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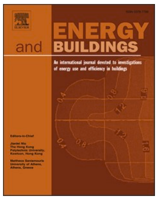

# Embodied impacts of key materials for UK decarbonised domestic retrofit: Differences between sources of embodied carbon and embodied energy data

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ABSTRACT

Low energy domestic retrofit consumes materials, such as insulation, membranes and glazing, with smaller quantities of structural timber, steel or concrete, which have associated embodied impacts from resource extraction, manufacture and end-of-life treatments. In retrofit design, coefficients for material embodied impacts vary widely between sources and can lead to different results in a life cycle energy or carbon analysis, and perhaps different material choices in retrofit implementation. This paper considers how and why results differ between sources, and whether such data is suitable for making climate-beneficial design decisions. Embodied energy and carbon coefficients for 18 key retrofit materials were obtained from two widely used LCA databases and their similarity was quantified. The data collected illustrates that 70% embodied energy and embodied carbon data is within 20%, but that 30% of data was more than 20% different. Consistency of product naming and the absence in the datasets of key retrofit materials are factors identified contributing to variation, and present real constraints in practice. Furthermore, this exercise showed that embodied impacts for the types of materials most prominent in retrofits are less-well characterised than other major construction materials, and presents another layer of uncertainty. The data showed embodied energy was more consistent between sources than embodied carbon. This raises doubts about the predominant use of embodied carbon over energy for such analyses and establishes that a focus on embodied carbon over embodied energy has less power to reduce greenhouse gas emissions than considering both metrics together. It is concluded that obtaining such data with confidence is challenging and requires expertise in LCA, and is therefore unlikely to be accessible to most retrofit designers. Datasets need to be more complete and offer higher confidence to ensure delivery of high quality and meaningful results for climate-beneficial design decisions.

## 1. Introduction

There is an urgent need to reduce energy demand in UK homes. The domestic housing stock is responsible for 26 % of the UK's energy consumption [1], predominantly for space heating and hot water, and yet progress in decarbonising the electricity grid has masked a stagnation in energy demand reduction [2]. However, because electrification of heating is in competition with electrification of transport, improving the thermal efficiency of housing stock through deep retrofit is considered a necessity [3].

Low energy retrofit offers a complimentary approach to decarbonisation of energy supplies. Fabric-first retrofit presents an attractive option for many homes because it offers additional benefits over simply decarbonising the energy supply; namely improved comfort, and reduced energy bills. Especially pertinent in recent years as UK occupants face extraordinary rises in energy prices, the energy bill reduction brought about by reducing energy demand (and therefore carbon emissions) through improved thermal efficiency will be locked-in, whereas decarbonising the energy supply in isolation may leave occupants exposed to energy price volatility.

Current estimates suggest that 26 million domestic retrofits will be required in the UK in order to reduce carbon emissions from dwellings

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*Abbreviations:* LCA, Life Cycle Analysis; EE, Embodied Energy; EC, Embodied Carbon; GHG, Greenhouse Gas; $CO_2e$, Carbon dioxide equivalent; WLC, Whole Life Carbon; RICS, Royal Institution of Chartered Surveyors; ICE Database, Inventory of Carbon and Energy Database; BSRIA, The Building Services Research and Information Association; BECD, Built Environment Carbon Database.

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and meet the Paris Climate Change targets [3]. These must take place concurrently with an estimated nearly 6 million new build dwellings,[1] as well as new construction in other sectors such as commercial, public buildings and infrastructure. However, all new construction and the installation of new materials for retrofits comes with an embodied energy (EE) and embodied carbon (EC) investment, i.e. those impacts associated with the resource extraction, manufacture, and end-of-life waste disposal [4,5,6,7,8]. The definition of embodied energy varies from source to source, but for the avoidance of doubt, a comprehensive definition for the context of retrofit is proposed as "the energy used for extraction and processing of raw materials, manufacturing, construction, maintenance and refurbishment, decommissioning and end-of-life waste processing, all transport of materials at any stage of the life cycle, and the feedstock energy embedded in the construction materials" [9]. Embodied carbon (as carbon dioxide equivalent, $CO_2e$) on the other hand relates to the carbon dioxide and other greenhouse gas (GHG) emissions (methane, nitrous oxide, industrial gases) associated with those same life cycle stages. These originate from both fuel combustion for energy, as well as other emissions from industrial and agricultural processes, deforestation, landfill etc [10].

Embodied energy and carbon analyses offer insight into the whole-life-cycle impacts of a construction project. A Life-Cycle Analysis (LCA) may be used to assist in determining the extent of, and material choices for a retrofit or building design [11,12,13]. Whole-life carbon (WLC) is of growing interest in construction [14], and industry is slowly beginning to adopt LCA, with several industry bodies now issuing guidance documents; for example RICS 'Whole life carbon assessment for the built environment, 1st edition' [15], RIBA 'Embodied and Whole Life Carbon Assessment for Architects' [16], LETI 'Embodied Carbon Primer' [17] and UKGBC 'Net Zero Whole Life Carbon Roadmap' [18], and the Built Environment Carbon Database has recently been launched as a central place to upload and access WLC data[2] [19]. However in spite of this emerging interest in practice, and contrary to a concerning confidence in industry that methodologies for LCA are already robust [20], Moncaster et al. [20] and Hoxha et al. [21] show that the differences in LCA impact arising from methodological choices and material impact uncertainties can be higher than the impact of different building designs using the same method. In the case of domestic retrofit, where the objective is to reduce the operational energy or carbon of an existing building, the margins for operating energy reduction and the physical constraints of the existing building may indicate use of specific materials, and yet the achievable operating energy savings may be offset by the associated embodied impacts, which could be detrimental in the context of climate change. An existing body of literature addresses the high levels of uncertainty associated with embodied carbon coefficients [20,21,22,23,24,25]; in the context of retrofit, these uncertainties may be exacerbated due to the bulk of materials in use being more poorly characterised than those which dominate new build construction projects. The Authors' previous work has shown that the relationship between embodied energy and operating energy in low energy domestic retrofits is not well understood [9].

There is an extensive and growing body of literature relating to embodied impacts of construction materials and new buildings [20,25]. According to Minunno et al. [26] there is an emphasis in the embodied energy and carbon literature on concrete, reinforcement bars, steel and timber. These heavy-weight, structural materials make the largest contributions to the life cycle impacts in many studies [20,21,23], with Marsh, et al. [23] reporting itemised structural materials which sum to 70 % of product stage embodied carbon (excludes windows, doors and insulation). In typical life-cycle studies, a practitioner adopts a principle of capturing the major impacts, but may omit particular items on the bill of quantities on the basis of them contributing negligibly to the embodied impacts. This means that in some studies, the recorded impacts are limited to those arising from the main structure [20]. RICS has published well-regarded industry guidance on LCA and allows this limit to be drawn at 95 % of total costs [15]. This is an important point, since issuing such guidance enables LCA studies to proceed without becoming overly burdened by the necessity of data completeness and captures the vast majority of the major contributions in new buildings. Nevertheless, the literature focusing on retrofit is very much more limited [9]. By comparison to new construction, retrofits are characterised by light-weight materials, such as insulation and membranes, as well as glazing, and then internal finishes. Therefore, the usual assumption that the dominant materials will be heavy structural elements would lead to inaccurate findings. Moreover, if the materials dominant in retrofit are either more poorly characterised, or have high uncertainties, the embodied impacts of these retrofits remains highly uncertain. With 26 million retrofits to undertake in the UK alone, and the vast material requirements implicated for these, it is imperative that the embodied impacts of these can be well understood, provide transparent and comparable results, and be simple enough to calculate for practitioners to adopt into their design process.

As a parallel consideration, the ideal metric for measuring life cycle impacts, whether embodied energy or carbon, is also unclear. Whilst both metrics have advantages, both also have limitations which are not necessarily acknowledged or realised amongst those reporting or using them, and which may further compromise the usefulness of a study. At a fundamental level, reporting only embodied carbon can disguise the inefficient use of energy resources, limiting the amount of decarbonised energy which is then available to other uses. Also, embodied carbon is spatially and temporally transient, varying with the carbon intensity of the grid and therefore also the power supply, which makes it difficult to ascribe a representative value, whilst embodied energy is static. Nevertheless, embodied carbon arguably better represents environmental impact and GHG impacts. But whether embodied energy or carbon better serves the needs of an LCA for the design of low energy retrofits is unresolved.

To contribute to these areas of knowledge, key materials associated with typical retrofits in the UK are investigated. This paper specifically explores two different sources of embodied energy and carbon ($CO_2$ equivalent) data with a focus on retrofit. Ecoinvent data, a subscription product accessed with SimaPro, is regarded as one of the most comprehensive life cycle datasets globally. The comparator, the ICE database (The Inventory of Carbon and Energy), is a free, UK-focused dataset of building materials, assembled by Circular Ecology; The version used was published by BSRIA in 2011 [27]. It has been reported previously that there is a wide range of data for LCA and embodied carbon studies, which can result in highly variable decisions and designs [20,22]. This paper considers how if a retrofit practitioner was to use these two datasets, how and why their results might differ, and whether these tools are suitable for use by retrofit and building designers for the purposes of mitigating the climate change impact of their designs. Moreover, in a more recent version of the ICE database, V3.0 released in 2019, ICE's authors have chosen to omit embodied energy from this, citing that embodied energy is "not typically assessed as part of modern studies. Embodied carbon is considered as a more useful indicator" [28]. This statement is considered by the present authors, and is also discussed in this paper.

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[1] If an average of 176,000 new homes are built every year between now and 2050. 176,000 is the 90th%ile of the total new dwelling completions in England between 2002 and 2021 [47], scaled based on the England to UK population ratio.

[2] In the BECD, of the limited number of unique records accessible (n=71), many of these related to road infrastructure (n=45), several others were not UK-based, and several others were tagged with "test"; therefore the number of relevant building-related assets recorded was unclear, estimated to be between 10 and 20.

## 2. Method

A simple comparison of materials commonly used in retrofit was undertaken in order to explore the variability between two sources and highlight any issues which a practitioner may encounter when undertaking their own analysis. A range of materials appropriate to domestic retrofit was selected from the ICE database, as detailed in Table 1, to be cross-checked against a second data source; Ecoinvent data. The 18 materials represent examples (but not an exhaustive list) of plausible materials which may be deployed in various quantities in a whole-house deep retrofit. Insulations feature prominently in this list, which includes natural, fossil- and mineral-derived products, and includes insulants which may be used either in floors, walls or roofs. Polypropylene and polyethylene are included for their use in damp-proof membranes, as well as in technical wind- and air-tight membranes required to protect highly insulated structures. Timber, sand, lime, plasterboard and steel feature as rather general building materials which may be used in varying quantities for making-good, or small-scale structural adjustments, as well as support structures and matrices for other insulation. Finally, cement panels/slate and ceramic tiles are included as representative of some exterior cladding systems (common for external wall insulation), or roofing materials. The approach taken in this study was deliberately simple in order to reflect how these datasets may be used in practice.

For these materials, both embodied energy and embodied carbon data were recorded (in this study embodied carbon refers to embodied carbon equivalent or global warming potential, not just $CO_2$ emissions) using energy data from ICE DB V2.0 [27], and the most recent carbon data from ICE DB V3.0. For comparison, similarly named materials were identified using Simapro and Ecoinvent data (version 3.4). Embodied energy and embodied carbon data were derived based on 1 kg of that material using the in-built methods "Cumulative Energy Demand V1.10 / Cumulative energy demand" and "IPCC 2013 GWP 100a V1.03″,[3] and for all three system models ″Allocation at point of substitution“, ″Allocation cut off by classification“, and ″Consequential“. The values derived from Ecoinvent (allocation cut off by classification) and ICE data were compared using simple numerical analysis, determining a "similarity rating" as per Equation **(1)**: *1- relative difference* (always relative to the maximum of Ecoinvent or ICE). This provided a normalised set of values between zero and one for identifying those which were most similar (one) or dissimilar (zero).

$$\textit{\textbf{similarity rating}} = 1 - \frac{|\boldsymbol{x}-\boldsymbol{y}|}{\mathbf{max}(\boldsymbol{x},\boldsymbol{y})} \tag{1}$$

For example, using mineral wool from Table 1, the similarity rating for embodied energy is derived as follows;

$$\begin{aligned}\text{Similarity rating for EE Mineral wool} &= 1 - |EE_{ICE} - EE_{Ecoinvent}|/\max(EE_{ICE}, EE_{Ecoinvent})\\ &= 1 - |16.6 - 17.3|/\max(16.6, 17.3).\\ &= 1 - 0.7/17.3.\\ &= 0.960\end{aligned}$$

If a suitable or obvious comparator to the ICE dataset material was not found in the Ecoinvent dataset, a similar sounding material, or sometimes more than one, was selected. This process is considered to be representative of how a practitioner might select products for their analysis. In the numerical analysis, a comparison was made between each of the materials, resulting in some of the materials having more than one score. The full names of each material are recorded in Table 1.

## 3. Results

Table 1 presents embodied energy and carbon data for the 18 materials collected from the ICE and Ecoinvent datasets, alongside the "similarity rating". This analysis, whilst not quantitative in relation to the material quantities used in a particular retrofit, is indicative of the issues surrounding data selection for LCA. Embodied energy and carbon data, in MJ and $kgCO_2e$ per kg, ranged widely according to the material in question. The similarity ratings determined from these values ranged between nearly one (very similar) to as low as 0.03 (very different) but without an obvious correspondence between the embodied energy and embodied carbon datasets. The data is explored further in Fig. 3.1, which shows the cumulative relative frequencies of the similarity ratings between materials in the ICE and Ecoinvent datasets for embodied energy and embodied carbon; if two datasets are very similar, the area under the curve would be expected to be minimal. This provides a visual quantification of how similar the two data sources are in relation to either embodied energy or embodied carbon. The embodied energy line shows a slow rate of increase from 0 to 0.85 followed by a steep increase up to 1. The embodied carbon line shows a flat line up to 0.35 followed by a slow increase up to 0.8, and then a steep increase up to 0.95 where it reaches a maximum. This illustrates a wider range in the magnitude of differences in embodied energy (the minimum recorded similarity rating being lower), but also a tendency for the embodied energy data to be overall more similar than the embodied carbon data (more of the data has a higher similarity rating for embodied energy than for embodied carbon). Fig. 3.1 shows that 75 % of the embodied energy data has a similarity rating of $\geq 0.85$, indicating that there is only up to 15 % difference between the large majority of the materials studied in these datasets. On the other hand, it shows that less than half (45 %) of the embodied carbon data has a similarity rating of $\geq 0.85$, and therefore that the majority of the embodied carbon data is more than 15 % different. It also illustrates that none of the embodied carbon pairs had a similarity rating of $> 0.95$, whereas 40 % of the embodied energy pairs did.

At the low end of the curve, none of the embodied carbon data was as different as the most different embodied energy data; the embodied energy for cork was 4 MJ/kg in ICE compared to 118 MJ/kg in Ecoinvent, nearly 30 times higher. The next most dissimilar records for embodied energy were timber (0.267), sand (0.435), and then fibreglass (glasswool)/glass wool mat (0.596) and polypropylene (0.757). For embodied carbon, the most dissimilar were high impact polystyrene/extruded polystyrene (0.351), sand (0.421) and timber (0.462), then polypropylene (0.595) and steel (0.730). 15 % of all materials had a similarity rating for embodied energy lower than 0.5, indicating that values between the datasets are a factor or two or more different, and this figure rises to 18 % of materials for embodied carbon.

These results indicate that on the whole, embodied carbon data is more variable between these two sources than embodied energy. Whilst it is acknowledged that these percentages are a function of the sample of materials chosen, and these figures are not weighted to the proportions

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[3] Timber data was converted to /kg using CIBSE Guide A softwood average timber density 563kg/$m^3$.

**Table 1**
Embodied energy and carbon data for various materials from ICE database and Ecoinvent. The final columns include a numerical indicator of similarity, with 1 being identical, 0 being very different; colour shading shows those which are most similar (pale) and dissimilar (dark). Records in column 1 marked with a * indicate a record from ICE which has been repeated for comparison against more than one material in the Ecoinvent dataset. Blank cells indicate that no suitable data was identified.

| Material | | Embodied Energy (MJ/kg) | | Embodied Carbon ($kgCO_2e/kg$) | | Similarity Rating (from Eq.1) | |
|---|---|---|---|---|---|---|---|
| **ICE name** | **Ecoinvent name** | ICE | Ecoinvent | ICE | Ecoinvent | EE | EC |
| *High impact polystyrene | Extruded Polystyrene {GLO} | 87.4 | 102 | 3.42 | 9.74 | 0.857 | 0.351 |
| | Polystyrene high-impact {GLO} | 87.4 | 89.5 | 3.42 | 3.74 | 0.977 | 0.914 |
| General purpose polystyrene | Polystyrene, general purpose {GLO} | 86.4 | 89.2 | 3.43 | 3.76 | 0.969 | 0.912 |
| Polyurethane Rigid Foam | Polyurethane rigid foam {RER} production | 102 | 102 | 4.26 | 4.5 | 0.995 | 0.947 |
| Polypropylene, Orientated Film | Polypropylene, granulate {RER} | 99.2 | 75.1 | 3.43 | 2.04 | 0.757 | 0.595 |
| General polyethylene | Polyethylene, low density, granulate {GLO} | 83.1 | 80.8 | 2.54 | 2.27 | 0.972 | 0.894 |
| Fibre cement panels - uncoated | Fibre cement roof slate {GLO} | 10.4 | 10.7 | | 0.967 | 0.972 | |
| Ceramics - Tiles and cladding panels | Ceramic tile {GLO} | 12 | 12.9 | 0.78 | 0.861 | 0.930 | 0.906 |
| Timber - sawn softwood[4] (EE); Timber softwood, no carbon storage[5] (EC) | [3]Sawnwood, softwood, raw, dried (u=20%) {RER} \| market for | 7.4 | 27.7 | 0.263 | 0.121 | 0.267 | 0.462 |
| *Cork | Cork slab {GLO} | | 153 | | 1.89 | | |
| | Cork, raw {GLO} | 4 | 118 | | 0.0573 | 0.0339 | |
| *Lime (general) | Lime, hydrated, loose weight {RoW}\| market for lime, hydrated, loose weight | 5.3 | 5.19 | 0.78 | 0.934 | 0.979 | 0.835 |
| | Lime, hydrated, loose weight {RoW}\| production | 5.3 | 4.75 | 0.78 | 0.906 | 0.896 | 0.861 |
| | Lime hydraulic {RoW}\| production | 5.3 | 5.09 | 0.78 | 0.919 | 0.960 | 0.849 |
| Fibreglass (glasswool) | glass wool mat {GLO} | 28 | 47 | | 2.86 | 0.596 | |
| Rockwool | rock wool {glo} market for | 16.8 | | 1.12 | | | |
| Mineral wool | stone wool {glo} market for stone wool | 16.6 | 17.3 | 1.28 | 1.36 | 0.960 | 0.941 |
| General gypsum plaster | Stucco {GLO} | 1.8 | 1.53 | 0.13 | 0.104 | 0.850 | 0.800 |
| Plasterboard | Gypsum plasterboard {glo} market for | 6.75 | 5.77 | 0.39 | 0.42 | 0.855 | 0.929 |
| Sand (general) | Sand {GLO} market for | 0.081 | 0.186 | 0.0051 | 0.0121 | 0.435 | 0.421 |
| *Steel, general UK average recycled content | Steel, unalloyed {GLO} | 20.1 | 21.5 | 1.46 | 2 | 0.935 | 0.730 |
| | Steel, low-alloyed {GLO} | 20.1 | 21.5 | 1.46 | 1.75 | 0.935 | 0.834 |
| Steel, coil (sheet) galvanised, uk(EU) average recycled content | No comparable records identified | 22.6 | | 1.54 | | | |

of materials used in a retrofit, these materials nevertheless represent a random sample of commonly used building materials and highlight the potential challenges associated with data selection for a retrofit LCA. The direction of the difference is not captured by the similarity rating, however the values in Table 1 show the majority of the records to be higher for Ecoinvent data, for both embodied energy (Ecoinvent 13; ICE 7) and carbon (13; 4). The exceptions to this are embodied energy data from ICE is higher for all three lime records, plasterboard, general gypsum plaster, polypropylene and polyethylene. ICE embodied carbon data is also higher for plaster, polypropylene and polyethylene, as well as timber.

## 4. Discussion

The possible reasons for discrepancies between the data sources are numerous and sometimes complex, and relate to factors including the physical similarity of the materials being compared, how specific properties of a material are accounted for, the geographical origin of the data, and the methods and boundaries of the life-cycle studies behind the data. It is acknowledged that some variation is attributable to genuine variability between products with the same characteristics but perhaps different manufacturing processes, geographies and origins [29]. However variation associated with uncertainty, or arising from methodological difference means that data between sources is not fairly comparable, and this opens up questions about data suitability and representativeness, but also about whether the data available is serving the needs of the analysis it is being used for. There is an additional question however, pertaining specifically to how the variation in embodied energy between the data sources is different to the variation in embodied carbon between these same sources. This emphasises a need to scrutinise which metric offers the best insight for evaluating life-cycle impacts of retrofit projects.

### *4.1. Sources of variation between the datasets*

#### *4.1.1. Naming and material data absences*

Firstly the naming of the materials is sometimes ambiguous, which could lead to inaccuracies in material choices for the analysis. Neither dataset includes a detailed description of the materials, and often, different names are given for materials which are ostensibly the same. They have either generalised or been very specific, have used slightly different terminology, or an obvious comparator is entirely absent. For

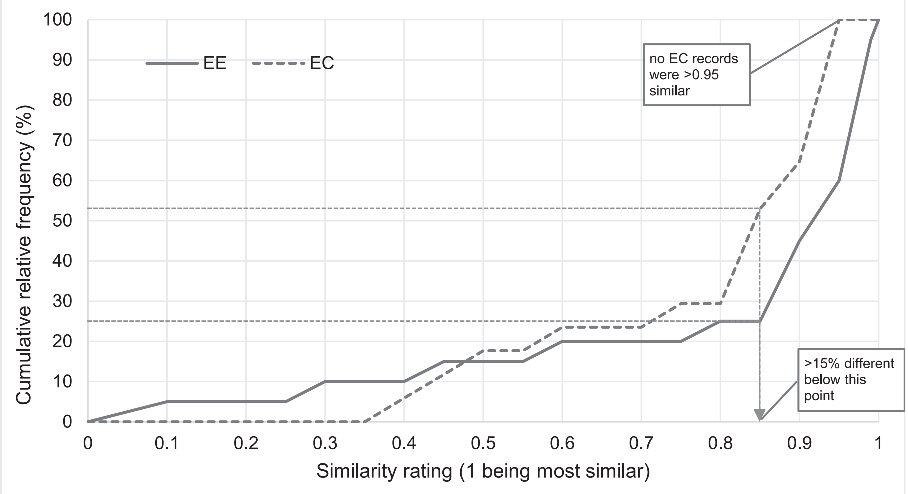

**Fig. 3.1.** The cumulative relative frequencies of the similarities in data pairs of embodied energy (EE) and embodied carbon (EC) values taken from the ICE and Ecoinvent datasets, based on 18 materials and their variants.

example "lime (general)" versus hydrated or hydraulic lime or (especially confusing in this case) a record was found for simply "lime"; this record for "lime" was later removed from the analysis since it was apparent that it may have referred to agricultural lime, not lime for construction, which is an inherently different material, and yet this was not explicit in the documentation. Other examples included: "general gypsum plaster", "base plaster", "plasterboard" and "gypsum plasterboard"; "mineral wool", "Rockwool", "rock wool" and "stone wool", which whilst similar in application and appearance to, are quite different in their embodied energy and carbon values to "fibreglass (glasswool)" and "glass wool mat"; "steel, general UK average recycled content", vs "steel, unalloyed" or "steel, low-alloyed"; whilst for "steel, coil (sheet) galvanised…" no records containing the term "galvanised" could be found in Ecoinvent. There were other notable absences from both data sources, for example no suitable records were identified for sheep's wool or polyisocyanurate (PIR) insulation (this may be included within "polyurethane", but there was nothing to indicate this was the case). Whilst this analysis is discussing the comparison of materials between two data sources as an academic exercise, in practice this challenge of semantics and nomenclature translates into the life cycle analysis for any construction project and presents a genuine barrier to the pursuit of legitimate, accurate and useful data. It seems obvious to state that if a material cannot be found within the data source by the name it is known by, representative values for its embodied energy or carbon cannot be deployed into the analysis. The analysis may proceed with a surrogate value for a similar-sounding material which has no certain basis in reality, or the analyst must pursue alternative sources of data, which will almost certainly be very time consuming, and may still bear little in the way of suitability or valid methodological background to the other data being deployed.

A good example from Table 1 is the ICE record for "fibreglass (glasswool)" in the category of "insulation": several search terms were used to find a comparable record in Simapro including "fibreglass", "glasswool", "glass wool", "fibre glass", "fiber glass", "glass fibre" and "glass fiber". Only the terms "glass wool" and "glass fibre" returned any results, and of the results returned, the most suitable records were "glass fibre" and "glass wool mat". Initially the record "glass fibre" was selected for comparison, and given that the words are the same, albeit in a different order, it would seem plausible that the material being described is the same, however on closer inspection, the record "glass fibre" sits within the category of glass, and so may in fact refer to the filamentous glass used as a reinforcing material in resins etc. The alternative record of "glass wool mat" sits within the category of construction > insulation, (even though this is not terminology likely to be used in the UK industry, which tends to use roll, blanket, batt, slab or sheet) and so was selected for the comparison, however the embodied energy (47 MJ/kg) is more different to the ICE record (28 MJ/kg) than that of "glass fibre" (39.7 MJ/kg).

A similar ambiguity arose with records for plaster. The ICE record for "general gypsum plaster" was taken to mean the loose-powder style plaster which is mixed with water and applied to walls with a trowel to create a smooth finish for decorating, commonly used in the UK. A suitable record for comparison was sought in the Ecoinvent dataset, the results for which are summarised in Table 2. In order to obtain the detail regarding the composition of these materials the network diagrams had to be generated and analysed, an example excerpt of which is shown in Fig. 4.1. None of the materials found in SimaPro with the search terms "gypsum" or "plaster" seemed suitable, yet "stucco", identified only

**Table 2**

Search results containing the term "plaster" using the Ecoinvent database in SimaPro when seeking a comparator for ICE record "general gypsum plaster" (EE 1.8 MJ/kg; EC 0.13 $kgCO_2e/kg$).

| | Embodied energy MJ/kg | Embodied Carbon ($kgCO_2e/kg$) | Material inputs as identified in the SimaPro network diagram | Comments on suitability as a comparator for "general gypsum plaster" |
|---|---|---|---|---|
| Gypsum plasterboard | 5.77 | 0.42 | Folding box board; stucco | Plasterboard cannot be applied wet; commonly requires a finishing skim coat of wet plaster. |
| Thermal plaster, outdoor; | 8.87 | 0.894 | Portland cement; lime; polystyrene foam slab; | First impression was this was thermally setting plaster, actually looks to be thermally insulating plaster with polystyrene backing board. |
| Base plaster | 1.95 | 0.277 | Portland cement; silica sand | Gypsum plaster does not usually contain Portland cement |
| Cover plaster, mineral | 1.83 | 0.156 | Lime; silica sand; stucco | Would not expect plaster to contain lime. |
| Stucco | 1.53 | 0.104 | Gypsum, mineral | Likely most suitable comparison, but stucco is a word rarely used in the UK in this application. |

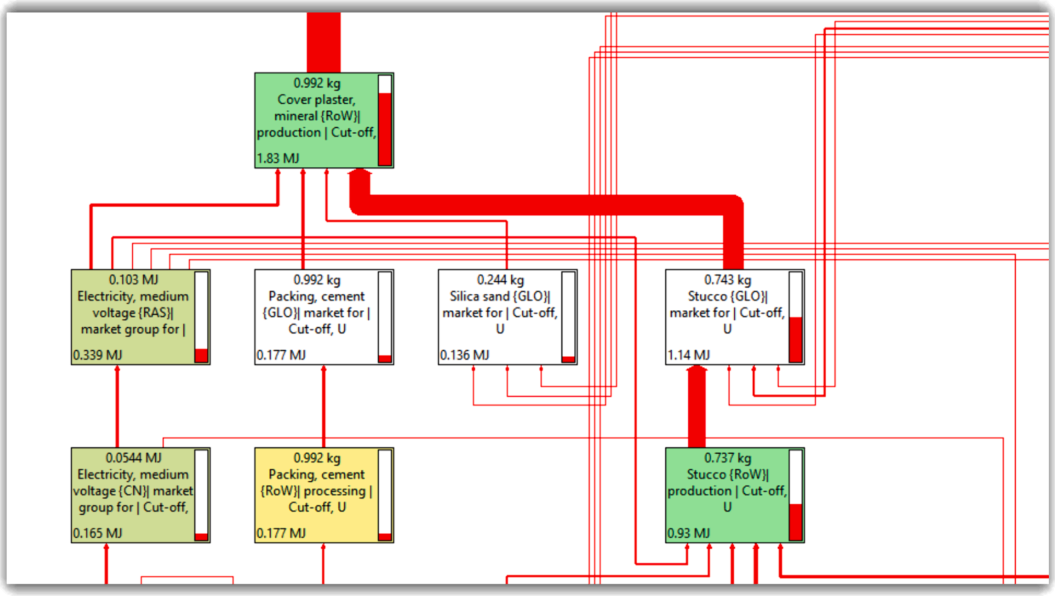

**Fig. 4.1.** Example excerpt of network diagram for the material "cover plaster, mineral" in SimaPro. This reveals the material inputs which go into "cover plaster, mineral" to include stucco and silica sand. Electricity and "packing, cement" (interpreted to mean packaging materials for loose cement) are also inputs considered in the life cycle. ("Cut-off, U" means "Cut-off, Unit Process").

through analysing the other materials, appears to offer a good comparison in composition terms. If another of the records had been selected as the most similar-sounding, i.e. base plaster, or gypsum plasterboard, the difference to the ICE data may have been greater, but the accuracy of the comparison would be poorer.

The data provided in these databases needs to be supplied in a format which readily offers clarity on the material in question. When a life cycle analysis for a construction project may have different materials numbering in the hundreds or even thousands, an analyst does not have the time to spend interrogating a variety of different options to ensure the intended material has been selected. And whilst certain building design tools may integrate embodied impacts into their workflow, the smaller scale and niche nature of retrofits may result in designs being delivered without such sophisticated tools, and therefore embodied impacts are unlikely to be determined automatically, necessitating simple-to-use but robust solutions. Moreover, whilst it is recognised that a database cannot ever be entirely comprehensive, where commonly used materials are entirely absent, unsuitable substitutions may be made. For example, the professional statement published by RICS recommends the use of PIR insulation as "generic insulation" where details are absent, however as already pointed out, PIR did not feature in either ICE or Ecoinvent. Concerningly, the RICS guidance also recommends the substitution of "equivalent or closely similar" products in a whole-life-carbon analysis where specific data is unavailable [15]. Whilst this is perhaps the only realistic advice RICS can offer, it does open opportunities for unsuitable substitutions; it is cautioned here that similarity in performance or appearance is not necessarily a good indicator of similarity in composition or therefore embodied carbon. And it should be emphasised that using the wrong or unsuitable record *cannot* support the design decision making required to lower energy or carbon impacts.

#### 4.1.2. Methods and boundaries

Secondly, in relation to these two data sources there are methodological differences which may account for some of the differences in the data. The ICE database methodology is described in guidance from the Building Services Research and Information Association, referred to here as the BSRIA guidance [27]. In essence, the ICE database provides aggregated literature data which has undergone careful selection and some processing to report an average of the values they identified, whereas Ecoinvent builds up the product data from constituent parts, which they call unit processes.

ICE implement five key criteria to ensure high quality and comparable data, namely: compliance with ISO 14040/44; boundaries are set as cradle to gate; British data is preferred; newer data is favoured; and embodied carbon data is obtained from sources where life cycle carbon emissions have been considered with British emission factors applied. Further to this, their handling of the calorific value of materials results in plastics retaining feedstock energy in the data presented, but the calorific energy content of timber is excluded. Moreover with the boundaries set as cradle to gate and therefore end-of-life processes not considered, the carbon storage benefits of timber are also excluded [27].

Ecoinvent functions on a different basis to ICE, by building up the products from a library of unit processes. The processes represent average production conditions for a geographical area. The way the impacts from these processes are assigned to producers and consumers is determined by the system model chosen by the analyst. There are three main system models; "Allocation at the Point of Substitution" (APOS), "Allocation cut-off by classification" (*cut-off*), and "Consequential" (which will not be discussed further). In practice, the two allocation methods yield different results by attributing the benefits of waste recycling or creation of by-products to either the first lifecycle, wherein at the end-of-life a waste material is processed to be used again, rather than permanently discarded/landfilled, or to the second or another lifecycle wherein the new product is made using recycled materials or byproducts and so it benefits from using recycled or unburdened content. If both the first and second lifecycles take the benefit of recycling, this results in double counting and an incorrect result. The unit processes (with their assigned system model) are aggregated into a supply chain, from which a life cycle inventory is derived, and to which life cycle impact assessment methods are applied with the relevant impact categories. It is at this stage that numerical values for embodied energy, carbon, or other environmental indicators can be obtained. [30].

The BSRIA guidance states that the ICE database is attributional rather than consequential [27], and so it is considered to be most similar to either the APOS or *cut-off* system models in Ecoinvent. APOS shares the waste burdens between the producers (first lifecycle) and the users benefitting from using the waste-derived by-products (second lifecycle); this is called the 50:50 method in the BSRIA guidance. Alternatively, *cut-*

*off* attributes the recycling benefit to the user of the recycled materials (second lifecycle), and wastes to the producer (first lifecycle, "polluter pays"); this is called the "recycled content approach" in the BSRIA guidance. In Annex B of that guidance, it is explained that the ICE database data can only legitimately conform to the "recycled content approach" on account of end-of-life activities being excluded from a cradle-to-gate boundaries, and the 50:50 method necessarily requires consideration of end-of-life activities to allocate recycling benefits to a future lifecycle. For this reason, the comparison between the ICE database and the Ecoinvent cut-off system model is considered to be entirely reasonable, and unlikely to be a major cause of variability between the datasets, but subtleties within this may contribute some variation.

Further to these different approaches, none of the documentation relating to either database describes the underlying methodology, namely whether they use process analysis or input–output analysis. Details on these methods are discussed extensively in other literature [12,31,32,33,34,35], but in summary, process analysis uses a bottom-up approach to audit energy consumption along a supply chain, whereas input–output analysis uses product monetary costs alongside the energy costs and government statistics for an economic sector to estimate embodied energy. IO analysis is considered to be more complete and result in higher estimates of embodied energy or carbon than with process analysis [31,35], however it is also thought that most studies use process analysis [25]. Whilst the Ecoinvent documentation for version 2 (superseded in 2013) describes the database as based on process life cycle inventories, and not economic input–output analyses except in specific circumstances [36], the equivalent documentation for version 3 does not make this explicit, and so it remains unclear [37]. Documentation for the ICE database does not address this at all.

In relation to the impact assessment methods, Ecoinvent methods "Cumulative Energy Demand V1.10 / Cumulative energy demand" and "IPCC 2013 GWP 100a V1.03″ were used for embodied energy and embodied carbon respectively. Cumulative energy demand utilises higher heating values (HHV) (gross calorific values), which is comparable to the method used by the ICE database. It is the only available single issue impact assessment method in SimaPro to represent both non-renewable and renewable energy. Both the BSRIA guidance and Ecoinvent "Cumulative Energy Demand" define embodied energy as total primary energy [27,36]. For embodied carbon, "IPCC 2013 GWP 100a" was developed by the Intergovernmental Panel on Climate Change and contains climate change factors with a timeframe of 100 years. The BSRIA guidance describes using "a basket of greenhouse gases (on a 100 year timescale)" for embodied carbon equivalent (they do report embodied carbon separately for some items but this was not considered in this study), so is deemed to be a suitable comparison for embodied carbon, however the specific compounds are not given, and therefore any discrepancies may be a source of some of the variation.

#### 4.1.2.1. *Handling of feedstock carbon and energy in timber.*

The BSRIA guidance for the ICE database offers a detailed account of how timber data is handled. There are three key considerations: Firstly they exclude the energy content (calorific value) and the biogenic carbon of the wood itself. Secondly they include bio-derived energy used for processing the timber, i.e. timber offcuts used for kiln drying. Thirdly, the carbon storage benefits of timber (and possible negative embodied carbon coefficients) are specifically excluded on account of it offering only cradle-to-gate data, and therefore the end-of-life scenario being unknown. They also highlight that negative carbon coefficients can easily be inappropriately used, i.e. by increasing the amount of timber in a construction to the extent that it is overused to give a smaller embodied carbon figure, which is obviously contrary to general sustainability objectives.

Ecoinvent reports a much higher embodied energy value for timber than ICE (27.7 MJ/kg; 7.4 MJ/kg), and yet a lower embodied carbon value ($0.121\ \mathrm{kgCO_2e/kg}$; $0.263\ \mathrm{kgCO_2e/kg}$). The embodied energy value is nearly four times higher; it is unclear from the Ecoinvent documentation whether the calorific value of timber is included, but typically for softwood, the gross calorific value (GCV) would be around 20 MJ/kg [38]. It is stated by ICE that the calorific value of timber is excluded, so this would conveniently make the two sources comparable, although this is not assumed to explain the difference. Scrutinising the network diagram for timber in SimaPro suggests that bio-derived energy is used for processing the timber, which is comparable to the ICE data.

Regarding embodied carbon, the Ecoinvent value is less than half that of ICE. Inclusion of the biogenic carbon of the timber in Ecoinvent when it is excluded by ICE would be unlikely to result in this direction of difference. Given the reasonable comparability of the methodologies with respect to allocation, the difference is therefore likely attributable to other factors, such as geographies, carbon factors, or other reasons. The BSRIA guidance explains that timber is the most problematic of materials to estimate on account of high natural variation in moisture content, production, and fuel mix. The use of timber in construction is increasing for structural and insulation purposes, in part owing to its perceived sustainability [39]. The uncertainties associated with estimating embodied carbon and energy in timber risk over-estimating carbon savings for construction in general, but in retrofits too. Therefore the importance of specific, realistic and accurate estimates for timber are paramount.

#### 4.1.2.2. *Geographies.*

The ICE database is specifically focused on the UK market, however Ecoinvent is developed in Switzerland and therefore has a different geographical focus. Within Ecoinvent, the data is tagged with a particular geography, and so the user selects the most appropriate for their study. None of the data used in this study had UK data available, and so European or Global data was used. Therefore, since the ICE and Ecoinvent geographies differ, this may explain some of the source of variation between the datasets.

### 4.2. *Energy or carbon for life cycle studies?*

In the sample of materials analysed in this study, the embodied energy figures were more similar between the datasets than the embodied carbon figures. This could indicate that embodied carbon data may be less reliable than embodied energy data. This section discusses the possible implications of this, and other characteristics of embodied energy and embodied carbon, for those undertaking life cycle analyses for building design improvements.

According to BSRIA [27], embodied energy data is used to determine embodied carbon, often using a typical fuel mix (in this case for the UK) with emission factors applied and process related carbon emissions added on. However, they explain how this leads to higher uncertainty in the embodied carbon data than in the energy data. Firstly, the fuel mix may vary between facilities, leading to under- or over-estimating carbon emissions. Secondly they stated that a smaller proportion of the data collected provided figures for embodied carbon, GWP (global warming potential), or fuel mix, and so embodied carbon coefficients were verified using less data. Despite this, they state that more recent studies are focused on carbon, but often at the expense of energy data [27]. This finding is reflected by Pomponi and Moncaster [22] and also by Cabeza et al. [25] who showed that whilst the term "embodied energy" was more prominent in academic literature than "embodied carbon", once the term "carbon footprint" was also considered, the combined number of occurrences focusing on carbon analysis was higher than literature occurrences of embodied energy. In the present author's experience, the greater prominence of carbon is reflected across many sectors (construction, food production, policy etc [14,19,40]) with "carbon footprint" becoming common parlance, whilst "embodied energy" remains a term which is largely unfamiliar in everyday conversation, or indeed the terms are often used interchangeably, even amongst those practicing LCA. It is however emphasised by the BSRIA guidance from 2011 that both embodied carbon and energy are important metrics, and should be reported together.

When this BSRIA statement is considered in practice, in the context of the ICE database over a decade on, and with the now legacy-embodied energy data which can be accessed only through a secondary source (via BSRIA [27]), the Authors' query why ICE has chosen to omit embodied energy data and assert that embodied carbon is "a more useful indicator", with little in the way of explanation. Pomponi and Moncaster [41] also state a preference for embodied carbon, over energy, on account of its representation of climate change, that it represents more than just embodied energy, and its good correlation to other ecological and environmental impact categories. Notwithstanding, it has been found in this study that embodied energy data is more consistent between sources than embodied carbon data, and so it could be argued that there is lower uncertainty with embodied energy.

Allowing the argument that embodied carbon is "a more useful indicator" to perpetuate could be as damaging as the sort of carbon accounting which leads to overuse of timber with a negative embodied carbon in order to yield a lower total embodied carbon. As already stated, reporting embodied carbon is supposed to describe the climate impact of a building's materials. Perhaps consequently, embodied carbon has been adopted as the metric of choice amongst many stakeholders, policies, institutions and campaign groups. Nevertheless, there are limitations with reporting life cycle or embodied carbon (as opposed to energy) which are not necessarily acknowledged or maybe even realised amongst those reporting or using it.

### 4.2.1. *Where are the embodied impacts occuring?*

The major limitation with reporting only embodied carbon is that it is relatively easy to decarbonise an inefficient process (e.g. manufacturing a product) by transferring to a renewable energy source. Whilst this will achieve a reduction in carbon emissions associated with that single facility, when taking a more holistic or global viewpoint, which climate change mitigation demands, this may turn out to be myopic. If on the other hand attention was also paid to embodied energy, and that same process underwent measures to reduce energy consumption, alongside changing to a renewable energy source, the excess or surplus decarbonised energy could be deployed to more than one process. This need to use renewable energy resources efficiently for producing construction products is emphasised by Anderson and Moncaster [42]. Instead of simply decarbonising the supply chain, building designers could choose an alternative product with both lower embodied carbon *and* lower embodied energy. This reduces the need for as much renewable energy infrastructure, but can only be quantified and therefore acted upon if embodied energy is also part of the discourse. It is necessary to stop treating decarbonised energy as though it was an infinite resource; in practice, there are constraints on how much renewable energy can be produced, whether because of, for example, grid capacity, or issues relating to land area and public acceptance, but importantly, because renewable energy has its own embodied carbon impact [42].

The question this leads to is "where should the boundaries of our life cycle analyses be drawn?". Perhaps even more pertinent is "where do we want our embodied impacts to occur?". Improving manufacturing processes to make lower impact materials for retrofit, or improving the thermal performance of homes requires materials which have embodied impacts. And yet growing the provision of renewable energy supply and battery storage for managing power grid intermittency will also have embodied impacts. It is highly likely that there is a strong distinction between the types of materials required for retrofitting homes (as mentioned previously) versus the types of materials used in renewable energy infrastructure, such as wind turbines, solar photovoltaics, hydroelectric schemes, or large scale battery storage, as well as the grid infrastructure upgrades required to distribute the power. Such products are known to use large amounts of steel, concrete, specific metals and other technical materials, all of which are known to have their own embodied impacts [43,44,45]. Furthermore, development of new sites for renewables can have major environmental impacts *in situ*, owing to land use change, disruption of the natural environment, biodiversity loss etc [44,45]. In contrast, the materials required for domestic retrofits are likely to be predominantly those with lower environmental impacts. Moreover, whilst such materials may be invasive to home occupants in their installation, they will be unlikely to have the broader environmental impacts on the same scale as a new wind farm or hydro scheme. In fact, as already stated, retrofits will enhance people's living environments, resulting in a more comfortable and healthy home.

The schematic illustration in Fig. 4.2 shows an example scenario of decarbonised heat and power (light blue) on the left, versus decarbonised heat and power with energy efficiency measures (orange) on the right. In both scenarios, decarbonised power is supplied to a facility making retrofit products (e.g. insulation). Decarbonised heat equipment (e.g. heatpumps) is manufactured at a second facility which supplies the domestic market. Renewable energy infrastructure (e.g. wind power and

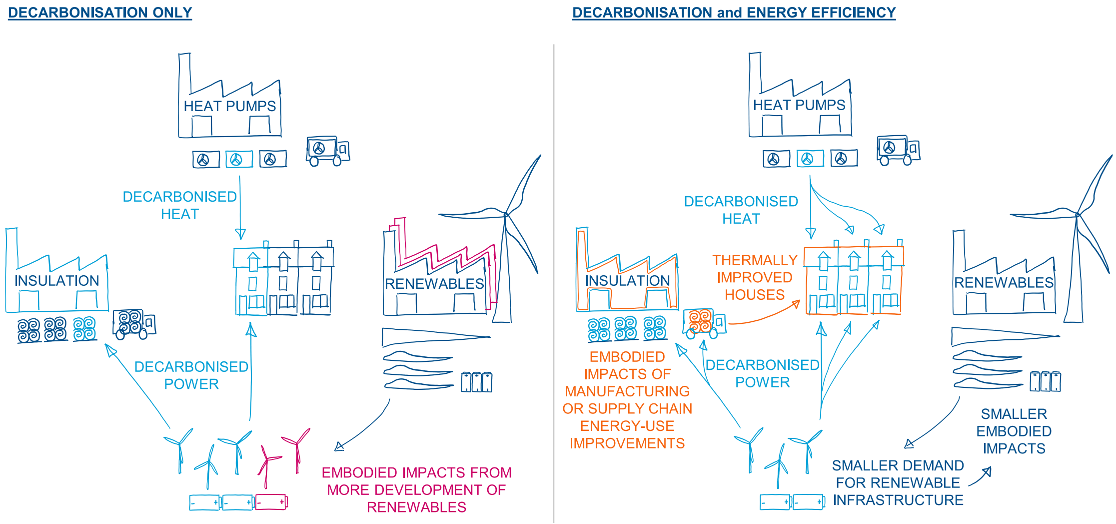

**Fig. 4.2.** A schematic illustration showing a scenario of decarbonised heat and power (light blue) on the left, versus decarbonised heat and power with energy efficiency measures (orange) on the right. In both scenarios, decarbonised power is supplied to a facility making retrofit products. Decarbonised heat equipment is manufactured at a facility supplying the domestic market. Renewable energy infrastructure is manufactured at a third facility. Embodied impacts occur in different places in each scenario.

batteries) is manufactured at a third facility. In the left hand scenario, more renewable energy (both heat and power) is used to supply fewer homes and make less insulation, thus maintaining the status quo on operating energy. Decarbonisation of this energy requires larger renewable energy infrastructure (pink), and therefore the embodied energy and carbon impacts of manufacture and installation are larger. Whilst embodied impacts are avoided within the boundary of the decarbonised house in this scenario, they are externalised, occurring elsewhere. In the right hand scenario, the homes have undergone retrofit measures to reduce their heat demand, whilst the insulation manufacturing facility has undergone process efficiency upgrades. Both of these interventions have "used" embodied energy and carbon, however this scenario now requires less renewable energy to make larger quantities of insulation and to supply power to more homes; the same amount of decarbonised heat can also supply more homes. Because less power is needed overall, fewer renewable energy installations are required, and so embodied energy and carbon savings can be made in this area.

The boundaries considered when looking at the carbon or energy impacts of a retrofit need to be very carefully considered. Decision making for an individual property for whether to retrofit or not, and what materials to use, can have far reaching consequences, and even more so when the scale of the task is multiplied up to a national scale and millions of properties. Whilst new renewable and battery storage infrastructure will be required regardless of retrofit, it is perhaps not unrealistic to suggest that the large scale retrofitting of homes could negate the need for entire developments of renewable energy. However the current trend for reporting carbon data, often without energy data, makes it possible to overlook externalised impacts. The superficial analysis presented here evidently merits further research and quantification, but sets out a compelling case for why embodied energy should be considered to drive energy demand reductions, not just embodied carbon.

#### 4.2.2. *Other reasons to consider embodied energy as well as carbon*

There are other reasons to consider embodied energy as well as embodied carbon. Firstly its pertinent to highlight that specifically, it would be advantageous to consider embodied energy as *final energy* (although the data sources discussed here report primary energy) for reasons discussed at length in Hurst and O'Donovan [9] but which are expanded here to include the comparison with embodied carbon. Final energy allows the isolation of effects arising from changes within the boundary of, for example, a manufacturing process, or the thermal envelope, whereas primary energy conflates this with impacts of power supply, in the same way as embodied carbon does. The fundamental energy required to manufacture something (i.e. the energy for processing or chemical reactions of ingredients) will be the same for a material regardless of the auxiliary machinery or processing which occurs, or of the power source. However the carbon intensity of manufacturing could vary with the power supply.

Related to this, embodied energy, as final energy, is temporally and spatially static, whereas embodied carbon is transient. That is, whether a material is being manufactured in location A or B, today or in x years' time, the energy required to do this is the same (unless efficiencies have been made to the process). However a material manufactured today would not have the same embodied carbon as that same material manufactured tomorrow, or in x years' time. This is because the carbon intensity of the energy used to make it will vary. In general terms, grid carbon intensity is decreasing year on year, but day to day it is variable with (in the UK) the amount of solar PV or wind power being generated [46]. Additional factors, such as geopolitical instabilities affecting fuel security will increase the level of uncertainty. The same variability occurs between different locations. For example if a product is manufactured at different sites, and perhaps in different regions or countries, the carbon intensity of the power supplying those manufacturing sites could also be variable. And whilst ideally site-specific embodied carbon data would be used, in practice this is nearly impossible to achieve (and not pursued by either of the databases discussed in this study), and so assumptions, approximations and generalisations are made in the form of correction factors, which add uncertainty to embodied carbon estimates [22]. Compilers of embodied carbon datasets rely on correction factors to translate energy usage into carbon emissions (amongst other inputs) [27], which are forecasted estimates, or static in time, which do not well represent actual emissions. This transience presents a compromise if embodied carbon is to be used as a design tool. When using LCA to design better buildings, the LCA numbers must come before the design is complete in order to select the lowest carbon materials, and therefore before the design has been built. Marsh et al. [23] highlight this as a risk in relation to selection of specific manufacturer's products at design stage, whilst another brand of product is procured during build. More generally however, the nature of embodied carbon data means that values are dynamic in both space and time, and therefore forecasted values cannot ever be expected to present an accurate picture of the eventual embodied carbon. RICS [15] advise avoidance of using "future decarbonisation" to ensure that overly optimistic estimates are not made; instead they advocate the use of present-day carbon factors. For both carbon or energy metrics, the true value is unknowable, but efforts can be made to reduce uncertainties to get closer to a true value. In either case, they might be invited to deploy embodied energy with higher levels of certainty, or at least present both carbon and energy metrics, which could enable better decisions to be made.

Pomponi and Moncaster [22] suggest that another issue with the large range of embodied carbon values (as illustrated in their paper) is the corresponding wide scope to "handpick" the values to achieve a desired result. Of course this is also possible with embodied energy, however they go on to explain that if embodied carbon data was geographically and technologically specific, the scope for this would be much more constrained. This argument could also apply to embodied energy data; however it is demonstrated by the present authors that there is, on the whole, less variation with embodied energy than embodied carbon, and therefore the opportunity to select favourable data and manipulate the outcomes of a study is already more limited. Such manipulation could exacerbate the problems already described regarding design decision making.

Additionally, and captured partly by the above discussion, it is arguably easier to present favourable carbon figures by use of decarbonisation of grid energy, and carbon offsetting in both operating and embodied carbon contexts than it is to present impressive sounding energy use reductions. It is possible to transition a process to "100 % renewable energy" "zero carbon", or "carbon neutral", yet unfortunately these outcomes are perfectly possible without reducing energy use at all, as illustrated previously in section 4.2.1. Moreover energy use reductions need a baseline to demonstrate improvement against, and it would be impossible to reduce actual energy use to zero. Carbon reductions might therefore be considered to sound more impressive or impactful than energy use reductions. It is perhaps bold, but not implausible to suggest that decarbonising energy could even disincentivise energy efficiency improvements, whether in manufacturing or other sectors, because impressive carbon reductions can already be claimed. However if framing decarbonisation differently, even "zero carbon" energy contributes to climate change in so far that if less of that zero-carbon energy is used in any process, the surplus can go to another use (i.e. via the grid), and limit the amount of high-carbon energy that another user needs.

Finally, embodied energy is arguably more intuitive to understand than embodied carbon. When designing buildings, especially low energy buildings, the focus is on reducing operational heat losses and minimising active heating or cooling, and measured in kWh, not in carbon. The kWh is a unit which is familiar not only to building designers, but also to the layperson. The unit of carbon however, as mass $CO_2$e, or carbon dioxide equivalent, referring to all greenhouse gases and weighted according to global warming potential, is a more abstract concept for most people; it is difficult to get an impression of what this might look like, and it cannot be easily measured, or read from a meter like a kWh.

Collectively, these reasons outline the importance of acknowledging embodied energy alongside embodied carbon. The single-issue focus of embodied carbon over embodied energy has less power to drive improvements to GHG reductions than looking at embodied carbon and energy side-by-side.

### *4.3. Putting embodied energy and carbon into retrofit*

The reality of many life cycle studies in construction is that the complexity of the projects necessitates that assumptions and simplifications are made to enable any sort of estimate of the embodied energy or carbon. The Pareto Principle is described in the BSRIA guidance: This states that 80 % of outcomes are attributable to 20 % of the inputs [27]. The purpose of their referencing this is to highlight the need to focus on the major contributions to the life cycle, and by doing so a reasonable estimate of the impact will be derived, without the need to delve into the $n^{th}$ level of detail, which would often be practically impossible in terms of finance and time. This is especially convenient because it's unlikely that data for all items will be available. In new construction projects the masses of materials tend to be heavily weighted towards structural elements; concrete, steel, timber, masonry, glazing etc, and so small items, such as wall ties or door furniture might be omitted [27]. Marsh et al. [23] support this, where in their study on a new educational building they found that 13 of 93 construction products contributed 80 % of the product stage EC, and these included concrete (32.4 %), bricks (11.9 %), cross laminated timber (9.79 %), steel (11.74 %), lime mortar, glazing (7.7 %), glulam (2.1 %), and insulation (1.9 %); therefore dominated by structural materials. However for retrofit, the emphasis is very much shifted: the common absence of the heavy structural elements means that the impacts of retrofits are much more likely to be dominated by lighter weight materials; insulation, membranes, fixings, ventilation equipment etc (with the exception of glazing, which is heavy). The emphasis of the impact may well fall to the "smaller items", and maybe those for which data is difficult to obtain. For example, airtightness membranes, commonly used in low-energy buildings, as well as in retrofits, are composed of polypropylene fleece backing and facing with the technical membrane sandwiched between. Polypropylene has a high embodied energy and carbon, however neither database had a polypropylene record in a format which seemed suitable for a membrane backing application (oriented film and granulate). Neither was there a record deemed suitable to represent the technical membrane. Another example, as mentioned previously, is the absence of polyisocyanurate (PIR) insulation, which when laminated with a foil facing is a very commonly-used rigid board insulation. If these items are commonly overlooked because they are deemed not to make a significant contribution on a single retrofit basis according to typical construction LCA, or the practitioner has to estimate from an assimilation of a product's "best guess" or assumed constituent parts, and so cannot be adequately characterised in the LCA, a realistic estimate of the retrofit's impact may never be known, and therefore nor can the impact of the UK's 26 million possible retrofits. This in turn may lead to retrofits proceeding which cost more in embodied energy and carbon than they are likely to save in operation.

Nevertheless, circumnavigating retrofit in favour of focusing only on decarbonisation of power and heat may serve to externalise the embodied impacts of the retrofit. At the scale of the UK's whole housing stock needing energy performance upgrades, failing to understand the quantitative energy and carbon impact of retrofit could lead to poor decisions at a national scale. This could transfer embodied impacts from manufacture of retrofit materials to the manufacture of additional renewable energy infrastructure, as well as propagate broader environmental impacts from converting terrestrial and marine environments to power generation facilities. Pomponi and Moncaster [22] remind us that where operating energy or operating carbon can be mitigated at a later stage in a building's life, i.e. by retrofitting, embodied energy and embodied carbon cannot; what is invested at the construction phase, whether in a new build or a retrofit, or renewable energy infrastructure, is locked in. By implication, this means that post-design or even post-construction LCA is of limited use at best. It is therefore imperative that the right decisions are made at the design stage.

## 5. Conclusions

Discrepancies between datasets will yield different outcomes for life cycle studies however whilst some variation between data sources is expected, it is important for users to understand why the differences arise, and the implications for their particular study.

The data collected in this study illustrates that most (>70 %) embodied energy and embodied carbon data is quite similar (within 20 % of each other) between Ecoinvent and the ICE database. This provides some confidence to the estimates being generated for projects using either source. However this also indicates that 30 % of data is more different. There are various reasons that data sources may vary including boundary and methodology differences which are well described in the literature. In addition to these, this study has identified that material naming has the potential to present barriers to a robust analysis, as does the absence of certain materials from the datasets. These problems are likely to be amplified in retrofit studies wherein the dominant materials tend to be lightweight materials, and "smaller items" will assume a greater prominence in the findings. It may be less possible to make assumptions and simplifications about the most influential materials than it is in new-build construction projects.

When looking to report either embodied energy or embodied carbon, the findings of this study suggest that embodied energy is more consistent between the sources than embodied carbon, but ideally both metrics should be reported. Embodied carbon offers detail on GHG emissions and climate change potential that an embodied energy value could not provide on its own. Nevertheless, embodied energy reveals where savings can be made which could have implications for the better sharing of renewable energy resources, and therefore could even affect the scale of renewable energy infrastructure required, and consequently mitigate embodied impacts arising from that sector. Additional factors favouring the reporting of embodied energy include that it is more intuitive to understand, is static in space and time, is less susceptible to manipulation than embodied carbon, and may form the basis of the embodied carbon estimates. On the other hand, embodied carbon varies with grid carbon intensity, and therefore changes year to year, as well as from place to place. This means that estimates of future embodied carbon have much higher uncertainties associated with them than embodied energy forecasts. It also means that aged embodied carbon data will have potentially diminishing relevance, and therefore the need to keep updating records is more demanding than for embodied energy (this upholds the use of the legacy embodied energy data, from a source more than a decade old, formerly published as the ICE database.). Taking a cynical view, the ability to manipulate embodied carbon impacts, i.e. by carbon offsets, carbon storage and sequestration, or selecting especially optimistic carbon factors, facilitates the potentially nefarious objectives of a developer, or indeed a government, of effecting minimally disruptive change to the status quo, whilst claiming tremendous climate benefits. If the boundaries of a carbon analysis are extended to encompass the whole global system, as must be realised to mitigate climate change, the origin of the carbon reduction is inconsequential – whether in this building or that, this country or that. The important thing is that real reductions in GHG emissions occur: If a manufacturing process decarbonises and the embodied carbon of a material reduces due to changing to a lower carbon energy source, rather than by improving the efficiency of the process, it will continue to use more energy than may be really necessary, and that low-carbon energy source cannot be shared so widely, fewer processes can benefit from the low-carbon source, and more of that infrastructure will be required. Scrutinising embodied energy ensures that such manipulation cannot occur, and therefore higher confidence can be provided for the data.

When the need for climate change action is as pressing as it has now become, embodied energy or embodied carbon impacts cannot be ignored simply because it is inconvenient to obtain data, or that data has high uncertainties associated with it. However, the reality is that in many cases, the life cycle analysis for a retrofit will be conducted by a person without a deep background knowledge of the topic. They will be subjected to the same hurdles as described here, without necessarily the time to give it the thought required. Designers need access to the tools to run analyses in real time when iterating their design. Tools which open up LCA to non-expert users need to be much more complete and have higher confidence in the data, to ensure that the analysis delivers a high quality and meaningful result, for climate-beneficial design decisions.

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## CRediT authorship contribution statement

**Lois J. Hurst:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Tadhg S. O'Donovan:** Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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