Cite this article
Anderson J and Moncaster A (2023)
Embodied carbon, embodied energy and renewable energy: a review of environmental product declarations.
Proceedings of the Institution of Civil Engineers – Structures and Buildings **176(12)**: 986–997, https://doi.org/10.1680/jstbu.21.00160

Research Article
Paper 2100160
Received 06/10/2021;
Accepted 13/12/2021;
First published online 25/04/2022

Structures and Buildings

Embodied carbon, embodied energy and renewable energy: a review of environmental product declarations

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Environmental product declarations (EPD) to EN 15804 provide information about the embodied carbon dioxide of construction products – their life cycle greenhouse gas emissions – alongside reporting the use of renewable and non-renewable primary energy and secondary fuels, among the other environmental indicators. As the number of EPD to EN 15804 increases, they become a useful data resource to consider these impacts. In moving towards a reduction in the embodied carbon of products, it is necessary to use renewable energy resources efficiently to allow the transition to net zero; this is because of the increasing demands on renewable energy to decarbonise industry, transport and domestic energy consumption and the limited capacity to expand renewable generation. This paper reviews published EPD data for structural and reinforcing steels, cement, bricks and structural timber products, and considers, for the cradle to gate 'product' life cycle stage, exploring the relationship of embodied carbon with embodied energy (total energy used), the balance of renewable and non-renewable energy, and the efficient use of energy. It is found, for bricks and timber, that EPD show products that use a greater percentage of renewable energy have higher embodied energy, suggesting a less efficient use of renewable energy for these products.

Keywords: built environment/embodied carbon/embodied energy/energy efficiency/renewable energy/statistical analysis/structural materials/sustainability

1. Introduction

Environmental product declarations (EPD) to EN 15804 (CEN/TC 350, 2013) provide information about the environmental impacts associated with construction products (note that for construction product EPD, EN 15804 or ISO 21930 (ISO, 2017) provide the core product category rules (PCR)). Prior to their introduction, reviews of embodied energy (defined herein as the total of all the energy consumed in the processes associated with the production and life cycle of a product) and embodied carbon dioxide (defined herein as the total of all the greenhouse gas emissions and removals associated with the production and life cycle of a product) were hampered by differing definitions of embodied energy (Cabeza *et al.*, 2013). This, and differing assessment methodologies, were also found to be problematic by Hammond and Jones (2008, 2011) when they reviewed life cycle assessment (LCA) studies for construction products to produce the *Inventory of Carbon and Energy.* EPD now provide a data source with much greater consistency, owing to the use of EN 15804 as a common PCR which sets system boundaries, allocation approach and other methodological constraints. EPD include the greenhouse gas emissions associated with the life cycle of construction products – their production, transport, installation, repair and maintenance and end of life – known collectively as embodied 'carbon' (reported using the impact indicators of climate change or global warming potential (GWP), alongside a range of other environmental impacts, and resource indicators covering the use of renewable energy (defined herein as energy from renewable non-fossil sources, e.g. wind, solar, hydropower, sustainable biomass) and non-renewable energy (defined herein as energy taken from a source which is depleted by extraction, e.g. fossil fuels or uranium) and secondary fuels (defined herein as fuel recovered from previous use or from waste derived from a previous product system; renewable secondary fuels (RSFs) include fuels recovered from cooking oil and waste wood or landfill gas, while non-renewable secondary fuels (NRSFs) include fuels recovered from synthetic rubber tyres or motor oils). However, not all life cycle stages are mandatory. The amendment of EN 15804 in 2019 (CEN/TC 350, 2019) now requires newer EPD to report impacts of the end of life and beyond (modules C and D); however, other life cycle stages (construction (A4–5) and use (B1–7)) remain optional, and intermediate products (like cement, which are not used on their own in buildings, but are only used to make final construction products) are still exempt from this additional reporting.

The number of EPD to EN 15804 is increasing, with over 10 000 at the start of 2021. They are rapidly becoming a useful data resource to consider the impact of construction product types such as structural steel, cement, brick and timber, particularly for the mandatory cradle to gate 'product' stage covered by modules A1–A3, and EPD are also an encouragement to manufacturers to reduce the carbon impacts of their products. As the carbon impact is closely correlated to fossil fuel use in manufacture, this in turn suggests that there will be an increasing pressure on renewable energy resources and nuclear energy. However, these resources have their own associated embodied impacts and limited capacity; therefore, it is also necessary to use renewable energy resources efficiently in the production of construction products to allow the transition to net zero.

Primary energy (defined herein as energy that has not been subjected to any conversion or transformation process) provides the total amount of energy from primary sources which has been used to create a product. In EPD, this energy is split into renewable primary energy (e.g. wind, hydro, solar, biomass) and non-renewable energy (fossil and nuclear), and the distinction between the two is critical for understanding the impact of products and materials. It should be noted that the calculation approach for the primary energy total indicators (PERT – primary energy renewable (total) and PENRT – primary energy non-renewable (total)) is not defined in any detail in EN 15804, although the approach for the primary energy material indicators (PERM – primary energy renewable (materials) and PENRM – primary energy non-renewable (materials)) is provided, and the primary energy as energy indicators (PERE and PENRE) are both derived by deducting the respective primary energy material indicator from the primary energy total indicator. However, for renewable sources, primary energy is normally calculated in EPD using the ‘energy harvested’ cumulative energy demand approach defined in Frischknecht *et al.* (2015), as this is the approach used in the two major life cycle inventory databases, ecoinvent and GaBi.

Ignoring losses from transmission and distribution and the embodied impact of the infrastructure and supply chain impacts for fuels, the renewable primary energy for a wind turbine or photovoltaic (PV) installation will be the amount of electricity generated by the turbine or PV. By contrast, for fossil fuel and biomass energy, significantly more fuel is used for generation as the process of converting heat to electricity has significant losses. The thermal efficiency of combined cycle gas turbine generation in the UK is only 48.8% (BEIS, 2020). This means that for a product with an electricity demand of 100 MJ/t, if the electricity is generated from natural gas in the UK, the product will have a primary energy demand of over 200 MJ/t (100/0.488); however, if the electricity is generated by wind, then the same product will have a primary energy demand of just 100 MJ/t. Generally, therefore, use of renewable electricity reduces the amount of primary energy required. However, this is not the case for biomass energy, which generally has lower thermal efficiencies (30–34%) than coal when used for power generation (Magiri-Skouloudi *et al.*, 2019). This would mean the fuel demand for 100 MJ generated from biomass in a power plant (not combined heat and power (CHP)) would be over 300 MJ (100/0.32). Note that the embodied supply chain impacts for biomass-fired electricity generation can also be quite high; Raugei and Leccisi (2016) suggest for biomass it could be 86 MJ per 100 MJ generated, compared to 1.6 MJ for hydroelectricity, 5–5.3 MJ for wind and 30 MJ for PV (c-Si). This would mean a primary energy demand over 400 MJ for the delivery of 100 MJ of electricity from a biomass power plant. Therefore, if production moves from the use of gas-fired grid electricity to renewables other than biomass, the primary energy demand of manufactured products would be expected to reduce, and if moving to biomass, to increase. In both cases, the embodied carbon of the product would be expected to reduce, however, as renewable energy has much lower GWP per MJ than fossil energy. Nuclear energy has a similarly low GWP per MJ as renewables, but has a normal efficiency of 38–40% (BEIS, 2020) so 100 MJ electricity would have a primary energy requirement of 256 MJ (100/0.39).

Other researchers have reviewed EPD to consider the variation in embodied carbon of stone wool insulation (Silvestre *et al.* (2015)), glass-wool insulation (Hodková and Lasvaux (2012)) and cement, bricks, wood-based materials, steel, gypsum plasterboard, glass-wool slabs, stone-wool slabs and ceramic tiles (Ganassali *et al.* (2018)), but these studies did not consider the relationship with primary energy or secondary fuel use. Anderson and Moncaster (2020) explored the relationship of embodied carbon (A1–A3) and non-renewable primary energy use and secondary fuel use reported per tonne in EPD for cements, but did not look at renewable primary energy. Anderson and Moncaster (2020) also reviewed the embodied carbon (A1–A3) of in situ concretes reported in EPD, but did not consider their energy use. Rasmussen *et al.* (2021) reviewed the correlation between embodied carbon (A1–A3) and PERT, and PENRT as reported in EPD for structural timber products (cross-laminated timber (CLT), glulam, laminated veneer lumber (LVL) and sawn timber). Rasmussen and co-workers found only a low correlation (R^2) between embodied carbon and PERT (0.0192), and embodied carbon and PENRT (0.1162); they did not explore the correlation with PERE (renewable primary energy used as energy, so excluding the energy content of the actual timber itself) or the correlation with the total energy consumption.

This paper reviews published EPD data for key construction materials including structural and reinforcing steel, cement, brick and structural timber products. It takes the cradle to gate life cycle stage (A1–A3) as this is mandatory for all EPD, and for all the products other than timber, it is the most impactful life cycle stage. The data from EPD for other life cycle stages also have considerably less comparability and more variation due to the different scenarios modelled – for example, see Anderson *et al.* (2019). The paper considers embodied carbon, the use of renewable energy, non-renewable energy (collectively primary energy demand) and the use of secondary fuels for each material. It explores the relationship between embodied carbon and energy demand, the balance of renewable and non-renewable energy use for different products, and the use of secondary fuels, and considers whether there is any evidence that renewable energy is being used less efficiently than non-renewable energy.

2. Method

The research is based on the analysis of published EPD to EN 15804 or ISO 21930 (CEN/TC 350, 2013, 2019; ISO, 2017). These standards are almost identical methodologically, and in terms of the climate change and resource efficiency indicators considered, both amendments (+A1 : 2013 and +A2 : 2019) to EN 15804 provide the same results, so it was not considered necessary to exclude any EPD on this basis. EPD are published by EPD programmes, and the EPD for the relevant product types (steel, cement, timber, brick) were sourced from all known EPD programmes globally, based on the programmes listed in the briefing paper developed by Anderson (2020) for ASBP. The following sub-types of products were considered:

- steel – structural steel (section, tube etc.) and reinforcing steel
- cement – CEM I cement
- structural timber – CLT, glulam, LVL and kiln-dried sawn softwood timber
- brick – clay facing brick and Ziegel bricks (i.e. perforated clay blocks, as commonly used in Europe).

An overview of the EPD reviewed is provided in Table 1. As EPD globally were considered, a large number of countries of production are included in the EPD studied. This means that there will be considerable variation, for instance, in the GWP impact and energy sources for grid electricity used in the countries; for example, Switzerland, Norway and Sweden all have less than 3% of the grid sourced from fossil fuels, whereas Oman, Belarus and UAE have 97% or more (IEA, 2020). The significance of electricity use will vary for different products – for electric arc furnace (EAF) steel it is a significant input, but for the other products studied, electricity use is not expected to be significant. In addition, it is possible according to ISO 14067 (ISO, 2018) to make use of on-site renewables, directly connected renewables or the purchase of ‘green electricity’ with tracked guarantee of origin to increase the percentage of renewable energy used in comparison to the national grid mix. Where relevant, the authors have included any geographical aspects of their findings in the discussion below.

Data from the EPD were extracted, covering the product type and sub-type (e.g. timber and CLT), declared unit, mass of declared unit (for non-mass declared units), and then for modules A1–A3, the embodied carbon (the global warming potential indicator from the EPD) and the following resource indicators – PERT, PENRT, and use of secondary fuels (renewable and non-renewable) (SFR and SFNR) were taken. For timber products PERE and PERM were extracted (PERM reports the energy content of the timber product itself). The sequestered carbon dioxide within the timber was also extracted from the EPD if provided, or calculated using the approach in EN 16449 (CEN/TC 175, 2014).

Although EN 15804 + A2 (CEN/TC 350, 2019) makes it mandatory to report modules C and D, cement is considered an exception to this requirement and many of the EPD reviewed used EN 15804 + A1 (CEN/TC 350, 2013) and so did not report these modules. Additionally, where EPD report these modules, there are differences in the scenarios modelled, particularly for timber as described in Anderson *et al.* (2019), meaning comparison is not possible. This is also the case for modules A4 and A5 when reported, so this study has only reviewed the reported results for modules A1–A3.

For each product, a common declared unit was chosen and, if necessary (e.g. where some steel EPD reported results per kilogramme), indicator results were converted to apply to that unit, as shown in Table 2.

Table 1. EPD considered in this study

Product type	Sub-type	EPD	Countries of production
Steel	Structural steel – BOF	18	AE, AT, AU, BY, CA, CH, DE, DK, ES, EU, FI, FR, HU, IT, JP, KR, LI, LV, LX, MX, NO, NZ, OM, PO, PT, RO, RU, SE, UA, UK, US
	Structural steel – EAF	10	
	Structural steel – DRI	2	
	Reinforcing steel – BOF	56	
	Reinforcing steel – EAF	13	
	Reinforcing steel – DRI	4	
Cement	CEM I	33	CH, DK, ES, EU, FR, IS, IT, JP, LV, NO, NZ, SE, UK
Structural timber	CLT	13	AT, AU, CH, DE, ES, IT, LA, NO, SE
	Glulam	12	AT, AU, CH, DE, IT, NO, PO, RU, SE
	LVL	2	FI, PO
	Kiln-dried sawn softwood	41	AT, AU, CZ, DE, DK, ES, EU, FI, FR, IT, LA, NO, NZ, SE, UK, US
Brick	Clay facing brick	25	CA, DE, DK, ES, FR, FI, IE, UK, US,
	Ziegel brick	38	BE, CZ, DE, ES, FR, IT

Table 2. Product types and sub-types and their declared units

Product type	Sub-type	Declared unit
Steel	Structural steel	Tonne
	Reinforcing steel	Tonne
Cement	CEM I	Tonne
Timber	CLT	Cubic metre
	Glulam	Cubic metre
	LVL	Cubic metre
	Kiln-dried sawn timber	Cubic metre
Brick	Facing brick	Tonne
	Ziegel brick	Tonne

Evidence from industry supports the potential increase in energy consumption as a consequence of actions to reduce carbon dioxide emissions (‘decarbonisation’ actions). For example, the UK cement decarbonisation strategy (BEIS and MPA, 2017: p. 21) states some actions ‘might make cement manufacture less energy and electrically efficient’, such as use of biomass fuels with higher moisture content, and the British Geological Society state that carbon dioxide capture and storage (CCS) is energy intensive and would increase the fuel needs of a coal-fired electricity plant by 25–40% (BGS, 2021), meaning processes using such decarbonising electricity and materials production could become more energy intensive.

2.1 Total energy consumption and embodied carbon (A1–A3)

For each product type and sub-type, the total energy consumption (PERE and PENRE) and use of secondary fuels (renewable (RSF) and non-renewable (NRSF)) were plotted against the embodied carbon for modules A1–A3. Embodied carbon is provided by the impact indicator GWP for EPD compliant with EN 15804 + A1, and by the impact indicator climate change total for EPD compliant with EN 15804 + A2.

For steel, the use of secondary fuels was insignificant across all EPD so only the total primary energy consumption (PERE and PENRE) was used. For timber, ideally the embodied carbon used in the analysis would exclude the sequestered carbon stored within the product, as this is emitted or transferred to the next product system at the end of life of the product. However, it was not possible to adjust the reported embodied carbon in this way due to a lack of transparency in some EPD, so the total energy consumption was modelled against the reported global warming potential for A1–A3, which is normally negative for timber products due to the inclusion of the stored sequestered carbon.

The degree of correlation has been considered by finding the linear regression for the variables considered and using the coefficient of determination (R^2) to measure how well-observed outcomes are replicated by the linear regression, effectively the square of the Pearson product–moment correlation coefficient.

2.2 Total energy consumption and the percentage of renewable energy

In the second analysis, the same total energy consumption was modelled as in Section 2.1, against the percentage of renewable energy used. This is calculated by comparing the use of PERE and RSF to the total energy consumed.

2.3 Renewable energy consumption and non-renewable energy consumption

In the third analysis, the use of renewable and non-renewable energy, both from primary energy and secondary fuels was modelled. This was shown on a graph together with the average energy consumption for the product sub-type per relevant declared unit, 50% of the average energy consumption, and plots showing 10, 20, 33 and 50% renewable energy usage, as shown in the example in Figure 1, where the average total energy demand for the example product sub-type is 20 000 MJ/t. This graph allows the distribution of renewable and non-renewable energy to be considered consistently for each product.

2.4 Plausibility of data

It should be noted that this level of scrutiny is not normally given to the resource indicators provided in EPD, although all EPD results have been verified by an independent expert according to ISO 14025 (ISO, 2010). In some cases, it is possible that the results are erroneous. In such cases where the resource indicators appear to be outliers or they are not plausible, the authors have contacted the EPD programme and requested that a check is made. Where, as a result, the authors have been notified of corrections, corrected data have been used.

3. Results

3.1 Steel

3.1.1 Use of renewable energy for steel

For both structural and reinforcing steels, the use of secondary fuels was insignificant. The use of renewable energy for

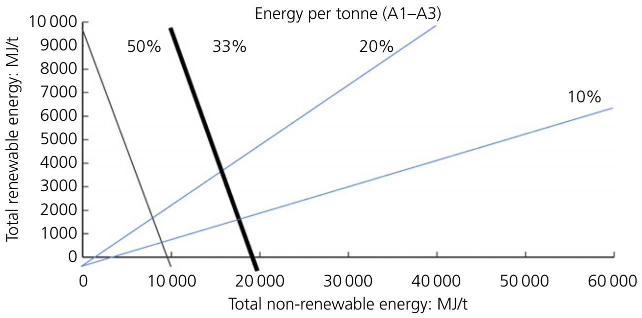


Figure 1. Example showing the common format of the graphs for the third analysis showing percentage renewable energy and average primary energy demand (bold black line) and 50% of average energy demand (black line)

structural steels was on average 7% of total energy use, for reinforcing steels it was 14%. There were several steels using more than 50% renewable energy; four of these EPD were for production in Norway, and one each for Denmark, Finland (around 50% renewable grid electricity) and Japan (which has 19% renewable grid electricity) (IEA, 2020). Those with the lowest percentages of renewable energy (less than 2%) were from Qatar, USA, Mexico, Finland, Italy, Romania, South Korea and Australia. Interestingly, structural steel made in the basic oxygen furnace (BOF) process used around 5% less renewable energy than BOF-manufactured reinforcing steel. However, reinforcing steels made using the electric arc furnace (EAF) process used 4% less renewable energy than did structural steels. Of the 30 BOF EPD, two Canadian EPD used 22% renewable energy, but the others used much lower percentages. For steels produced in the EAF, 10% of the 67 EPD used over 50% renewable energy. The percentage of renewable energy for all steel EPD considered is shown in Figure 2.

3.1.2 Relationship between embodied carbon and use of renewable energy (A1–A3) for steel

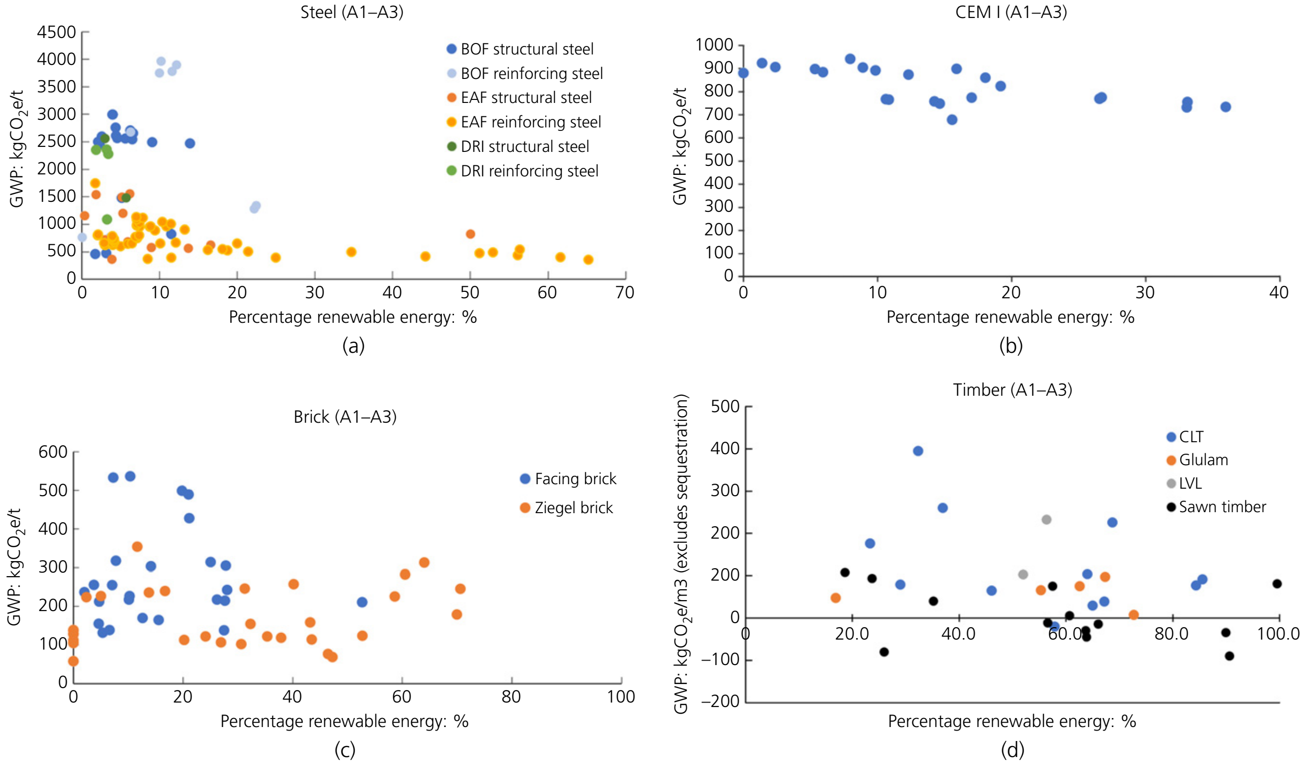
Figure 2 shows the relationship between embodied carbon and the percentage of renewable energy used. For all steels, there is a trend for reduced embodied carbon impact as the percentage of renewable energy used increases.

3.1.3 Total energy consumption and embodied carbon (A1–A3) for steel

Figure 3 shows there is strong correlation between primary energy and embodied carbon for BOF steels ($R^2 = 0.834$, less so for EAF steels ($R^2 = 0.154$) due to several outliers, for example several EAF EPD report extremely low primary energy figures. For reinforcing steels, the correlation between primary energy and embodied carbon was very strong for BOF ($R^2 = 0.937$) and strong for EAF ($R^2 = 0.59$).

3.1.4 Total energy consumption and the percentage of renewable energy for steel

Figure 4 shows the relationship between primary energy demand and the percentage of renewable energy used. For structural steel, there is no obvious drop in primary energy demand as renewable energy usage increases for BOF steel ($R^2 = 0.00006$), but for EAF there was a slight trend reducing primary energy demand with increasing use of renewable energy ($R^2 = 0.454$). For reinforcing steel, the results for BOF steel show little correlation ($R^2 = 0.03$). For EAF steels, however, as with structural steel using EAF, there is a slight trend to reducing primary energy demand with increasing use of renewable energy ($R^2 = 0.41$).



(a) (b) (c) (d)

Figure 2. Relationship of embodied carbon to percentage renewable energy for (a) steel, (b) cement, (c) brick and (d) timber products

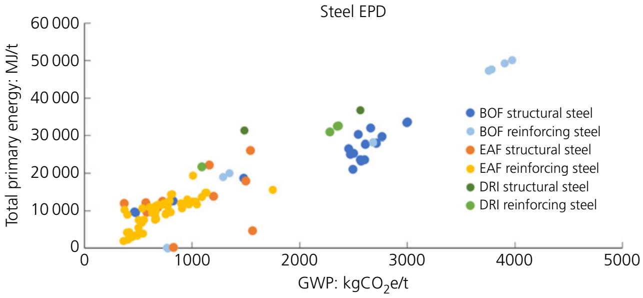


Figure 3. Primary energy demand plotted against embodied carbon (A1–A3) for the steel product sub-types

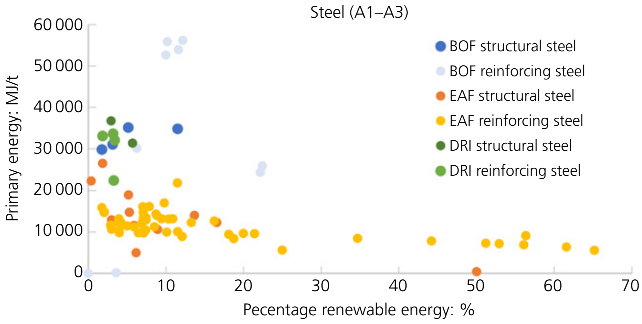


Figure 4. Primary energy demand plotted against percentage renewable energy for the steel product sub-types

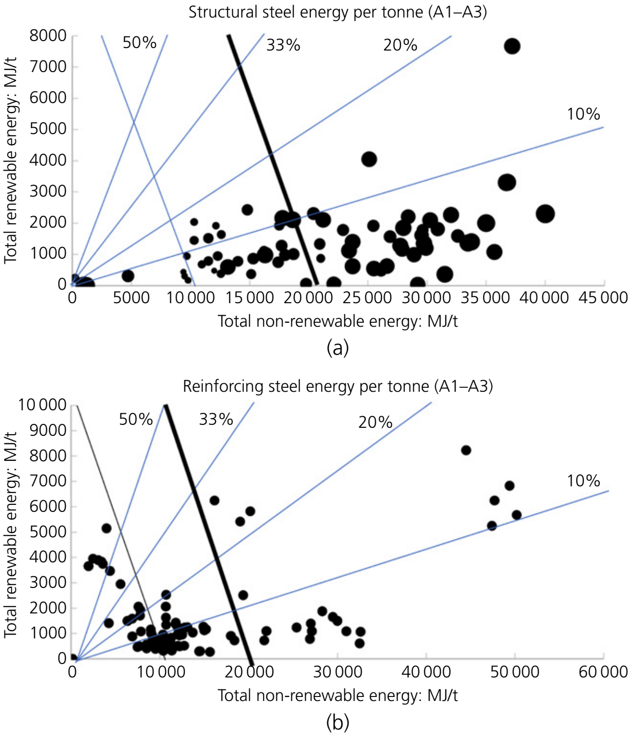


Figure 5. Renewable plotted against non-renewable energy (A1–A3) for the steel product sub-types (a) structural steel, (b) reinforcing steel showing percentage renewable energy and average primary energy demand (bold black line)

3.1.5 Renewable energy consumption and non-renewable energy consumption for steel

Results for renewable and non-renewable energy were then plotted on a graph as discussed in Section 2.3, shown in Figure 5. As can be seen, for structural steel, all of the EPD fall with renewable energy below 20%, and most below 10%. Those with 10–20% renewable energy are mainly those using less than the average total energy demand.

For reinforcing steels, there is a greater distribution, with some EPD having over 50% renewable energy. All of the EPD with over 33% renewable energy have less than 50% of the average energy demand, although there are several EPD with high energy demand and using between 10–20% renewable energy.

3.2 Cement – CEM I

3.2.1 Use of renewable energy generally for CEM I

The average use of renewable energy in CEM I cements is 15%, split equally between PERT and RSF. Six EPD used more than 25% renewable energy, two each from Sweden, New Zealand (82% renewable electricity grid) and Latvia (50% renewable grid). Two EPD had less than 2% renewable energy, from Italy (40% renewable grid) and Israel (5% renewable grid). There is considerable use of waste and secondary fuels derived from waste in the cement industry, with NRSF 16% of energy use on average. The percentage of renewable energy for all CEM I EPD is shown in Figure 2.

3.2.2 Relationship between use of embodied carbon and renewable energy (A1–A3) for CEM I

Figure 2 shows the relationship between embodied carbon and the percentage of renewable energy used. For CEM I, there is a trend for reduced embodied carbon impact as the percentage of renewable energy used increases.

3.2.3 Total energy consumption and embodied carbon (A1–A3) for CEM I

As discussed by Anderson and Moncaster (2020), there are significant differences in practice around the reporting of the use of secondary fuel sources – but the use of both renewable and non-renewable secondary fuels should be reported according to EN 15804 (CEN/TC 350, 2013). For this reason, and the high process carbon dioxide emissions from cement, there is not such a clear correlation between energy and GWP for CEM I ($R^2 = 0.05$), as shown in Figure 6.

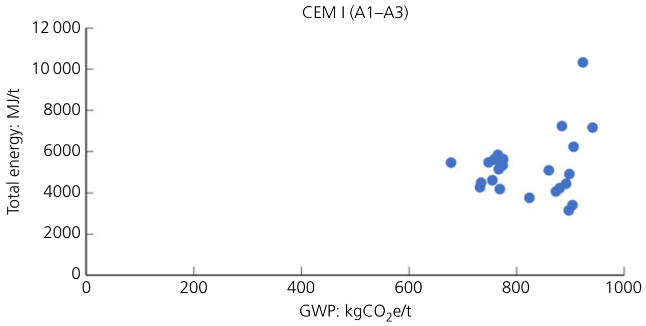


Figure 6. Total energy plotted against embodied carbon for CEM I

3.2.4 Total energy consumption and the percentage of renewable energy for CEM I

In Figure 7, when looking at the percentage of renewable energy, there is a slight reduction in primary energy demand with increasing percentage of renewable energy, but the correlation is not strong ($R^2 = 0.127$).

3.2.5 Renewable energy consumption and non-renewable energy consumption for CEM I

Figure 8 compares renewable and non-renewable energy as discussed in Section 2.3 and shows that those EPD with more than 10% renewable energy use almost all have below average energy use. Those with the highest energy use all have very low use of renewable energy (<10%).

3.3 Brick

3.3.1 Use of renewable energy generally for brick

Renewable primary energy accounts for 6.5% of energy use for bricks on average, and renewable secondary fuel accounts for nearly 9%, but for several products it is the major energy source. Non-renewable secondary fuel is hardly used. The percentage of renewable energy for all brick EPD is shown in Figure 2.

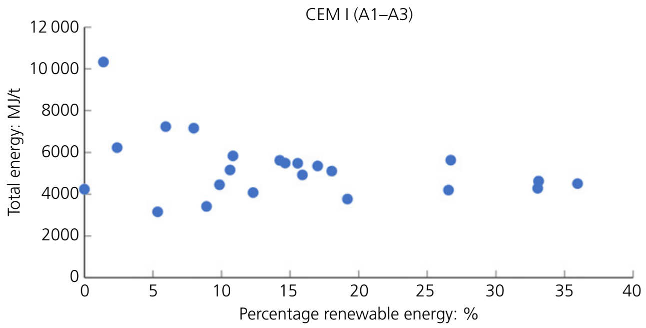


Figure 7. Primary energy demand plotted against percentage renewable energy for CEM I

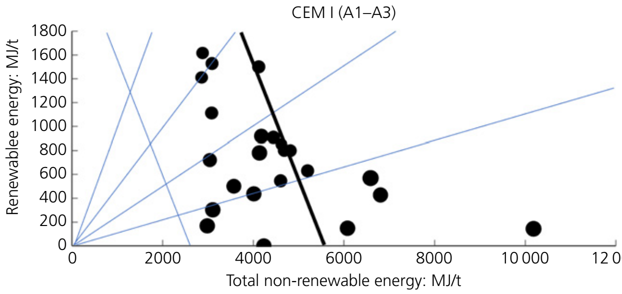


Figure 8. Renewable plotted against non-renewable energy (A1–A3) for CEM I showing percentage renewable energy and average primary energy demand (bold black line)

3.3.2 Relationship between use of embodied carbon and renewable energy (A1–A3) for brick

Figure 2 shows the relationship between embodied carbon and the percentage of renewable energy used. For all facing bricks, there is a trend for reduced embodied carbon impact as the percentage of renewable energy used increases; but for Ziegel bricks, there is no clear correlation between the two variables.

3.3.3 Total energy consumption and embodied carbon (A1–A3) for brick

Figure 9 shows the relationship between energy and embodied carbon. For both facing brick and Ziegel brick, there is a trend for increasing embodied carbon with increased energy consumption ($R^2 = 0.724$ for facing brick and $R^2 = 0.46$ for Ziegel brick).

3.3.4 Total energy consumption and the percentage of renewable energy for brick

Comparing total energy with the percentage of renewable energy used, Figure 10 shows that there is a slight increase in energy used with increasing renewable energy, although the correlation is low ($R^2 = 0.03$) for facing bricks, and a greater increase in energy used for Ziegel bricks gives a strong correlation ($R^2 = 0.628$).

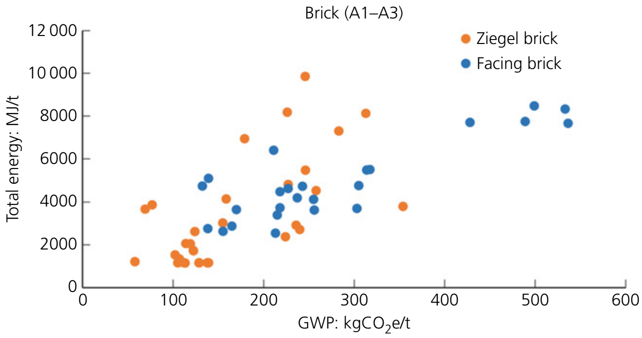


Figure 9. Total energy plotted against embodied carbon for the two brick product sub-types

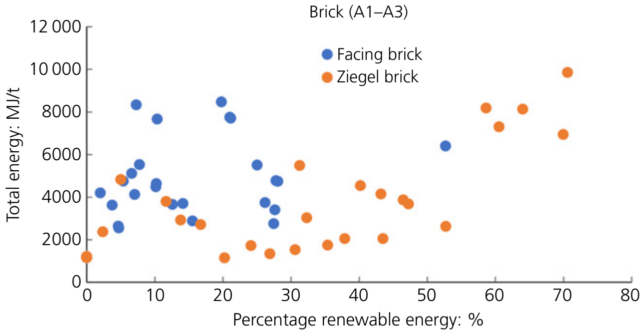


Figure 10. Primary energy demand plotted against percentage renewable energy for the brick product sub-types

3.3.5 Renewable energy consumption and non-renewable energy consumption for brick

Figure 11 shows the relationship between renewable and non-renewable energy, as discussed in section 2.3. For facing brick, the one EPD with over 50% renewable energy has greater than average energy use. For Ziegel brick, four of the EPD with over 50% renewable energy use have more than double the average energy use, with one EPD having over 70% renewable energy use, which has over three times the average energy use, although the remaining one has close to average energy use.

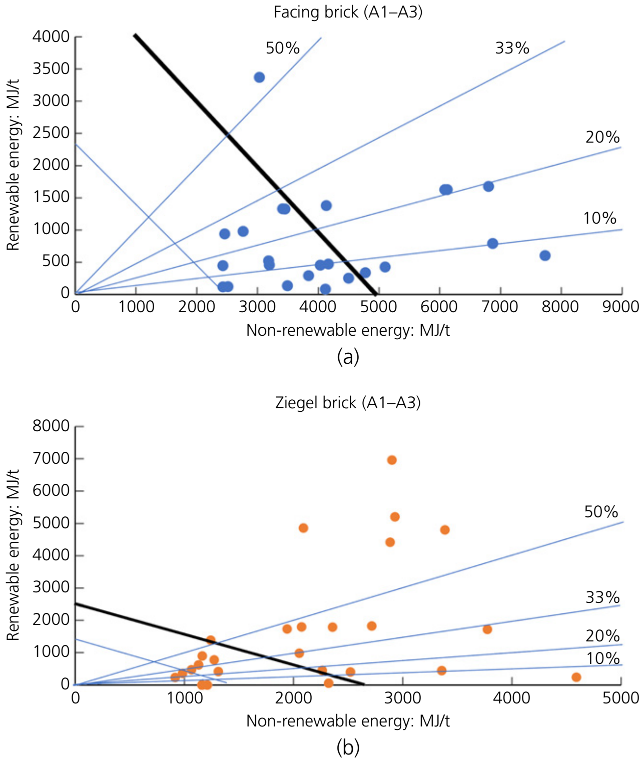


Figure 11. Renewable plotted against non-renewable energy (A1–A3) for the brick product sub-types (a) facing brick, (b) Ziegel brick showing percentage renewable energy and average energy demand (bold black line)

3.4 Timber

3.4.1 Use of renewable energy generally for timber

The use of renewable energy is more common in timber EPD, with averages of around 60% for sawn timber, 55% for CLT and LVL and 64% for glulam. For sawn timber, two products use significant amounts of renewable secondary fuel, but most use none (the average is less than 3%) and use of non-renewable secondary fuel is insignificant. The percentage of renewable energy for all timber EPD is shown in Figure 2.

3.4.2 Relationship between use of embodied carbon and renewable energy (A1–A3) for timber

Figure 2 shows the relationship between embodied carbon and the percentage of renewable energy used. For all product groups except Ziegel bricks, glulam, sawn timber and LVL, there is a trend for reduced impact of embodied carbon as the percentage of renewable energy used increases; for Ziegel bricks, glulam, sawn timber and LVL, there is no clear correlation between the two variables.

3.4.3 Total energy consumption and embodied carbon (A1–A3) for timber

As timber has renewable energy as feedstock, included as PERM, and non-renewable energy used for adhesives included as PENRM, only the resources used for energy have been considered in the analysis – in other words, the PERE, PENRE, RSF and NRSF results have been taken to give the total energy used for timber. The graphs have been split into those showing the results for the product sub-type, sawn timber, and those showing the engineering timber product sub-types, cross-laminated timber (CLT), glulam and laminated veneered timber (LVL).

3.4.4 Total energy consumption and the percentage of renewable energy for timber

Looking at Figure 12, there is not a very strong correlation for total energy used and embodied carbon owing to several outliers (e.g. $R^2 = 0.008$ for sawn timber, $R^2 = 0.07$ for CLT).

Figure 13 shows the relationship between total energy consumption and the percentage of renewable energy used. For all the products there is a slight trend to increased energy use as the percentage of renewable energy increases, but the correlation is low ($R^2 = 0.0524$ for sawn timber, 0.0966 for CLT and 0.112 for glulam (there are only two LVL EPD)). The trend is influenced by a couple products with the percentage of renewable energy over 80%, which have high total energy consumption in comparison with other products in their sub-group.

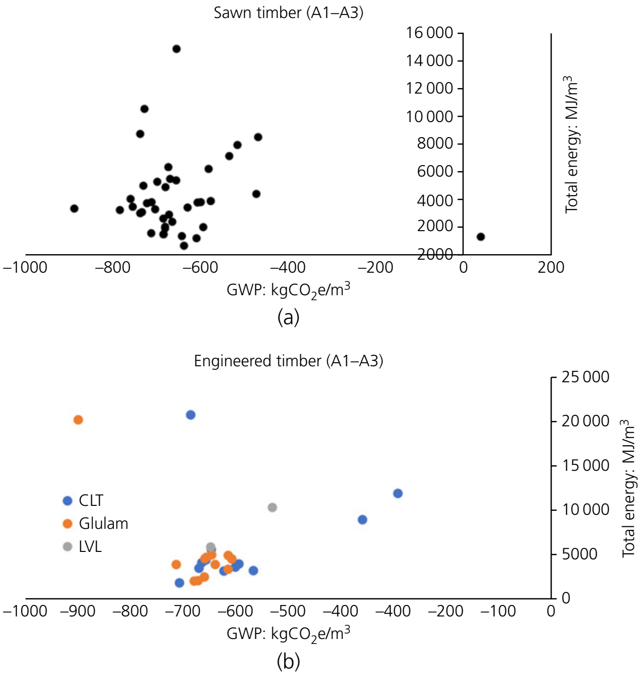


Figure 12. Total energy plotted against embodied carbon for the timber product sub-types: (a) sawn timber and (b) engineered timber

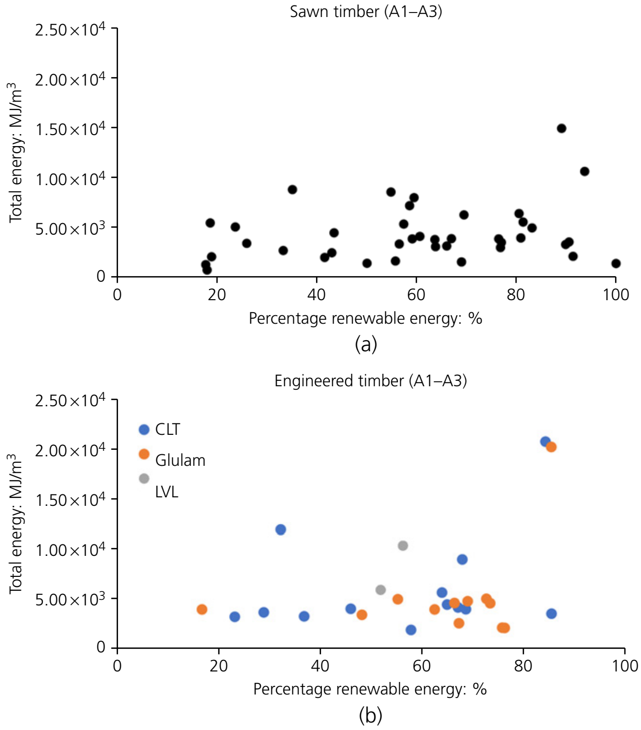


Figure 13. primary energy demand plotted against percentage renewable energy for the timber product sub-types: (a) sawn timber and (b) engineered timber

3.4.5 Renewable energy consumption and non-renewable energy consumption for timber

When looking at the relationship between renewable and non-renewable energy, as shown in Figure 14, 15 of the 19 products with energy consumption over the average use more than 50% renewable energy. Nine of the 12 products with renewable energy consumption below 33% have below average energy consumption. For both products groups, however, the greatest number of products is seen in the sector of the graph showing below average energy consumption and more than 50% renewable energy consumption.

4. Discussion of the results

4.1 Use of renewable energy (A1–A3)

Use of renewable energy varies considerably by product type. For BOF steels, use of renewable energy was generally low (average 7% and maximum of 22%); this is most likely as a result of the substantial barriers to reducing the carbon

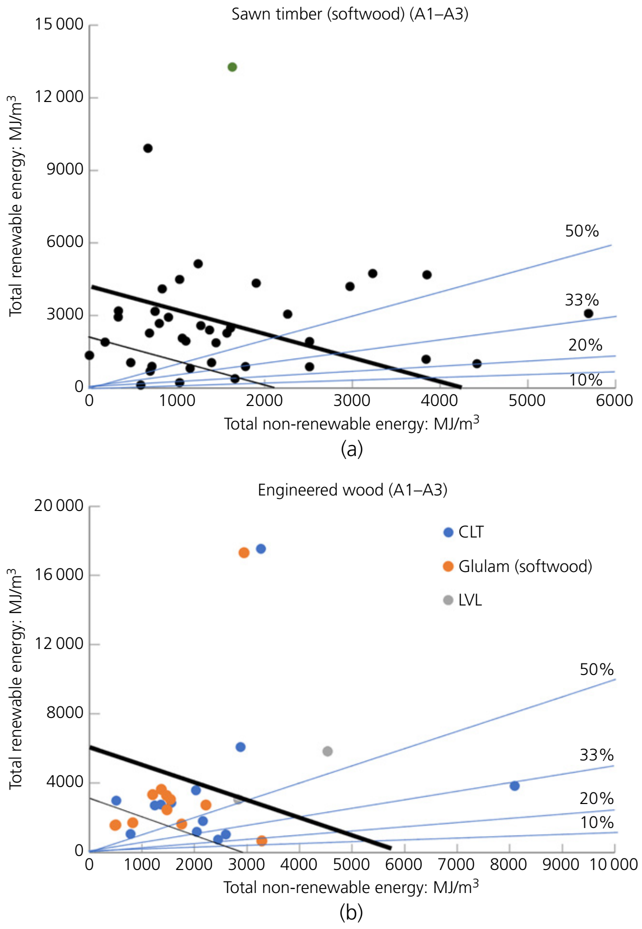


Figure 14. Renewable plotted against non-renewable energy (A1–A3) for the timber product sub-types (a) sawn timber (softwood), (b) engineered wood showing percentage renewable energy and average primary energy demand (bold black line)

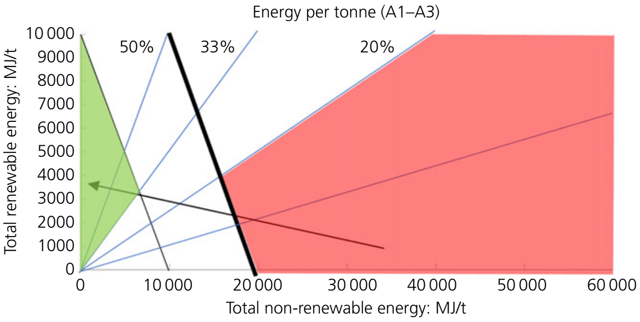


Figure 15. Example showing the common format of the type of graph used to distinguish between low-carbon products in terms of their embodied energy, and particularly their efficient use of renewable energy

dioxide emissions of BOF steel production, such as those highlighted by Griffin and Hammond (2019). For EAF steels, however, owing to the significance of electricity for EAF and the greater ease with which renewable electricity can be sourced, the average was 14% with a maximum of 65%, with very little use of renewable secondary fuels (RSFs) for either type of steel. For CEM I cement and both types of brick, renewable energy accounted for 15% of the energy used on average, and a maximum of 36% for CEM I, 52% for facing bricks and 72% for Ziegel bricks, with 50% of the renewable energy coming from RSFs for cement and nearly 60% for bricks. The cement industry in the UK has been using renewable secondary fuels such as meat and bone meal, processed sewage pellets and waste paper and wood for many years (MPA, 2008). Brick manufacturers in the UK were using 11% secondary material input in a similar time period (Smith, 2011) and some brick manufacturers in the UK have been capturing the landfill gas created from landfills within their clay quarries to generate electricity, – see, for example, Ibstock (2015). For timber, over 50% of energy on average came from renewable sources, with 64% for glulam, but very little was RSF. Saw mills, engineered timber and wood panel producers have used their own wood waste as a fuel for many years, often using CHP to provide both heat and power, and sourcing the remainder of their heat demand from timber; for example, in 2009, the European timber industry reported it sourced up to 75% of its energy from wood (CEI-Bois, 2009).

4.2 Relationship between embodied carbon and increased percentage of renewable energy (A1–A3)

For steel, CEM I, facing brick and CLT, there is a trend for reduced embodied carbon impact as the percentage of renewable energy increases – potentially this is due to the use of renewable electricity or renewable energy burnt with higher efficiencies, all with better ratios of energy delivered to primary energy. For Ziegel brick, sawn timber, glulam and LVL, there is, however, no correlation between the two variables. Potentially this is can be attributed to the use of renewable fuels with a higher delivered-to-primary energy ratio.

4.3 Relationship between total energy consumption and embodied carbon (A1–A3)

Both steel ($R^2 = 0.4/0.45$) and brick ($R^2 = 0.72/0.46$) showed a correlated relationship between increasing energy use and increased embodied carbon. For cement and timber, there was no strong correlation. This is likely to be due first to the higher use of renewable energy in timber products, as renewable energy is generally associated with lower carbon emissions, and second to the sequestered carbon for timber and the carbon dioxide emitted from calcination of cement, both of which significantly influence the embodied carbon results without having an impact on energy use.

4.4 Relationship of increased percentage of renewable energy and total energy consumption (A1–A3)

The hypothesis is that greater use of energy from renewable sources may be associated with a reduction in the efficiency with which energy is used, and this would result in increased energy consumption. For steel produced using BOF, there was no strong correlation found, but for EAF steels, there was a correlated ($R^2 = 0.4$) trend to reduced energy consumption with increased percentage of renewable energy used. For cement, a slight decrease in energy consumption with increased percentage of renewable energy used was found, but the correlation was low. Both brick and timber showed a slight increase in energy consumption with increasing percentage of renewable energy used – the correlation was strong for Ziegel bricks ($R^2 = 0.63$), but low for the other products.

It is concerning that both brick and timber show increased energy consumption with increased use of renewables, because in order to reduce carbon dioxide emissions (decarbonize), these industries are going to need to move to significantly greater use of renewable energy. The timber industry uses significant amounts of timber for energy and those in the brick industry using more renewable energy use significant amounts of waste-derived secondary fuel (see Section 4.1). There is perhaps a perception that both because energy derived from wood is seen as 'carbon neutral', and because waste-derived energy does not have a financial cost, there is no need to consider the efficiency with which these energy sources are used, as there would be with fossil fuel-derived energy. In fact, wood-derived fuel is not carbon neutral: the Department for Environment, Food and Rural Affairs' (DEFRA's) greenhouse gas conversion factor for wood chip is 6.5 g CO_2e/MJ, and for wood pellet is 14.7 gCO_2e/MJ compared to 66 g CO_2e/MJ for natural gas (BEIS and DEFRA, 2021).

4.5 Relationship between renewable and non-renewable energy use (A1–A3)

For steel, most EPD showing high use of renewable energy (>33% for reinforcing steel and >50% for structural steel) had below average energy consumption. For cement, almost all of the EPD with >10% renewable energy had below average energy consumption. For brick, most of the EPD with >50% renewable energy had very high energy use. For timber, except for two sawn timber EPD, all of the EPD with above average energy consumption used >33% renewable energy, 14 of the 18 used >50% renewable energy. These findings are similar to those highlighted in 4.4 again suggesting the likelihood that renewable energy resources in these product sectors are not being used efficiently.

4.6 Action for specifiers

To support the transition to net zero, specifiers must not only select products that have reduced embodied carbon, but also look to find products that achieve this without using renewable energy inefficiently. In particular for timber and bricks, where evidence was found that increased use of renewable energy is associated with higher embodied energy, specifiers are recommended to address this first by demanding EPD for the products they consider so they can review their environmental performance, particularly with regard to embodied carbon in view of the need to achieve net zero. After initially selecting products with lower embodied carbon for their chosen specification (where products have a common declared unit and are functionally equivalent as the comparison rules in EN 15804 require ((CEN/TC 350, 2019)), they should identify the location of the products on the relevant graph (Figure 5 for steel, Figure 8 for cement, Figure 11 for brick and Figure 14 for timber) showing the relationship of non-renewable and renewable energy (note that each graph has a different axis scale and range). The zone of the graph coloured red in Figure 15 indicates products that have above average primary energy use, and less than 20% renewable energy and over 80% non-renewable energy use – these products are therefore likely to have high embodied carbon. The zone of the graph coloured green in Figure 15 has at least 33% renewable energy use, and below average primary energy use – these products are therefore likely to have low embodied carbon. Where possible, it is recommended that the low-carbon, energy-efficient products located in the equivalent zone of the graph coloured green in Figure 15 are selected over products in the equivalent zone of the graph coloured red to ensure that products are selected that are low in carbon, produced efficiently in relation to their embodied energy and have higher proportions of renewable energy.

5. Contribution of the findings to the field and potential applications

In this paper, the use of renewable and non-renewable energy in the manufacture of key construction materials has been evaluated through the analysis of EPD published in the last 5 years. The analysis identifies any current trends or relationships between the variables – embodied carbon, embodied energy, renewable and non-renewable energy use, as well as secondary fuels. As industry transitions to net zero over the next 30 years, it will be important to check not only that products have low embodied carbon, but also that they use low-carbon sources of energy, such as renewables and nuclear energy, efficiently, so that no excessive demand is placed on their capacity, because this will hinder the transition. This study thereby provides a mechanism for identifying those products that use both embodied energy and renewable energy efficiently, while reducing embodied carbon emissions. In the future, it should provide a useful resource for benchmarking the progress that the construction materials industry has made towards decarbonisation.

Acknowledgements

The authors would like to acknowledge the Open–Oxford–Cambridge Arts and Humanities Research Council (AHRC grant number AH/R012709/1) Doctoral Training Partnership for funding J.A.'s research and supervision by A.M. The authors are grateful to the consortium of Green Building Councils who provided additional funding for collection of data as part of the Life Level(s) project funded by the European Union (https://lifelevels.eu), and to Julia Barnard who assisted in collecting and tabulating initial data from EPD for structural products other than cement. The authors would also like to thank the Whitbybird Foundation for funding the initial analysis of cement and concrete EPD.

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