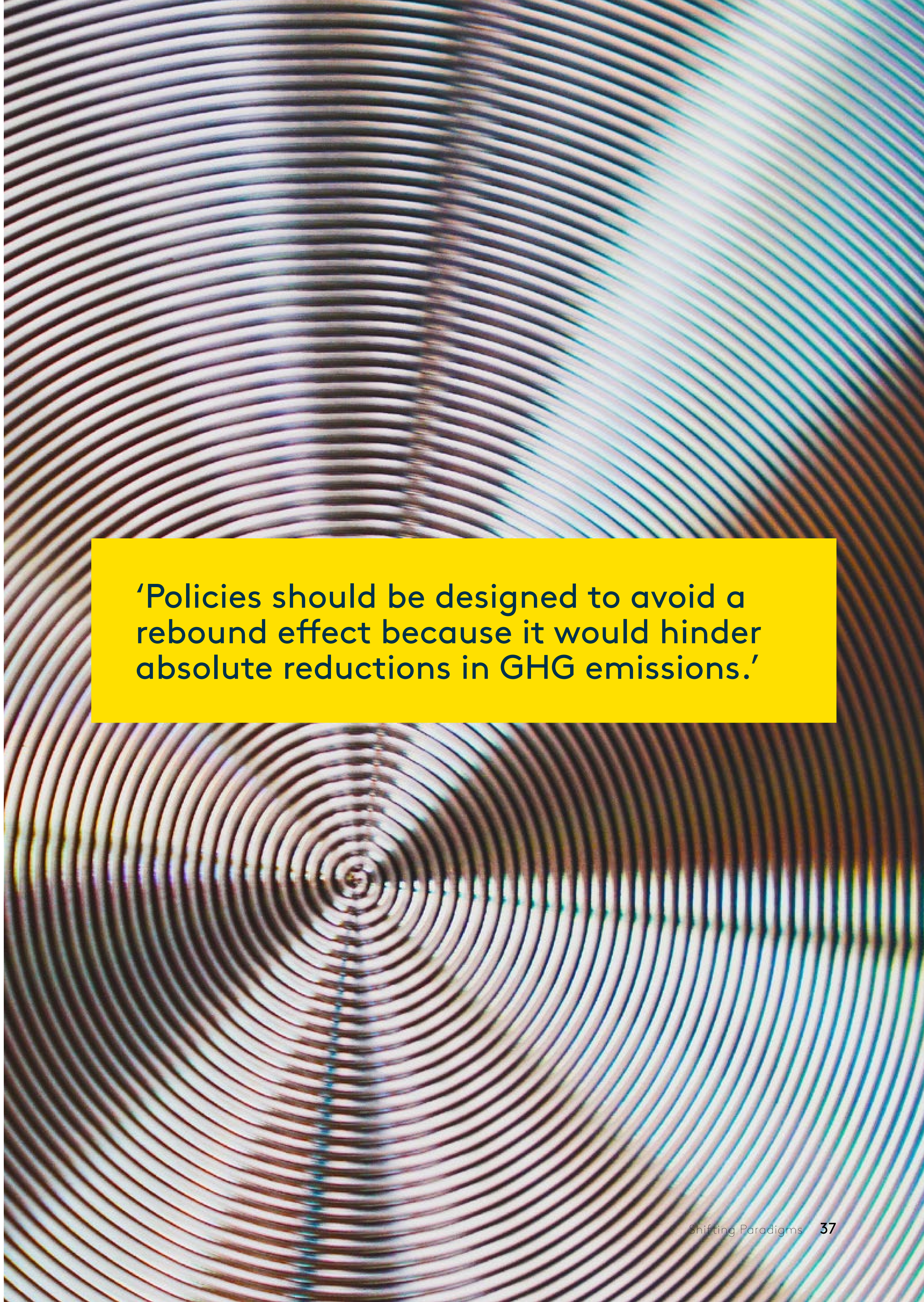
3 Further insights into which measures are cost effective in the EU and which require additional incentives, such as a carbon cost or tax, would be useful in determining the regulatory target for embodied carbon. However, none of the case studies examined considered the recent rise in inflation across the European continent. Increased energy prices have likely improved the competitive position of construction methods and materials with a reduced energy and embodied carbon footprint.

4 Last, the broader context is also relevant to creating incentives to avoid or minimise new construction and, when it is unavoidable, minimise its embodied carbon. Examples of policies that should be maintained or, even, strengthened to help reduce embodied carbon in construction include:

a) *Pricing GHG emissions*. The price of GHG emission allowances in the EU reached nearly 100 EUR/tCO2e in February 2022.[141] This strengthens the business case for reduced embodied carbon as high carbon prices will have a disproportionate impact on the price of carbon-intensive construction materials.

b) *Pricing waste disposal*. Recycled materials tend to have a smaller carbon footprint (Figure 3) than new ones. Landfill gate fees support the business case for recycling and help increase the availability of recycled materials.[98]

c) *Making use of public procuremen*t. Municipalities and other government bodies do not have to wait for the EU to issue regulations on embodied carbon. They can leverage their spending power now by defining embodied carbon as a criterion in public procurement, using existing metrics and experience from EU member states.[142]



annex 1

Methodology and scope

This research focusses on publications that provide information on price and/or embodied carbon impacts in the construction sector, although few examine both. Given that limitation, the research includes publications that provide information on technologies that could reduce embodied carbon and review impacts on either embodied carbon or cost.

2%
Appendices were excluded from the scope. The embodied carbon of their materials is negligible compared to that of the building's and may be less than 2%

The scope of the literature review has been defined as follows:

1 The project focusses on the EU but the geographical scope includes the UK as substantial research on embodied carbon reductions in the built environment was conducted there when the country was still an EU member. To expand the number of data points for specific interventions, publications from outside the EU and UK were added, prioritising publications that examine high-income countries.

2 The results address both buildings and infrastructure. Thus, the conclusions cover the construction sector as a whole, although the resource base for buildings is more extensive than for infrastructure.

3 Most of the articles and resources identified were academic. The results and visuals present the data sources, allowing the reader to assess their independence and credibility.

4 Appliances were excluded from the scope. The embodied carbon of their materials is negligible compared to that of the building's and may be less than 2%.[143]

5 The research focusses on the cost implications and mitigation potential of specific interventions at the level of a building or piece of infrastructure. Some measures rely on the availability of alternative construction materials with a reduced carbon footprint, such as clinker substitutes, recycled metals and sustainably produced wood. Several publications that provide insights into technical potential across a certain geography have been added. However, the research did not investigate the full extent to which the availability of these materials limits the implementation of certain embodied carbon mitigation strategies.

The research approach and definitions incorporate the following:

1 Embodied carbon refers to a product's emissions that are not related to its heating, cooling, ventilation, lighting and operating equipment.[144] The literature reflects a combination of two approaches to estimating embodied carbon: cradle-to-gate and life-cycle embodied carbon. The first refers to upstream emissions generated during extraction, production, manufacturing and delivery at the factory gate.[145] The second also includes emissions from construction, maintenance, renovation, decommissioning, and disposal or recycling. Both include intermediate transport (Figure 2). Some sources define whole life carbon to also include operational carbon.[146] Because the interventions examined have little impact on operational carbon, this briefing paper includes all of them.

Table 1 Share of embodied carbon per construction material in the reference house[13]

Construction material	Share of embodied CO_2 in the reference house
Concrete	24%
Bricks	15%
Plaster	3%
Steel	29%
Lime	7%
Tiles	6%
Wood	4%
Aluminium	4%
Glass	3%
Other	4%

2 Given the significance of renovation in reducing energy consumption in the EU, findings on renovation are highlighted and distinguished from new construction. In this paper, renovation refers to 'the process of returning something to a good state of repair' in the context of lifetime extension, but also includes improvement or retrofitting as part of reducing operational emissions from existing buildings through measures such as new heating equipment or improved insulation.[2]

3 The typology of six interventions used in this paper differs from the typology of approaches to tackle embodied carbon as defined by the UK Green Building Council.[17] Theirs is preferred because it defines the interventions as mutually exclusive. The typology adopted here does not provide similar precise boundaries because, for example, any single design intervention may include combinations of elements from the other five. However, the typology used here was adopted because it offered a convenient way to categorise all case studies and sources used (despite the overlap).

4 Some of the emission reductions achieved as a result of the EU's embodied carbon regulations could reduce the GHG emissions of the EU's trading partners because some construction materials used in the EU are imported.[33] Emissions embodied in imports constitute one-third of the EU's carbon footprint. However, this is a less significant issue for construction materials because the embodied[30] carbon trade balance of imported and exported construction materials from and into the EU is close to zero.[147]

5 The intervention to decarbonise the production of construction materials poses a challenge: only a few sources publish data on the impact of decarbonising the production of construction materials on the price of the end product. Most report only on the impact on the price of the construction material. To translate reported impacts per tonne of product into impacts at the level of a house, data from Greece[143] and the UK[148] on the embodied carbon composition of houses by construction material (or their price composition) were used (table 1).

‘The stakeholders who design buildings or define the design criteria should be an important policy target.’

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