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# Embodied Carbon of Roofing Slate: Implications for Material Selection

## A Historic England and Historic Environment Scotland research study

JH Sustainability Ltd

Volume 1 of 1

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# Foreword

Natural slate has long been favoured as a roofing material for many of the UK's historic buildings, valued for its longevity, weather resistance, visual compatibility and strong associations with local building traditions. Yet over the past century, the UK's indigenous slate industry has seen a significant decline, challenged by competition from cheaper imports, changes in construction practice and constraints on quarrying and skilled labour.

While the idea of conserving historic building fabric using traditional materials is well established, more recently the environmental case for those materials has become increasingly important. As awareness grows around the climate impacts of construction, embodied carbon has become a key consideration, particularly in the retrofit and repair of existing buildings.

In response, Historic England and Historic Environment Scotland commissioned a study to examine the embodied carbon of roofing slate, with the primary aim of supporting the case for using indigenous slate for repairing historic buildings. The motivation was, if UK slate could be shown to offer both environmental and heritage benefits, this finding could strengthen demand and help sustain a struggling but culturally important industry.

The study set out to explore how UK slate compares to imported slate and modern alternatives to indigenous slate in terms of embodied carbon. It looked at both production and transport emissions, as well as factors such as lifespan, reuse potential and installation practices.

The key findings were that UK natural slate can offer meaningful environmental advantages compared to imported slate and alternative products. The most significant difference arises from transport emissions: slate imported from Spain, Brazil and China incurs far higher emissions than locally sourced UK slate. In some cases, transport emissions alone exceed the production emissions of UK slate.

Production emissions across slates are generally within a comparable range, but UK figures – based on older data – may not reflect improvements in quarrying and energy efficiency and grid decarbonisation. There is also anecdotal evidence that UK quarries make broader use of co-products, which may distribute environmental impacts more evenly.

Alternative roofing products such as concrete or fibre cement tiles typically have higher production emissions and are less suited to historic contexts.

Natural slate also has the advantage of longevity. While not formally recorded, UK slates – such as those from Wales and Cumbria – have demonstrated lifespans of more than a century. When viewed across the lifetime of a historic building, the durability of UK slates can substantially reduce the need for replacement, further lowering the embodied carbon impacts.

The report highlights the need for UK-specific environmental product declarations (EPDs), which would enable more accurate comparisons and support informed material choices.

Looking ahead, the report identifies several areas for further research. These include:

- understanding construction processes and co-product allocation
- more refined modelling of transport emissions through analysis of supply chain complexity and real-world transport routes
- a wider market study to assess the capacity and potential for scaling up UK slate production to meet demand
- empirical research on the long-term performance and durability of roofing materials

By improving the data landscape and understanding of embodied carbon of roofing slate, we can support better informed decisions in conservation and sustainable construction. This evidence base may also contribute to supporting the UK’s slate industry, aligning climate objectives with heritage values.

Historic England, Historic Environment Scotland

# Summary

The question of whether embodied carbon assessments can support a preference for indigenous natural slate – over imported slate or alternative products – is investigated. Data assessed come primarily from environmental product declarations (EPDs) from product manufacturers, but they are supported by additional material from academic literature. Data from these sources are reviewed alongside additional modelling of transporting the slate from various manufacturing sites to three different locations in the UK. Although more data are required relating to indigenous slate production, the embodied carbon assessment makes a strong case for preferring indigenous slate to imported slate because of the very significant emissions associated with the transportation of the latter material from overseas quarries to construction sites in the UK. The average emission saving associated with reduced transport (when indigenous slate is used instead of imported slate) is estimated to be 5kg$CO_2$e per $m^2$ of roof. Emission savings are also very likely when indigenous slate is used in preference to alternative products such as concrete tiles, even if these materials are produced in the UK. However, with significant variations between alternative products, it is difficult to quantify the savings.

## Author

Dr Jim Hart

## Acknowledgements

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Front cover image: Kirkby quarry, Burlington Stone Limited, Kirkby-in-Furness, Cumbria.
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# Introduction

This work explores the merits of different material choices, as applied to roofing projects in the UK, in terms of embodied carbon – an environmental criterion that is seen to be increasingly important in the design and specification of construction projects. The central question is whether, and to what extent, embodied carbon accounting supports the case for using indigenous natural roofing slate.

The study is designed to review and analyse published literature and data relating to the embodied carbon of natural roofing slate from different regions, comparing these findings with some alternative products. For the purposes of this report, a broad commercial definition of natural slate is used, rather than a strict petrographic definition. ‘Natural slate’, therefore, includes materials such as phyllite and mudstone, but excludes sedimentary rock owing to its niche status as a roofing material, with very little related embodied carbon data.

The report begins with a background section, exploring key themes concerning life cycle assessment, embodied carbon, durability and the slate market. This is followed by a section devoted to identifying and analysing embodied carbon data concerning roofing slate and alternative products. The concluding section summarises key findings and identifies areas for future research.

# Background

Roof coverings made of natural slate have long been part of the fabric of the built environment in the UK, in both urban and rural contexts. Slate has been used for roofing for millennia (Cárdenes et al., 2016; Hughes and Jordan, 2020), but large-scale extraction from quarries in the UK grew with the industrial revolution, with slate contributing to both domestic urbanisation and the country's trade balance.

Despite the subsequent decline of the domestic slate industry through the 20th century, evidence of UK slate on buildings is all around us. However, while roofing slates can be very durable, potentially lasting for centuries, roofs eventually need to be re-covered when the failure rate among the slates or their fixings becomes too high. Accordingly, there is a demand for slate for repairing existing buildings and for new building projects.

When the need for replacements or repairs are needed, two principal options are available. The first is to strip the roof, sort and redress the reusable slates by hand, supplement any losses with new slate of similar appearance and material properties, and re-roof. The second option is to strip the roof and dispose of the existing slate by the most economical means, and then re-roof using entirely new material. The new material could be indigenous slate from a UK quarry, imported slate or some other material altogether, such as concrete tiles. Reusing slates from a different site is another option. This practice may be viewed as a sustainable choice, aligned with the principles of a circular economy, but it is generally discouraged. It can lead to the accelerated removal of good slates from other buildings, particularly those that are viewed as less important or that are not protected by heritage legislation.

From environmental and social perspectives, the preferred options are either reusing the existing slate on the same roof (if it is in sufficiently good condition) or using new indigenous slate.

The reuse in situ option minimises resource extraction and transport. It also conserves the original appearance of the roof and supports traditional roofing skills. However, this process is labour intensive and takes longer than stripping and replacing with new slate, making it relatively expensive for the building owner.

Using new indigenous slate either reduces the environmental burdens of long-distance transport associated with imported slate, or it avoids the energy-intensive manufacturing processes of alternative roofing materials such as concrete tiles.

The purpose of this research report is to evaluate the relevance of embodied carbon to the environmental case for using indigenous slate, imported slate or alternative products.

## Embodied carbon and life cycle assessment

The term ‘embodied carbon’ refers to the greenhouse gas (GHG) emissions associated with the extraction, production, use and end of life (decommissioning, disposal) of materials and products (including whole buildings). It excludes operational emissions but may include potential future benefits from reuse or recycling. Embodied carbon is assessed through a data gathering and analysis method known as life cycle assessment (LCA). LCA results for materials and products are published by the industry in the form of environmental product declarations (EPDs), which report a range of environmental impacts at each life cycle stage (*see* Figure 1), including global warming potential (GWP) in units of $kgCO_2e$.[1] Published academic studies also present LCA results for various product and material categories, and these are included in the scope of this report. The GWP figures from such studies and the EPDs form the basis of the discussion of embodied carbon.

Considering the whole life cycle of a material, from cradle to grave, or even cradle to cradle (which includes the potential for future reuse and recycling), gives a more holistic view, but there is often a case for examining part of the picture in more detail.

This study takes a cradle to site perspective (A1–A4), encompassing cradle to gate stages (A1–A3) plus transport to site (A4). These stages are highlighted in dark blue in Figure 1, which shows how life cycle stages are defined in the relevant British and European standard covering EPDs for construction products (BS EN 15804:2012+A2:2019). Other modules (Installation, Use and End of Life) potentially of most significance to the study – discussed later in relation to EPDs – are shaded in light blue (A5 to B4, and D). The two modules below the line (B6 and B7) pertain to operational emissions and contribute to whole life carbon, but not embodied carbon. They are, therefore, outside the scope of this study.

The focus of this report is on stages A1 to A4, but it is important to be aware of subsequent life cycle stages and how they can vary between different products. The primary reason for taking a cradle to site perspective is because there is limited life cycle data available on embodied carbon of roofing slates and their alternatives. However, where data are available, they always include cradle to gate stages (A1–A3), and the

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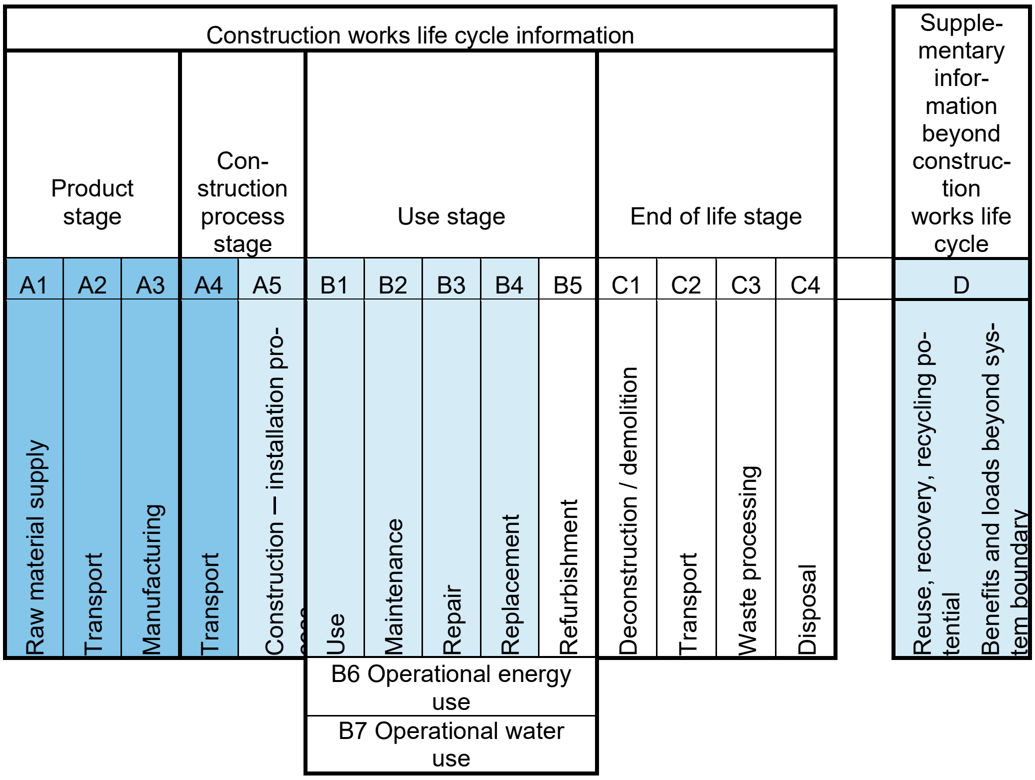
[1] Other environmental metrics provided by EPDs, and LCAs in general, cover issues such as ozone depletion, eutrophication, acidification, water deprivation, particulate matter and toxicity.

subsequent transportation to site (A4) can be reasonably modelled, based on knowledge of the production site and typical simplified scenarios for the construction site.[2] Assessment of all subsequent stages – including construction (A5), use (B1–B5 particularly maintenance, repair and replacement), end of life (C1–C4) and benefits beyond construction work lifecycle relating to the circular economy (D) – is scenario-based and relies on scenario-based assumptions about what happens to the slate after it leaves the producer's control. As the review of EPDs will show, these assumptions can vary for reasons that are unclear, introducing inconsistencies that can undermine comparisons between products. This is discussed further in the section Limitations, Gaps and Inconsistencies.



| Construction works life cycle information | | | | | | | | | | | | | | Supplementary information beyond construction works life cycle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Product stage | | | Construction process stage | | Use stage | | | | | End of life stage | | | | |
| A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | C1 | C2 | C3 | C4 | D |
| Raw material supply | Transport | Manufacturing | Transport | Construction – installation process | Use | Maintenance | Repair | Replacement | Refurbishment | Deconstruction / demolition | Transport | Waste processing | Disposal | Reuse, recovery, recycling potential<br>Benefits and loads beyond system boundary |
| | | | | | B6 Operational energy use | | | | | | | | | |
| | | | | | B7 Operational water use | | | | | | | | | |

Figure 1: Life cycle stages, adapted from BS EN 15804:2012+A2:2019 (BSI, 2021).[3]

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[2] Under BS EN 15804:2012+A2:2019, the product stage is mandatory, and for most products (including those within the scope of this research) the end-of-life stages and module D are also required as a minimum.

[3] The latest RICS guidance, for buildings and infrastructure, includes additional life cycle stages, which are outside the scope of this study.

## Roofing slate production process

Cárdenes et al. (2014) describe the production of roofing slates as being a relatively simple process, in which blocks are extracted from quarries using diamond wire and transported to a factory for further processing (the prior removal and disposal or replacement of overburden [the rock or soil above the slate] is taken for granted in the description). Diamond sawing technology is identified as a significant advancement, improving efficiency compared to earlier extraction methods that relied on explosives. However, Bascompta et al. (2022) suggest that using explosives to extract natural stone results in lower embodied carbon. Regardless of the quarrying method, at the factory, the blocks are sawn into smaller blocks, split into the required thickness by hand, cut to the required dimensions and packed in crates. Remarkably, according to Cárdenes et al. (2014), an estimated 85 to 90 per cent of the rock extracted from quarries is typically discarded to the ground as waste, with opportunities for recycling this material largely overlooked.

All the EPDs reviewed in this report generally provide similar descriptions of the slate production process, using diamond sawing technology, although two EPDs refer to the use of explosives in the quarry before diamond wires are used to cut slate into smaller blocks for transport. Some EPDs also refer to additional finishing processes, such as bevelling the slate edges and drilling nail holes.

The volume of roofing slate produced from a quarry typically represents only a small percentage of the slate extracted. The EPDs reviewed in this report assume that the remaining slate is treated as waste and is returned to the quarry.[4] However, in parts of the UK slate industry (not yet covered by EPDs), it is claimed that 100 per cent of the slate extracted finds a market – with the surplus used for applications such as walling stone or various grades of aggregate.[5] Where this is the case, the co-products can share part of the embodied carbon burden, as at the Valentia quarry in Ireland (Carrig conservation international, 2021). This distinction has implications for the cradle to gate embodied carbon of roofing slate, as sharing the environmental burden across multiple products reduces the proportion attributed to roofing slate.

BS EN 15804:2012+A2:2019 provides guidance on allocating environmental burdens among co-products. The standard requires that where co-products have significantly

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[4] This is explicit in all EPDs reviewed in this study except for one in which there is no statement.
[5] Communication from Burlington Stone Ltd regarding their Cumbrian roofing slate.

different overall values and processes cannot be subdivided, impacts are allocated according to economic value.

For example, the extraction and removal of a single block of slate (A1 and A2) is a process that cannot be subdivided among the co-products eventually produced from the block: if two-thirds of the revenue from the various co-products is attributable to the roofing slate, then two-thirds of the associated embodied carbon (A1 and A2) would be allocated to the roofing slate, with one-third distributed among the co-products.[6] At the manufacturing stage (A3), the situation may be more complex. Once the block of slate is subdivided, the processing of the different co-product streams begins to diverge, potentially requiring separate assessments for each stream.

## Durability of slate

An important consideration when calculating the life cycle embodied carbon of a slate roof is how long the material remains functional in situ. If the roof covering will need to be replaced one or more times during the lifespan of the building, the embodied carbon of those replacements must be accounted for alongside the carbon associated with the original installation.

Historically, the lifespan of a slate roof has often been limited by the quality of the iron or steel nails used to fix the slates: the failure of these nails is commonly referred to as ‘nail sickness’ (Historic Scotland, 2006). This is still an issue for many existing roofs. However, modern options such as copper and alloy nails offer the potential to hold slates in place for a much longer period. This shift places the durability of the slate itself into the spotlight, highlighting the significance of differences between various types of slate, and between slate and alternative roofing products. Durability becomes particularly significant when considering embodied carbon associated with roofing choices over a long time period.

The durability of roofing slate is a complex and technical subject, beyond the scope of this report apart from this brief commentary. Numerous factors influence the durability of roofing slate, of which the quarry’s location is only one. Other factors that affect durability include the difference in the properties of slate extracted from different parts of the same quarry, as well as the slate’s exposure to weathering and pollution once installed on the roof.

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[6] This is a hypothetical example, with fictitious data and a simplified calculation, to illustrate the general principle.

A predictive model for evaluating the lifespan of slate was proposed by Walsh (2002). It includes assessments suggesting that if Welsh slate is assumed to have a life expectancy of 100 years under representative conditions, then Spanish slate could be expected to last for about 50 years, while Cumbrian slate could slightly exceed 100 years. These findings are said to be broadly in line with the reputations of these materials. However, other imported slates are not addressed in the Walsh study, leaving a gap in comparative data.

In theory, slate standards could assist in predicting the lifespan of a particular type of slate. However, the standards are geared towards identifying qualities that may impact durability, rather than predicting life expectancy. An overview of the origins and purposes of various slate standards is provided by Cárdenes et al. (2016). The main standard relevant to the use of slate in the UK is the European standard series *Slate and stone for discontinuous roofing and cladding* BS EN 12326. It offers different levels of conformity and is divided into two parts covering product specification and test methods.[7] Slates must undergo various mechanical and weathering resistance tests to qualify for the CE mark, which signifies compliance. For North America, the ASTM C406 *Standard specification for roofing slate* classifies slates into grades (S1, S2 and S3) that indicate their expected service life.[8] However, the value of these classifications has been questioned, with poor correlation observed between durability and water absorbency of unweathered slates, for example (Walsh, 2008). Indian and Chinese roofing slate standards are also briefly discussed by Cárdenes et al. (2016).

# The slate market in the UK

## Indigenous roofing slate

The production volumes of indigenous roofing slate appear to be modest compared to the volume of imports, as discussed below. Data provided by Statista (2024) suggest that annual UK production of slate typically ranges between 25,000 and 48,000 tonnes. These data encompass a broad range of slate products, namely architectural and cladding, roofing and damp-proof courses. Walsh (2011) states that the production of roofing slate in the UK declined from a peak of around 450,000 tonnes in the 1890s to a low of only 23,000 tonnes in 1993. Nearly 20 years later, the production volume of roofing slate from North Wales (responsible for 85 per cent of UK production, with the two main quarries being Welsh Slate's Penrhyn and Cwt-y-Bugail) was said to have recovered to 35,000

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[7] See BS EN 12326-1:2014 and BS EN 12326-2:2011.

[8] S1: More than 75 years; S2: 40 to 75 years; S3: 20 to 40 years.

tonnes per annum (Walsh, 2011). Of this, the annual production volume of roofing slate from Penrhyn alone was approximately 14,000 tonnes (Hughes et al., 2016).

In England, slate is quarried in Cumbria and in Cornwall. In Cumbria, Burlington Stone's Kirkby quarry, which produces blue grey slate, is a key provider of roofing slate, with other quarries providing smaller volumes of Westmorland Green Slate. In Cornwall, roofing slate is sourced from Delabole quarry and Trevillett quarry. English roofing slate (in general) can be supplied in random sizes, and for Cumbrian slate this tends to be the preferred option potentially leading to a higher utilisation rate and lower wastage.

Scotland has a rich history of producing and exporting roofing slate, although this industry has now ceased. Production peaked towards the end of the 19th century, and the quarries of Ballachulish and the Slate Islands have now been inactive for more than 50 years. Efforts to revive the industry are continuing, with initiatives – on the island of Luing, for example – showing potential to restore a degree of slate production.

## Imported roofing slate

The countries of origin of the (primarily) roofing slate imported to the UK in 2023 are illustrated in Figure 2, based on data from HM Revenue & Customs. All countries contributing at least 1 per cent of the total mass are identified in the figure. Sixteen other countries, mainly in Europe, contribute to 2 per cent in the 'Others' category. It is likely that some of these European countries are re-exporting slate rather than quarrying it directly.

Spain dominates the market, providing 70 per cent of the UK's imports by mass.[9] Most of the remaining imports come from Brazil, followed by China. By value, Spain's share is even larger, at 79 per cent. This reflects its higher average price compared to Brazil and China. In 2023 Spanish slate was valued at an average of £776 per tonne, compared to £364 for Brazilian slate and £467 for Chinese slate.

HM Revenue & Customs registered roofing slate arriving at a number of different UK ports in 2023, suggesting that imported slate may typically be shipped to a port close to where it is needed. For imports from the EU, the main ports – in descending order of mass imported – were Avonmouth, Liverpool, Southampton, Greenock and Immingham. For imports from outside the EU, the main ports were London (including Gateway and Tilbury),

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[9] As a cross-check, the actual quantity reported for 2023, of 126,000 tonnes corresponds well to export statistics from Spain (to the UK), which show 112,000 tonnes for the first 11 months of the year.

Avonmouth, Southampton, Felixstowe, Belfast and Liverpool. Ports handling less than 3 per cent of the total volumes are excluded from both lists.

A comparison with data from 2019, the year before the pandemic, shows that the annual quantity of slate imports had grown by 27 per cent by 2023. Spain's dominant market share had largely remained unchanged, whereas China's much smaller market share almost doubled, indicating rapid growth in the quantity supplied by China. The quantity supplied by Brazil remained static over the period, resulting in a loss of market share, primarily to China.

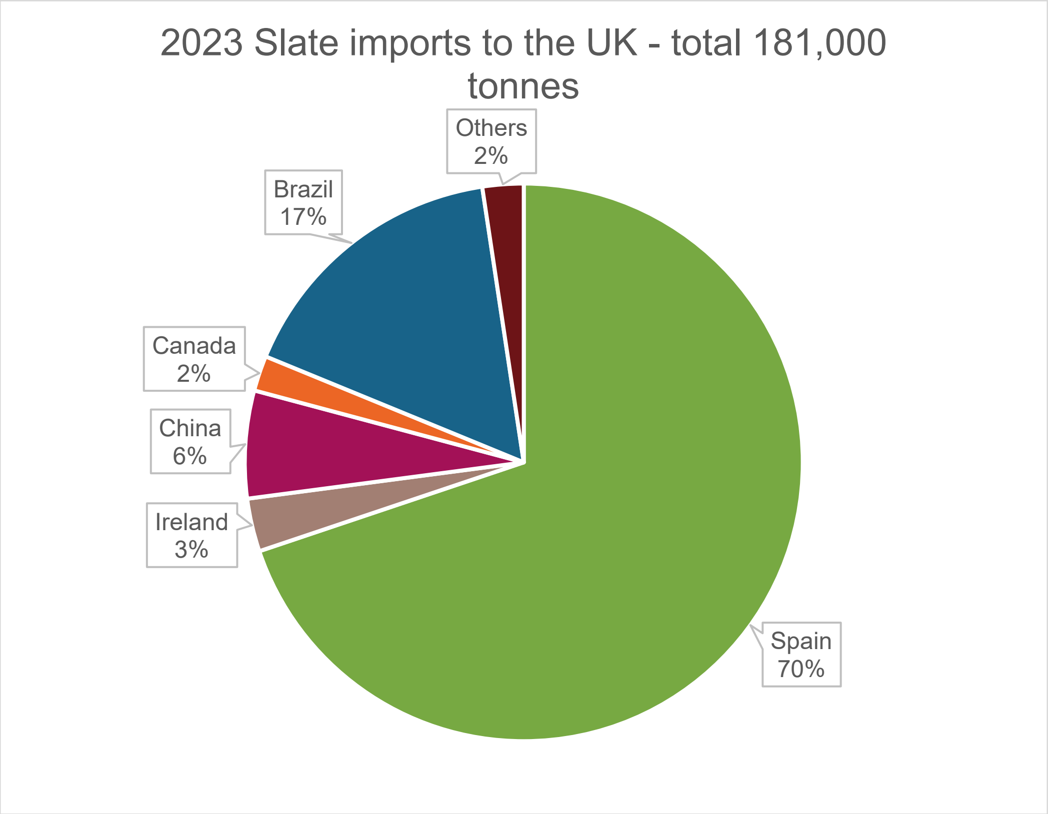

Figure 2: Origin of slate imports to the UK in 2023, by mass and country of origin. Data from HM Revenue & Customs under the code 68030010 (roofing and wall slates, worked).

For the purposes of this study, the imported slate of most interest is that sourced from Spain, China and Brazil. Of these, Spain stands out in terms of the availability of environmental data about its slate production. Although India has been cited as a rising power in the slate market (Cárdenes et al., 2016), it is apparently yet to make an impact in the UK roofing market.

China's growing market share can be attributed to its competitive pricing and the quality of its slate being acceptable to the UK market. Chinese products that conform to BS EN

12326 (W1, S1, T1)[10] are readily available.[11] The higher financial cost of transportation from the slate quarries in Shaanxi province (the origin of all Chinese slate identified in this research) to the UK is more than offset by the lower production costs.

The situation with Brazilian slate is somewhat different. Brazilian slate, from Minas Gerais, is technically a mudstone and so has several different properties to true slate (a metamorphic rock). For example, it is not easily dressed on site using hand tools because it is more brittle; instead, roofers require power tools to cut slates to size. Additionally, slate hooks are sometimes recommended for installation, to avoid the need for nail holes, which can risk breakages.[12] These practical considerations may be a factor in the loss of market share in the UK reported above. However, it is worth noting that there is Brazilian slate available that is certified to BS EN 12326, following work to ensure that the standard's definition of slate itself was broad enough to accommodate it (Cárdenes et al., 2016).

In their overview of the Spanish slate industry, Cárdenes et al. (2019) report that Spain accounted for around 90 per cent of global roofing slate production in the 1960s. Since then, the total volume of Spanish slate production has declined, along with its global market share. Spain was still the world leader in 2014, with more than 42 per cent of the global market, although it faced increasing competition from China. During this period, Brazil's market share developed from a low base, before declining somewhat from the early 2000s onwards. While slate production occurs in various parts of Spain, the greatest volume is extracted from quarries in the northwest of the country. Spanish slate is exported primarily to France, Germany and the UK because slate is not widely used domestically within Spain.

Cárdenes et al. (2019) note that the 'environmental impact of roofing slate mining is rather high', which serves as a reminder that the embodied carbon of the finished product (the slate roof) is not the only environmental impact criterion by which it should be evaluated. Although many of the challenges that have beset the Spanish slate industry in recent decades have been significantly mitigated, the environmental impact of slate extraction remains a pressing issue. Problems associated with excessive spoil heaps (uncontained

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[10] The document includes in-text links to external sites (for example, commercial sites) for minor points of interest, which were checked in March 2024. These may become obsolete over time, but the more important documents are formally referenced.

[11] They meet the highest level – level 1 – for a number of criteria.

[12] It is worth noting that the use of slate hooks is often discouraged or prohibited in heritage contexts because they are visibly different from traditional nailing methods and they interrupt the visual rhythm of coursed slate roofs. Planning authorities and conservation officers often expect like-for-like repair, including traditional fixing techniques.

piles of waste material comprising more than 90 per cent of the extracted material) and water pollution are highlighted.

As noted previously, EPDs provide data on a range of environmental impacts, which ideally should be considered holistically. However, this involves normalising different types of impact (because they are measured on different scales) and weighting them according to their perceived relative importance. This process is complex and requires some level of expertise to ensure meaningful assessments.

# Embodied carbon data

Embodied carbon data presented in this section come primarily from EPDs produced with reference to BS EN 15804+A2 (or its predecessor BS EN 15804+A1). A smaller quantity of further data is included from a literature. This section also includes our own modelling of transportation from the factory gate to the construction site. The modelling is used to evaluate the importance of transport relative to other life cycle stages, when slate is sourced from different locations.

All the EPDs reviewed provide data on the product stage (A1–A3) as a minimum. Together with the functional unit[13] and time period, this is the most directly usable data, as data on subsequent stages depend on the specific scenarios chosen by the EPD producers such as installation methods and materials, maintenance needs, and end of life options. These are not always directly comparable.

At present, EPDs are not available for any roofing slate produced from UK quarries.

## EPDs for natural imported slate

Six EPDs for natural roofing slate were reviewed for this work: five relating to Spanish slate (Cluster da Pizarra de Galicia, 2021; Cupa Pizarras, 2019b, 2019a, 2023a, 2023b) and one to Argentinian Riverstone slate (Spanish Slate Quarries UK, 2023).[14] Of the Spanish slate EPDs, one was a sector-wide EPD from the Galician Slate Cluster,[15] with the remaining four covering a range of roofing slates produced by Cupa Pizarras. The oldest of these documents were published in 2019, and consequently expired in January 2024, while the others remain valid through to 2026 or 2028.

Most EPDs opted for a functional unit of 1m$^2$ of roof coverage over a period of 60 years (50 years in the case of the Galician Slate Cluster). However, two EPDs appear to have reported data based on 1kg of slate, despite declaring functional units of 1m$^2$ of roof coverage. For consistency, these numbers have been adjusted to align with the stated functional units. The exception is Argentinian Riverstone slate, which reported on a

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[13] A functional unit is more sophisticated than a simple volume unit, and it allows comparisons between products of the impacts associated with a particular job or function. In this case, the function is to provide covering for 1m$^2$ of roof over a period of (usually) 60 years.

[14] Full details of EPDs are included in the bibliography, and hyperlinks to those that are still available online are included in Appendix Table A3.

[15] The EPD for the Cluster da Pizarra de Galicia (referred to as the Galician Slate Cluster) presents average data of associated companies in the slate sector in Galicia and Castilla y León.

declared unit – a crate of slate[16] rather than a functional unit. Enough information is supplied to convert these data into a functional unit.

The cradle to gate (A1–A3) results shown in Table 1 are mostly clustered around a value of 4kgCO$_2$e/m$^2$ (production of the slate required for 1m$^2$ of roof results in 4 Kg of CO$_2$),but with two notably higher values of up to nearly 15kgCO$_2$e/m$^2$.

To derive a value for the cradle to gate embodied carbon of generic roofing slate, it is necessary to normalise the results to a standard thickness or mass. The standard mass chosen corresponds to the coverage used by the Galician Slate Cluster to represent the range of products available in the region: 39kg of slate per m$^2$ of roof. This coverage corresponds to an average slate thickness of about 6mm, taking into account the typical density of slate (around 2,800kg/m$^3$) and the degree of overlap assumed in installation. When adjusted for slate thickness, the average value for A1–A3 emissions is 7.4kgCO$_2$e/m$^2$. This value is strongly influenced by the higher value of the only product data not from Spain (Argentine Riverstone). However, as the EPD sample is small (four come from the same supplier), there would be no justification for treating the Argentine Riverstone EPD as a statistical outlier.

Table 1: Key embodied carbon data from six slate EPDs.

| | **Units** | **Spanish Heavy 3 (Cupa Pizarras)** | **Spanish 5mm (Cupa Pizarras 5, 12 and 50)** | **Galician Slate Cluster** | **Argentine Riverstone (phyllite)** |
|---|---|---|---|---|---|
| **Expiry date** | MM/YY | 01/24 | 01/24–06/28 | 12/26 | 01/28 |
| **Thickness** | mm | 7.5 | 5–5.3 | Various | 5.3 |
| **Mass on roof** | kg/m$^2$ | 51.9 | 30.4–33.5 | 39 | 32.1 |
| **A1–A3** | kgCO$_2$e/m$^2$ | 4.0 | 3.4–9.5 | 4.0 | 14.9 |
| **A1–A3: Normalised** | kgCO$_2$e/m$^2$ | 3.0 | 4.0–11.1 | 4.0 | 18.1 |
| **A4: EPD** | kgCO$_2$e/m$^2$ | 4.5 | 1.6–2.7 | 4.8 | 6.1 |
| **A4: Calculated and normalised** | kgCO$_2$e/m$^2$ | 4.1–12.1 | 2.4–7.8 | 3.1–9.1 | 9.5–11.2 |

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[16] The declared unit is a wooden crate containing 800 slates weighing 1,223kg (of slate), with 21 slates (on average) required per m$^2$ of roof.

Note: The Spanish 5mm data are from three EPDs (Cupa Pizarras 5, 12 and 50), produced at different times. The A1–A3 values are presented in two rows, the first being from the EPDs and the second being normalised to a standard slate thickness. Regarding A4 (transport to site), the table includes two rows: the first is from the EPDs, based on a generic scenario loosely set out in each document. The second row is the author's own estimation, normalised, and based on DEFRA/BEIS GHG emission factors (UK Government, 2023)17 and distances travelled to three hypothetical construction sites in London, Leeds and Glasgow, assuming the nearest likely port of entry in each case.

The wide ranges of the calculated A4 emissions are mainly caused by the significant difference in the two options for transporting slate from Spain (primarily overland through Spain and France, or by sea from a Spanish port), with the remaining variation relating to the construction site location. It is likely that modelling based on more detailed route information – avoiding worst case assumptions about transport modes and route choice (so, always using sea routes and the optimal choice of ports) – would put the true value towards the bottom of the range indicated in each case. This is explored in more detail in the Transport section below.

## Other embodied carbon data for natural slate

Historically, one of the earliest significant environmental data-gathering efforts for quarried products included a module on slate in North America. The data came from diverse locations, likely to be in the states of Vermont, New York and Pennsylvania (University of Tennessee Center for Clean Products, 2009), from facilities representing the production of 20,600 tonnes of dimensional slate (slate finished to specific sizes).[18] However, the applicability of the Tennessee study to this research is limited by its focus on aggregated slate products, rather than exclusively roofing slate. The Tennessee study examines dimensional slate, which is 'most commonly employed as roofing and flooring tile but is also frequently used for countertops, hearths, risers and treads, and landscaping'. Unfortunately, no data are provided to disaggregate these uses, making it challenging to isolate information specific to roofing slate.

The energy required to produce finished slate is reported in the Tennessee study to be 0.87MJ/kg, which is notably low compared to the values in the six EPDs analysed above (approximately 1.6 to 9MJ/kg). This discrepancy may be due to the inclusion of broader product categories, such as larger slabs of slate, which could skew the energy intensity

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[17] Emission factors used as follows: articulated truck 0.09499kg$CO_2$e/t.km; container ship 0.01977kg$CO_2$e/t.km; RoRo ferry 0.06328kg$CO_2$e/t.km.

[18] All figures quoted from this report have been converted from imperial units (in this case 260,000ft$^3$). A conversion rate of 1ft$^3$ to 79.3kg of slate is used here.

per unit of weight. Assuming an average emission factor for fuels corresponding to that of diesel, the associated GHG emissions are estimated at 0.065kg$CO_2$e/kg (with a possible range of approximately 0.04 to 0.12kg$CO_2$e/kg depending on the grid emission factor). The higher end of this range is potentially relevant to production systems that rely heavily on coal.

For a slate coverage of 39kg/$m^2$ (the average figure provided by the Galician Slate Cluster), this energy requirement corresponds to a GHG emission range of 1.56 to 4.68kg$CO_2$e/$m^2$, which is at or below the low end of the figures for A1–A3 presented in Table 1. This finding suggests that the energy requirements reported in the Tennessee study, and the associated emissions, may not fully reflect the impacts of roofing-specific slate production.

Regarding waste, the data from the Tennessee study show that 19 per cent of the material extracted remains within the quarry. Of the remainder, 74 per cent is later returned to the quarry as waste following production, demonstrating the efficiency of locating processing facilities near extraction sites. Ultimately, only 21 per cent of the material originally extracted is incorporated into final product.

In their study on the embodied carbon of dimension stone in the UK, Crishna et al. (2010 and 2011) analysed data from two slate quarries in England and Wales, using figures from 2008. They ascribed an embodied carbon value of 0.232kg$CO_2$e/kg of slate for the cradle to gate stages (A1–A3). This equates to a normalised figure of 9.0kg$CO_2$e/$m^2$, which is higher than most (but not all) of the data presented in Table 1. Since 80 per cent of the GHG emissions in slate production occur during the manufacturing phase, decarbonisation of the electricity grid since 2008 may have reduced these values significantly. In some cases, reductions of up to 50 per cent could be expected, potentially bringing these values in line with the EPD data for imported slate. However, owing to the limited information provided, particularly regarding the fuel mix, this adjustment cannot be calculated.

The Inventory of Carbon and Energy database (Jones and Hammond, 2019) reports a wide range for the embodied carbon of slate (0.007 to 0.063kg$CO_2$e/kg cradle to gate; 0.3 to 2.5kg$CO_2$e/$m^2$ when normalised). However, the source of the data is not provided, and the data do not appear to have been revised from the 2011 edition of the database. Even the upper limit of the range is below the values derived from the EPDs in Table 1. Given these uncertainties, these data should be treated with caution, and they are not included in analyses in this report.

# EPDs for slate alternatives

A selection of EPDs for alternative roofing products (limited to tile products) have been reviewed for comparative analysis in Table 2.

Only products with relatively recent EPDs, reporting in terms of GWP impact per m$^2$ roof area (or providing sufficient data for conversion), were considered for inclusion. The latter criterion excluded some current EPDs from the analysis. All selected EPDs pertain to products manufactured in Europe, with none identified from the UK at the time the research was carried out. The variation in A4 (transport) calculated emissions is linked entirely to the UK construction site location, except in the case of the Danish tiles for which alternative transportation modes were considered.

Table 2: Key embodied carbon data from four alternatives to slate.

| | **Units** | **Fibre cement** | **Fibre cement** | **Concrete tiles** | **Fired clay roof tiles** |
|---|---|---|---|---|---|
| **Origin** | Country | Belgium | Ireland | Denmark | Germany |
| **Expiry date** | MM/YY | 03/26 | 03/25 | 06/27 | 03/26 |
| **Functional unit stated** | Various | 1m$^2$, 60 years | 1m$^2$, 60 years | 1m$^2$, 100 years | 1t, cradle to gate |
| **Mass on roof** | kg/m$^2$ | 8.4 | 20.7 | 40.9 | 46.2 |
| **A1–A3** | kgCO$_{2e}$e | 6.8 | 16.2 | 9.1 | 7.2 |
| **A4: EPD** | kgCO$_{2e}$e | 0.13 | 0.06 | 0.45 | - |
| **A4: Calculated** | kgCO$_{2e}$e | 0.3–0.8 | 0.7–1.1 | 1.5–7.5 | 2.3–5.1 |

Note: Calculated A4 emissions (transport to three hypothetical UK construction sites, as in Table 1) are based on limited information about the location of manufacture. However, the relevance of this information to the UK market is debatable, as some products – concrete tiles, for example – may be sourced from UK manufacturers, resulting in significantly lower A4 emissions (The evidence to present A1–A3 figures in these instances is absent, because no EPDs for such products manufactured in the UK were identified.) (EPD Danmark, 2022; EPD Ireland, 2020; Gebr. Laumans GmbH & Co., 2021; SVK, 2021).

An additional EPD for a tiled roofing product (bituminous shingles) is available from the European Waterproofing Association, covering manufacturers in Italy, Turkey, Poland and Norway. However, details of bituminous shingles have not been included in Table 2 because the product is assumed to be unsuitable for roofing in the UK (other than outbuildings). The reported cradle to gate emissions are 5.96kgCO$_2$e/m$^2$, but no reference service life (RSL) is provided, limiting the comparability of bituminous shingles with other roofing products.

## Cradle to gate summary

When a roofing slate product has a corresponding EPD, that document is typically the most reliable source for cradle to gate embodied carbon data. In the absence of such documentation, a reasonable assumption is that the production process and corresponding embodied carbon will be broadly in line with those of a similar product (for example, when one natural slate is compared to another). However, selecting a precise representative value for A1–A3 embodied carbon is challenging, as different conclusions may be drawn from the available data. For example, it is debatable whether older values from academic literature should be included or excluded from the current analysis. It is also sometimes unclear whether the assessment of embodied carbon data for one product is independent of that for another product from the same company, and therefore whether more than one value from that company should be included when taking an average. In this work, all of the EPDs have been used in analysis without consideration of this issue.

With these caveats in mind, the data discussed in this section can be summarised as follows for cradle to gate analysis (A1–A3). With slate coverage normalised to 39kg of slate per m$^2$ of roof, the embodied carbon estimates are:

- Natural slate ranges from approximately 3 to 18kgCO$_2$e/m$^2$.
    - The average is 7.1kgCO$_2$e/m$^2$, although most values are below this.
    - The median is 4.2kgCO$_2$e/m$^2$.
- Alternatives to natural slate range from 6.8 to 16.3kgCO$_2$e/m$^2$.
    - The average is 9.8kgCO$_2$e/m$^2$.
    - The median is 8.2kgCO$_2$e/m$^2$.

Comparison of these data indicates that natural slate appears to have a clear but not overwhelming advantage over alternative roofing products. If the coverage of the slate were instead normalised to, say, 30kg/m$^2$ (approximate thickness 5mm), which may adequately represent slate used in many contexts in the UK, the advantage of natural slate would be more pronounced.

## Transport

In theory, transporting roofing slate from a quarry to a construction site involves two distinct stages. The first is the transfer of the raw slate blocks from the quarry to the processing plant (A2). The second stage is the transport of the finished slate to the construction site (A4).

In practice, roofing slate production facilities are typically co-located with the quarry.[19] This minimises transportation costs and simplifies material handling, as any slate waste generated during production can easily be returned to the quarry. As a result, GHG emissions associated with A2 can be assumed to be relatively insignificant. Furthermore, in most EPDs reviewed, A2 emissions are included in the aggregated A1–A3 values, making it difficult to analyse A2 emissions separately. For these reasons, A2 is not considered further in this discussion.

Most of the EPDs reviewed in this assessment provide a value for A4. In the natural slate EPDs, the brief statements about transport scenarios and the fact that the documents are produced by a UK EPD programme operator are consistent with the idea that the values represent imported slates used in the UK. An exception is the Galician Slate Cluster EPD, which presents a weighted average A4 value based on where the slate is used around the world, and the associated transportation methods. Since the majority of this slate is transported long distances within Europe (with very small percentages used either within Spain or outside Europe), the context is a reasonable proxy for transport to the UK (and the stated A4 emissions lie within the range modelled for imported slate in this study; *see* Table 1).

Conversely, most of the EPDs studied for alternative roofing products are not representative of the UK market. When an A4 value is provided, it typically only applies to transport within the country of production or a nearby region, rather than shipping to the UK. As a result, these values do not provide meaningful insight into UK transport emissions. At best, they offer a crude guide to the potential scale of A4 emissions for similar products manufactured and distributed within the UK.

The A4 transport values calculated for this study are presented in Table 1 and Table 2, with ranges reflecting different UK construction site locations and, in some cases,

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[19] It is explicitly stated in the Cupa 5 and Cupa 50 EPDs that the splitting sheds are located within the quarry. Other EPDs lack clarity on the point.

alternative transport methods (for example, road only or a combination of road and sea). The route assumptions behind this modelling are detailed in the Appendix, Table A1.

For natural slate products transported to UK construction sites from various sources within and outside the UK, Figure 3 illustrates the impact on A4 emissions of quarry location, construction site location and – in one case – route choice.[20] Weighted by market share, and assuming that imports from Spain take the sea route, the average value of A4 for imported slate is 6.1kgCO2$_e$/m$^2$. To support a direct and meaningful comparison, this analysis again assumes a normalised slate product in line with the average slate provided by the Galician Slate Cluster. In reality, most – if not all –the regions listed will supply slate in varying thicknesses, affecting weight and, consequently, transport emissions. For example, 5–7.5mm for slate in the Spanish EPD, 5–9mm in Brazil, 8mm and various other thicknesses in China, and in the UK a wide range from 5.5mm (Penrhyn) to 12mm (Kirkby). There may be other thicknesses outside of these ranges.

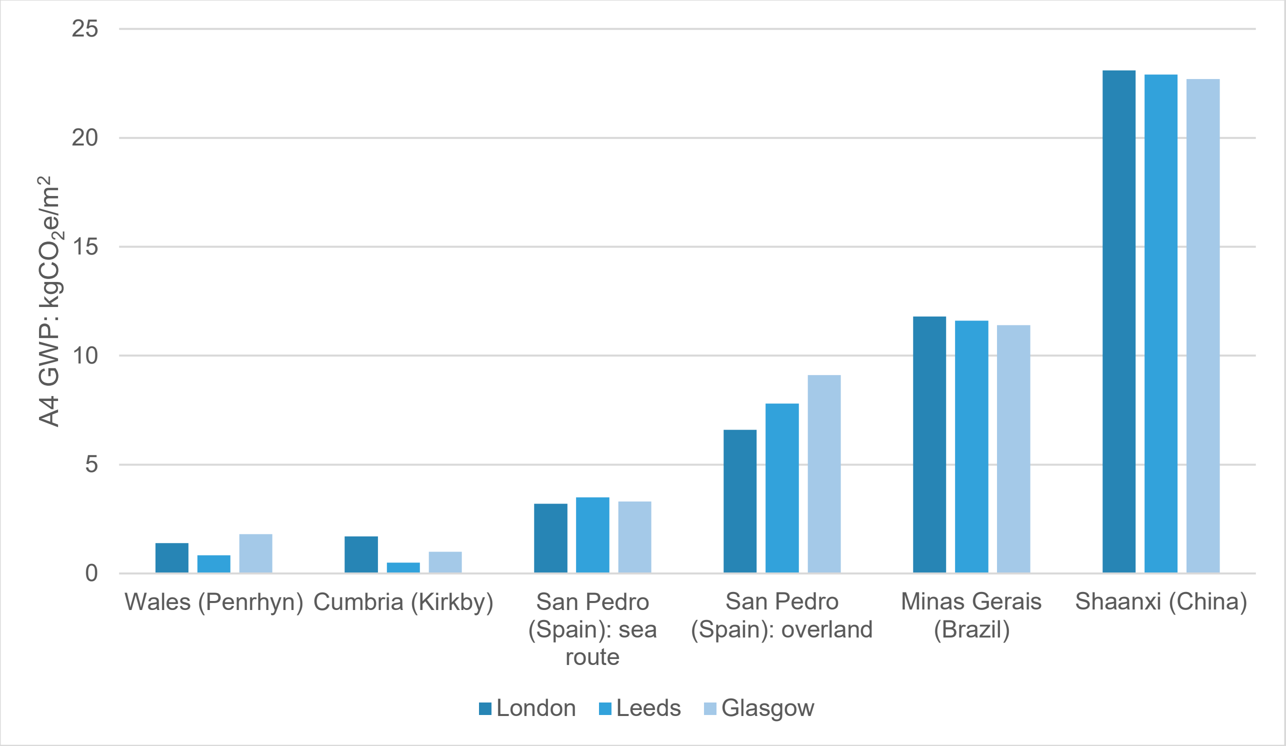

Figure 3: Calculated A4 transport emissions of natural slate from quarry region to construction site. Coverage of 39kg of slate per m$^2$ is assumed throughout: manual adjustments were needed to deal with variance from this to assess a particular slate. The analysis excludes the effect of breakages in transit and during installation, which would have the effect of increasing the quantity transported.

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[20] The same data are tabulated in the Appendix, Table A2.

The Galician Slate Cluster EPD estimates that the average roof slate coverage, for the products supplied by the cluster, is 39kg/m$^2$, which corresponds to an approximate thickness of 6mm. This figure is used for the calculations supporting Figure 3. However, the results presented can be scaled to suit different thicknesses of slate.[21]

The results shown in Figure 3 are calculated using the UK Government's GHG conversion factors (2023).[22] They are based on direct routes between the quarry and the construction site, using the most conveniently located port. In practice, the actual transport distances may be longer, with intermediate detours to depots and warehouses. However, quantifying these additional distances would require primary data from the supply chain, which was not available for this study.

Two options are included for Spanish slate: sea routes – from Bilbao, for example – to the most appropriate port in the UK, and overland routes via the Channel ports. There was conflicting information about whether overland routes are commonly used or not.

For the slate imported by sea routes, the location of the construction site within the UK is not a significant factor if it is situated in a well-connected town or city (such as those analysed). This is because slate is landed in significant quantities at several different ports around the UK, reducing the need for long onward transport routes. The differences in the A4 emissions between the three given UK locations are mainly attributable to the distance between each site and the port used in the analysis (for example, Glasgow is closer to Greenock than London is to Felixstowe).

Another clear finding for imported slate is that the A4 transport emissions are similar to the combined cradle to gate (A1–A3) emissions for Spanish slate, typically 4kgCO$_2$e/m$^2$. However, for slates from farther afield, such as from Brazil and in particular China (where transport emissions in the UK amount to approximately 23kgCO$_2$e/m$^2$), A4 emissions appear overwhelmingly important in comparison to UK slate (even though the actual cradle to gate emissions for these products remain unknown).

Transport emissions for indigenous slate are lower than for any of the imported slate options. In practice, the use of some indigenous roofing slate may be weighted towards

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[21] For example, in a context that requires a 7.5mm slate with a coverage of 52kg/m$^2$, all the bars in the graph (from locations that can provide that thickness) can be scaled up by 52/39. For a Spanish slate supplied to Leeds by sea, for example, the value increases from the 3.5 shown in the figure to 4.7 kgCO$_2$e/m$^2$.

[22] Among other things, these conversion factors translate distances travelled by a tonne of freight into GHG emissions: container ship 0.020 kgCO$_2$e/t.km; truck 0.095 kgCO$_2$e/t.km; RoRo ferry 0.063 kgCO$_2$e/t.km.

locations nearer to the quarry than the city locations analysed. In such cases, the A4 emissions will be even lower than the values indicated in Figure 3.

## Cradle to site summary

For all imported natural slate, A4 emissions represent a very significant proportion of the total embodied carbon. When trans-ocean shipping is involved, the transport emissions almost always exceed the likely emissions for the product stage (A1–A3). The one known exception is the Riverstone slate from Argentina, which has unusually high cradle to gate emissions (A1–A3). For example, assuming – in the absence of hard information – that the average product stage figure of 7.1kgCO$_2$e/m$^2$ adequately represents production in China, the cradle to site embodied carbon for slate from China would be approximately 30kgCO$_2$e/m$^2$, with transport accounting for much of the total.

A generic assessment of cradle to site (A1–A4) emissions for alternatives to slate (such as concrete or clay) is more challenging than for natural slate, because it requires knowing where the products used in the UK are manufactured. The sources of products covered by existing EPDs do not necessarily match the sources supplying the UK market.[23] While the concrete and clay data reviewed in this study suggest that the material weight per m$^2$ of roof shipped (approximately 40 to 46kg/m$^2$) is similar or slightly higher than that for natural slate (39kg/m$^2$), in the case of fibre cement the material weight per m$^2$ of roof shipped is much lower, ranging between 8 and 21kg/m$^2$. This lower material weight means that for any given transport distance, the A4 emissions for fibre cement will be lower than A4 emissions for any natural slate.

The embodied carbon values provide one of the keys to understanding the potential impact of switching to slate in general and indigenous slate in particular, if specifiers and clients were encouraged to do so. For example:

- If average indigenous slate has the same cradle to gate embodied carbon as average imported slate, then switching from imported to indigenous slate will achieve reductions in A4 emissions of approximately 5kgCO$_2$e/m$^2$ of roof. Scaled up, this would correspond to about 130tCO$_2$e saved for every 1,000 tonnes of slate.
- To evaluate the impact of a switch from alternative products to natural slate, more detail about the A4 GHG emissions associated with the alternative products would be needed – particularly regarding the location of manufacture. However, the

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[23] Cedral fibre cement slates are the only obvious exception to this, as these are produced in Ireland and the transport scenarios reference the UK.

average cradle to gate emission reductions would be approximately 69tCO$_2$e per 1,000 tonnes of slate.

## Installation, use and end of life stages

The primary focus of this research is the embodied carbon of roofing slate from cradle to site (A1 to A4). However, it is vital to consider the potential significance of subsequent life cycle stages, and how these may vary between products.

### Installation: A5

The GHG emissions associated with installing roofing slate are partly determined by the slate itself, and partly by the methods and materials preferred by the roofer. For example, breakage rates may be a function of the slate, the way it is handled or the geometry of the roof. As previously noted, Brazilian slates require power tools to be used on site,[24] for cutting the slates to size, in contrast to other types of slates that are typically workable using hand tools. Another key variable is the choice of fixing method and materials, such as nails and/or hooks, and whether these are made from, for instance, aluminium, copper or steel, and the associated embodied carbon of these materials.

Differing assumptions about installation methods and materials are made in EPDs, but without indication that these assumptions relate to the properties of the slate itself. One supplier of Brazilian slate[25] recommends the use of steel hooks, explicitly linking this advice to the properties of the slate, but no EPDs were identified for Brazilian slate. As a function of roof area, the associated emissions will vary with the size of slates chosen. A smaller average slate size will mean more fixings per m$^2$. This could also apply to the number of battens required, where these are part of the installation. On the other hand, specifying smaller slates – or using random slate sizes with diminishing courses – may increase the roofing slate production efficiency at the quarry by increasing the yield of usable roofing slate from each block extracted, thereby reducing product stage embodied carbon.

Most of the reviewed EPDs include the use of nails in the installation phase, typically assuming 150g of nails per m$^2$ of roof. For Riverstone slate, the amount assumed in the EPD is significantly higher, with more than 500g of copper nails per m$^2$ of roof specified. This could represent a substantial contribution to the overall embodied carbon: the Inventory of Carbon and Energy database reports a figure of 2.71kgCO$_2$e per kg of various

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[24] Confirmed in conversation with slate consultant Terry Hughes.

[25] https://europeanslate.co.uk/slate/brazilian-slate/

copper products, equating to approximately 1.35kg$CO_2$e/$m^2$ for the copper nails used to install Riverstone slate.

It is not possible to draw any firm conclusions from the EPDs studied about the relative importance of installation emissions (A5), as the reported values range widely – from less than 1 per cent to as much as 50 per cent of the cradle to gate (A1–3) emissions. There is some variation in the EPD assumptions, such as differing quantities of nails and varying breakage rates (typically 5 to 10 per cent), but these differences alone do not fully explain the scale of variation observed in the reported installation (A5) emissions.

## Use stage: B1 to B4

Of the use stages represented in Figure 1, only modules B1 to B4 are considered potentially relevant to this study. B5 covers refurbishment, which is more relevant to planning at the building level than it is to individual material choices, and B6 and B7 relate to operational carbon not embodied carbon.

### B1 (use)

Most of the roofing products considered here would have zero emissions associated with module B1 (use phase), as they are entirely passive materials that do not generate emissions during use. Exceptions are cement-based products, which undergo chemical transformation through carbonation in situ. This sequesters carbon dioxide from the atmosphere, allowing a negative embodied carbon value to be reported for B1. Two EPDs for alternative products include carbon sequestration values for B1. However, their reported values vary significantly: in one case, the carbon captured is negligible, while in the other, carbon sequestration offsets just under a quarter of the product’s cradle to gate emissions (A1–A3).

### B2 (maintenance) and B3 (repair)

The majority of EPDs reviewed here do not report data for the maintenance (B2) or repair (B3) stages. However, one fibre cement product EPD states that, while cleaning is not required, a single treatment with a water-based acrylic coating will likely be needed within the 60-year RSL, adding nearly 10 per cent to the product’s cradle to gate emissions. The Riverstone slate EPD reports on both B2 and B3, citing optional cleaning and breakages, respectively. It outlines a scenario in which a fraction of slates is replaced every decade as a result of breakages occurring ‘when other work is done on the roof’. However, the impact of these maintenance and repair stages on the total embodied carbon is relatively minor.

## B4 (replacement) and long-term durability considerations

A key issue in the use stage is the durability of the roofing products and the associated emissions if complete replacement (B4) is required. All the EPDs examined for this study either did not declare a value for B4 or reported a value of zero. Under BS EN 15804, a zero B4 value is valid if the product lasts for its stated RSL.[26] In most of the EPDs reviewed – for slate and non-slate alternatives – the RSL is 60 years (where stated). The Galician Slate Cluster EPD assumes a RSL of 50 years, but this may be a conventional figure in Spain rather than a specific durability estimate. No firm conclusions are drawn from this.

In some cases, justifications are given for assuming the products will outlast their RSLs. If these assurances are taken at face value, then the zero assessment is a good guide. A hypothetical product with a RSL of 30 years may report zero B4 emissions, but anyone using the EPD in a building assessment should allow for one complete replacement in the RSL of the building, with B4 matching the total of product and construction (A1–A5) plus end of life (C1–C4) embodied carbon. This effectively doubles the embodied carbon if none of the material can be reused on site.

The new RICS professional statement (2023) requires projects to consider a longer term perspective when assessing embodied carbon. While 60 years is the standard reference study period, domestic building projects – for example – are required also to assess the building envelope over 120 years to reflect long-term performance. Under this extended timeframe, many alternatives to slate may reasonably be expected to require at least one full replacement. Top quality natural slate fixed with copper or alloy nails may well be expected to survive 120 years or beyond. However, in some cases, it will be appropriate to consider a replacement cycle. This may include an option where around, say, three-quarters of the slate removed is recovered for reuse on the same roof, reducing the quantity of new slate (but not fixings) required.

To account for these replacement emissions over a 120-year period, Table 3 provides scaling factors that can be used for calculating approximate B4 values based on how many times a roofing material needs to be replaced. Since replacing a roofing product means producing, installing and disposing of it again, the total embodied carbon from all three processes must be included in B4 calculations. These scaling factors are applied to (multiplied by) the total GHG figures for life cycle stages A and C to give the B4 carbon

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[26] The RSL is technically the expected service life under a defined set of reference conditions. When the product is used in other contexts, it is possible that the expected service life will be less.

emissions for each scenario. The factors are provided for scenarios both including and excluding material decarbonisation, as recommended by RICS.[27]

Table 3: Indicative scaling factors for B4 estimation, over a 120-year reference study period.

| Scenario | No material decarbonisation | With material decarbonisation |
|---|---|---|
| 2 complete replacements | 2 | 1.17 |
| 1 complete replacement | 1 | 0.5 |
| 1 replacement with reuse | 0.3 | 0.15 |
| No replacement | 0 | 0 |

Note: Indicative scaling factor to be applied to total embodied carbon figure for stages A and C combined, to estimate value for B4 (replacement). Slates or tiles replaced every 40 years or 60 years. Some values in the table are approximations. Reuse assumes that around 75 per cent of the slate is reused, with the factor rounded up to allow for nails.[28]

As an example of the application of the scaling factors, if a roof covering has a life expectancy of 60 years, then one full replacement will be required, and the B4 emissions will repeat the module A and module C emissions of the original roof covering, thereby almost doubling the embodied carbon. If decarbonisation of the material supply chain is assumed, the B4 emissions – which occur in the future – are reduced, and can be assumed to be 0.5 times the original emissions from modules A and C.

The difference between the best cases represented in Table 3 (no replacement or one replacement with reuse) and the worst case (two replacements) is hugely significant, with the latter potentially tripling the life cycle embodied carbon over 120 years (and more than doubling it even when a material decarbonisation scenario is considered).

## End of life: C1 to C4

End of life modules cover deconstruction (C1), transport (C2), waste processing (C3) and disposal (C4). Few of the EPDs reviewed in this study report values for all the end-of-life modules,[29] meaning that a complete picture of the total carbon impact is not provided.

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[27] Material decarbonisation is the expected reduction of embodied carbon of materials in future, as the economy decarbonises: RICS recommends a linear reduction to 50 per cent over 60 years. In theory, this process could be quite straightforward for slate, through electrification, but much less so for concrete for example. These nuances are not, however, covered by the RICS method.

[28] For example, if the module A and module C emissions for a slate (or alternative) total 10kg$CO_2$e/$m^2$, and complete replacement is expected in years 50 and 100, then the estimation for B4, over a 120-year reference study period will be 20kg$CO_2$e/$m^2$, or 11.7 kg$CO_2$e/$m^2$ under the decarbonisation scenario.

[29] Of the slate EPDs, the Galician Slate Cluster is the only one that provides non-zero values for both deconstruction and transport.

When reported, however, the aggregated end of life emissions are consistently less than 10 per cent of the cradle to gate emissions.

There are no significant variations in the end-of-life impacts among the different products considered here. The more important factor relating to end of life concerns the benefits and loads reported in module D, when slate is recovered for reuse or recycling.

### Module D

This module captures the potential environmental benefit of slate reuse. Module D considers the avoided impact of producing new material when salvaged slates are reinstated in the next product system, rather than discarded.[30] Results from module D frequently report negative carbon emissions, which reflect the avoided carbon emissions from producing new material. However, a few points to note include:

- The assumed reuse rate is a key factor and should be a conservative value to avoid overestimating the environmental benefits.
- The benefits arise a long time in the future, meaning module D has no immediate impact on short-term climate change mitigation.
- A related point is that the benefits may be reduced by 50 per cent when taking account of decarbonisation using the RICS methodology.

Most of the slate EPDs do not report module D, despite sometimes claiming very high recovery rates. They, therefore, miss the opportunity to distinguish natural slate from any manufactured materials with poorer reuse and recycling potential.

## Limitations, gaps and inconsistencies

EPDs exist for a number of imported roofing slate products – mainly from Spain – but there are none, as yet, for indigenous UK slate. The only assessment of embodied carbon specific to the UK industry derives from data for 2008 (Crishna et al., 2010 & 2011). Accordingly, the estimation of embodied carbon of UK slate neglects the benefits of electricity decarbonisation since 2008 and partly rests on an assumption that the UK slate

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[30] Historic England does not promote the wider use of reclaimed slate from other buildings, as this could incentivise the theft and inappropriate removal of original roofing materials from historic structures. Therefore, when considering end of life scenarios, the focus should be on maximising the reuse of slates from the same building wherever possible, rather than relying on externally sourced reclaimed materials. In contrast, roofing materials such as concrete tiles or fibre cement typically do not allow for on-site reuse, leading to higher disposal-related emissions and no module D benefit.

industry has changed little in more than 15 years – or operates in a broadly similar way to the Spanish slate industry.

EPDs themselves have a wide range of limitations. LCA is an inexact science that frequently draws on data that are incomplete or only partially relevant in technical, geographical and temporal terms, and often with inconsistent system boundaries, making direct comparisons difficult. Sector-wide EPDs covering multiple producers – potentially with different production methods – provide a specific example of this. Variability in assumptions regarding energy sources, transport and end of life scenarios, for example, can lead to different results for similar products and supply chains. Another example is truncation error, whereby impacts are underestimated because upstream supply chain activities (relating to the manufacture of machinery, or the machinery that makes the machinery, for example) are neglected. Also, most LCAs do not account for market dynamics, meaning that the reported impact of a product does not necessarily correlate with actual global emission changes when production scales up or down.

It should also be remembered that embodied carbon is only one of many environmental metrics related to slate production. A comprehensive assessment should take a holistic view and consider other environmental impacts, such as land use, biodiversity and water consumption, alongside socio-economic concerns. Additionally, the risk of unintended consequences – such as incentivising the theft of original historic slates for resale – should be acknowledged in discussions about using reclaimed slate.

Several errors, inconsistencies, gaps and questionable assumptions were identified in the EPDs reviewed for this study. Most of these are minor in relation to this work, especially when appropriate adjustments are made. However, a summary of the various issues identified may assist with the interpretation of other EPDs. Examples include:

- Inconsistent units and data tables: One EPD presents values corresponding to 1kg of material rather than to the declared unit of 1m$^2$ of roof coverage, requiring the reader to make their own adjustments. This could be the source of a highly significant error in subsequent analysis if not corrected.

- Inconsistent information and data: There are sometimes internal inconsistencies within an individual EPD surrounding information provided for scenarios in different parts of the document (for example, for A4 and A5).

- Exclusion of maintenance and repairs: Most EPDs do not account for maintenance, minor repairs or partial roof replacement (for example, occasional broken slates/tiles), often reporting these as not declared or zero. This is potentially quite a significant failing, because some breakages are expected during the service life of a building.

- Misreported emissions: In some cases, the construction and installation (A5) emissions reported are not high enough to cover the stated rate of breakages, meaning that the A5 figure is insufficient to cover the provision of the extra material required.

- Incorrect biogenic accounting: One EPD reported net negative biogenic GWP across the whole product life cycle, and included this in the total GWP figures.[31] This is incorrect, because biogenic carbon sequestered during material production should be recorded as being released at a later stage. The net total over the full life cycle cannot, therefore, be negative.

- Widely varying recovery rates for reuse assumed at end of life: The assumed 90 per cent recovery rate for reuse in some instances seems unlikely, even in ideal conditions. However, this has very little impact on the GWP values, as this is primarily a module D issue, and this was not reported in these instances.

- Choices about which modules to report are widely varied: This inconsistency should improve in future as EPDs transition to BS EN 15804+A2. The new standard requires A1–A3, C and D as a minimum, unlike BS EN 15804+A1, which permitted a cradle to gate assessment only (as seen in several EPDs reviewed in this study).

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[31] Biogenic carbon (carbon sequestered from the atmosphere through photosynthesis) is present in packaging materials for a great many products, and as a constituent of a minority of products covered in this work (such as fibre cement).

# Conclusions/Further Work

## Key conclusions

Indigenous slate has a clear embodied carbon advantage over imported slate in terms of transport (A4) emissions, because of the lower GHG emissions associated with transport from the quarry to the point of use in the UK. The estimated emission savings from using indigenous slate compared to imported slate from each of the main supplying countries is shown in Table 4. On average, the savings amount to about 5kg$CO_2$e/m$^2$, when weighted by the quantity imported from each country.[32] The ranges relate to the different UK quarry locations considered as a baseline, and also the UK construction site locations considered.

Table 4: A4 embodied carbon emissions savings for indigenous slate compared to imported slate.

| **Comparison** | **Estimated A4 savings (kg$CO_2$e/m$^2$)** |
|---|---|
| UK versus Spanish slate (sea route) | 1.5–3.0 |
| UK versus Spanish slate (overland route) | 4.9–8.1 |
| UK versus Brazilian slate | 9.6–11.1 |
| UK versus Chinese slate | 20.9–22.4 |

Note: Data based on a representative slate coverage of 39kg/m$^2$.

The absence of any EPDs for indigenous slate in the UK is the most significant obstacle to making robust cradle to gate comparisons between indigenous and imported slate. The main reference point for life cycle data on indigenous slate (Crishna et al. 2010, 2011) is now of limited use, because the underlying data is more than 15 years old and the energy system has changed markedly since 2008.

Additionally, and partly because of the absence of EPDs, the zero-waste advantage of some UK slate has not yet been evaluated. When all the material extracted from the quarry has a marketable purpose – even when it does not meet the requirements for roofing slate – part of the environmental burden for extraction and processing can be allocated to those marketable co-products, thereby reducing the environmental burden of the roofing slate. By contrast, available information for Spanish slate suggests that potential co-product is returned to the quarry as waste rather than being marketed.

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[32] Sea route assumed for Spanish slate imports.

The available EPD data indicate that natural slate has, on average, lower cradle to gate (A1–A3) embodied carbon than some alternative roofing products. Most reviewed slate EPDs report emissions between 3.4 and 14.9kg$CO_2$e/m², with a median of 4.2kg$CO_2$e/m² (normalised to 39kg/m² of roof coverage). Alternative products typically range from 6.8 to 16.3kg$CO_2$e/m², with a median of 8.2kg$CO_2$e/m² (*see* Tables 1 and 2). Because of the variety of alternative products available and the limited associated data, more work is required to accurately quantify the advantage of natural slate in terms of A1–A3 embodied carbon emissions.

While indigenous slate may come at a higher capital cost than imported slate and alternative products, the lower transport emissions provide a strong incentive for its use in the construction industry. The likely confirmation of its lower embodied carbon footprint overall would provide compelling justification.

# Further research

A full understanding of the extent of the embodied carbon advantages of using UK slate is currently limited by a range of factors.

## Embodied carbon data

The absence of any EPDs or other recent data specific to the embodied carbon of indigenous slate clearly limits its comparison with other products. Obtaining an EPD for every slate product from every UK quarry or producer may be unrealistic given the modest market size. However, a sector-wide EPD for a typical or average indigenous roofing slate from a given operator, or even a group of operators, as provided by the Galician Slate Cluster, could offer a representative benchmark.

## Co-product allocation

For indigenous roofing slate, determining the allocation of embodied carbon to co-products requires market data and production processes to be analysed. This can be achieved if relevant industry stakeholders provide access to production data, allowing for more accurate assessment of how co-product use affects the overall embodied carbon of roofing slate. Accurate co-product allocation could potentially reduce the product stage emissions reported for indigenous slate to levels well below that for imported slate, adding to the advantage associated with reduced transport needs.

A rerun of the Historic Environment Scotland TP7 project (Crishna et al., 2010) focusing on indigenous slate would be an option to run alongside a co-product allocation study, if the continuing absence of EPDs is not resolved. This would bring the research up to date, taking account of decarbonisation of the electricity grid and any developments in slate production processes. Ideally, the work would involve producers from a significant proportion of the UK roofing slate industry, to ensure representativeness.

## Construction processes

The construction process (A5) is often assumed to contribute only a relatively small amount of embodied carbon, yet the data reviewed here suggest significant variability or uncertainty. Further study could quantity these uncertainties. It would involve consulting with roofing contractors and, ideally, site visits to assess a variety of projects, to gather and analyse data on installation methods, materials and waste generation.

Additionally, contractor insights could help to quantify typical maintenance and repair requirements (B2 and B3) for roof coverings – a subject almost universally neglected in the documents reviewed.

Roofing contractors may also be able to provide data about roofing slate from one building being reused on another, as some EPD module D assessments rely on an assumption that this practice is widespread. Although reusing slate in this way is a contentious topic, it would be helpful to understand more about the practice.

## Slate expected lifespan

The variation in the expected lifespan of roofing products can be a significant consideration in the LCA of a building, particularly when evaluating replacement (B4) embodied carbon emissions. This is especially true for assessments carried out over a 120-year period, as required by RICS, as a complement to the normal 60-year assessment.

While EPDs generally assume an RSL of 60 years or more for roofing materials, there is limited evidence on the actual longevity of slate. The same applies to alternative roofing materials. Since high-quality natural slate in the UK is often stated to last well beyond 60 years, a better understanding of real-world durability would enable more accurate embodied carbon assessments. Although such data may not necessarily over-ride information published in an EPD, it would provide essential context when there is no EPD and may help to refine embodied carbon assessments even where an EPD exists.

## Market study

In addition to investigating co-product allocation, a broad UK slate market study could provide much-needed context for embodied carbon analysis. Understanding the difference in embodied carbon between 1m$^2$ of roof of indigenous slate versus 1m$^2$ of roof of imported slate or an alternative material is only one piece of the puzzle. A more comprehensive approach would seek to understand the potential for aggregated embodied carbon reductions in the built environment by shifting material choices. This leads to key questions, such as:

- What is the current capacity and potential capacity of the UK industry to meet increasing demand for roofing slate?
- Could an increase in indigenous slate production reduce reliance on imported slate or displace alternative roofing materials?
- How do price differences and life-cycle costs influence material choices? Understanding these economic drivers is crucial to assessing the potential for material switching.
- If demand for indigenous slate increases, where will it be used and will the rise in demand increase the average distance from quarry to construction site, and so increase embodied carbon emissions from transport?

Finally, a market study could support broader research efforts, potentially giving insight into any of the research areas mentioned above.

## Evaluating detailed transport emissions

While this report provides a broad overview of transport emissions of roofing slate through modelling, accuracy could be improved by analysing supply chain complexity and real-world transport routes. The report assumes direct transport routes, but slate and other roofing materials may pass through multiple storage depots, distributers or processing centres before reaching the final destination, meaning that A4 embodied carbon emissions are underestimated. Further research could map real-world supply chains and account for indirect transportation routes. Furthermore, the report estimates emissions using standard transport assumptions, but more detailed mode-specific data could improve accuracy.

# Appendix

This appendix provides further details relevant to the transport modelling.

Table A1: Distances matrix used for transport calculations between quarries, manufacturing sites, ports and construction sites.

| | London (site) | Leeds (site) | Glasgow (site) | Port of Bilbao | Port of Rio de Janeiro | Port of Shanghai |
|---|---|---|---|---|---|---|
| **Penrhyn** | 382 | 228 | 476 | | | |
| **Kirkby** | 455 | 141 | 280 | | | |
| **Port of Dover** | 129 | 439 | 766 | | | |
| **Tilbury Docks** | 39 | 351 | 690 | 1500 | | |
| **Port of Felixstowe** | 150 | 352 | 678 | | 11868 | 22052 |
| **Port of Liverpool** | 344 | 121 | 355 | 1563 | 11727 | 21911 |
| **Greenock** | | | 40 | 1680 | 11849 | 22033 |
| **Dublin** | 288 | 275 | 480 | | | |
| **Southampton** | 129 | | | 1219 | | |
| **San Pedro de Trones (Spain)** | 1751 | 2065 | 2413 | 489 | | |
| **Papagaios (Brazil)** | | | | | 572 | |
| **Ankang, Shaanxi (China)** | | | | | | 1508 |
| **Copenhagen (Denmark)** | 1248 | 1558 | 1885 | | | |
| **Bruggen (Germany)** | 490 | 800 | 1127 | | | |
| **Brussels (Belgium)** | 322 | 632 | 959 | | | |

Note: All distances are in kilometres. Shaded cells are sea routes. Direct road distances from continental Europe to construction sites in London, Leeds and Glasgow do not include the 50km Calais–Dover link, which is assumed to be by RoRo ferry. Similarly, distances from Dublin (relevant to one of the alternative products) do not include the ferry link (106km). Two further sea distances not included in the table are: Buenos Aires to Tilbury (14,327km), and Copenhagen to Tilbury (1,726km).

Table A2: Tabulated data illustrated in Figure 3.

| | London | Leeds | Glasgow |
|---|---:|---:|---:|
| **Wales (Penrhyn)** | 1.4 | 0.84 | 1.8 |
| **Cumbria (Kirkby)** | 1.7 | 0.5 | 1 |
| **San Pedro (Spain): sea route** | 3.2 | 3.5 | 3.3 |
| **San Pedro (Spain): overland** | 6.6 | 7.8 | 9.1 |
| **Minas Gerais (Brazil)** | 11.8 | 11.6 | 11.4 |
| **Shaanxi (China)** | 23.1 | 22.9 | 22.7 |

Note: GHG emissions associated with transport (A4) from quarry location to construction site (London, Leeds or Glasgow) are in units of $kgCO_2e/m^2$.

Table A3: EPD hyperlinks.

**Slate:**

| | |
|---|---|
| Cupa 12 | Document expired and no longer available |
| Cupa Heavy 3 | Document expired and no longer available |
| Cupa 5 | greenbooklive.com/filelibrary/EN_15804/EPD/BREGENEPD000506.pdf |
| Cupa 50 | greenbooklive.com/filelibrary/EN_15804/EPD/BREGENEPD000507.pdf |
| Cluster da Pizarra de Galicia | csosteniblev4.s3.eu-west-1.amazonaws.com/dapcons/DAPcons_c-004-105_ENG-firmada.pdf |
| Argentine Riverstone | greenbooklive.com/pdfdocs/en15804epd/BREGENEPD000472.pdf |

**Alternative materials:**

| | |
|---|---|
| Concrete tiles | epddanmark.dk/media/py0l53y1/md-22037-da.pdf |
| Cedral fibre cement | Document expired and no longer available |
| SVK fibre cement | a.storyblok.com/f/51041/x/ce184c24b7/b-epd_21_0073_005_00_01_en_svk_slate_signed.pdf |
| Fired clay | laumans.de/wp-content/uploads/2021/09/2021-09-15_EPD_Laumans-EN.pdf |

# Glossary

This section provides brief statements outlining how key technical terms are used in this document.

**Decarbonisation**: A reduction in ***GHG emission factors*** over time as, for example, manufacturing becomes more efficient, and energy systems switch from fossil to renewable and other low carbon systems.

**Declared unit**: Defined in BS EN 15804:2012 as the quantity of a construction product for use as a reference unit in an ***EPD*** for an environmental declaration based on one or more information modules.

**Embodied carbon**: Defined in ISO 6707-3:2022[33] as the total of all the greenhouse gases emitted or removed in the processes associated with the extraction, production, transportation to site, installation, use, refurbishment, replacement and disposal at end of life of materials, products and construction works, expressed as $CO_2$equivalent. ($CO_2$equivalent expressed as $CO_2e$ in this document).

**Environmental product declaration (EPD)**: Defined in ISO 14020:2022 as an environmental statement that provides the environmental data of a product using predetermined parameters resulting from a ***life cycle assessment (LCA)*** and additional environmental information. EPDs require verification by a third party.

**Functional unit**: Defined in BS EN 15804:2012 as the quantified performance of a product system for use as a reference unit. This provides more information than the ***declared unit***, because it allows different products with the same function to be compared with each other.

**Global warming potential (GWP)**: An index, based on the radiative properties of ***greenhouse gases***, measuring the radiative forcing following a pulse emission of a unit mass of a given greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide ($CO_2$) (ISO 14050). Reported as mass – for example, kilogrammes – of carbon dioxide equivalent ($kgCO_2e$).

**Greenhouse gas (GHG) emissions**: Emissions of gases (such as carbon dioxide and methane) that contribute to global warming. The emissions of interest in this research report arise from human activities (for example, industry and transport).

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[33] ISO definitions referred to here can be viewed at iso.org/obp/ui

**GHG emission factor**: Defined in ISO 14067 as a coefficient that relates activity data with ***greenhouse gas emissions***. The **grid emission factor** is a particular case that relates electricity drawn from the grid to the GHG emissions associated with the production of that electricity.

**Life cycle assessment (LCA)**: Defined in ISO 14040 as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.

**Reference service life (RSL**): Defined in BS EN 15804:2012+A+:2019 as the service life of a construction product that is known to be expected under a set of reference in-use conditions and that can form the basis for estimating the service life under other in-use conditions. It is noted that the RSL should be referenced in the description of the ***functional unit***.

**Reference study period**: Defined in EN 15978:2011 as the period over which the time-dependent characteristics of the object of assessment are analysed. It is noted that the reference study period may differ significantly from the design life of the building.

**Whole life carbon**: Combines embodied carbon with operational carbon (which includes GHG emissions associated with energy use in a building). It is defined in ISO 6707-3:2022 as the total of all ***greenhouse gas emissions*** and removals, both operational and embodied, over the life cycle of a construction product or construction works including its end of life.

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