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sustainability

Article

Embodied Energy Consumption in the Residential Sector: A Case Study of Affordable Housing

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Abstract: Embodied energy has a significant effect on the total environmental impact of a project. However, emphasis is often placed primarily on operational energy, resulting in a knowledge gap about the current state of embodied energy use in affordable housing. To address this, the study investigates the level of embodied energy consumption in affordable housing, as well as the drivers, barriers, and techniques to reduce embodied energy. Based on a single embedded case study covering the period from cradle to end of construction, data were collected using embodied energy calculations of three affordable housing units in the project, semi-structured interviews with five design team members, and a cross-examination of findings with contract documents. The results were analysed using sensitivity analysis and thematic analysis. The findings revealed that all three house units fulfilled the baseline embodied carbon target of 800 kg CO_2/m^2 and both detached properties fell within the LETI (2020) target of 500 kg CO_2/m^2. However, all three properties would fail to meet the RIBA or 2030 LETI target of 300 kg CO_2/m^2. This suggests that improvements are necessary to achieve future targets. The results show that financial capabilities and operational energy prioritisation act as the main enabler and barrier for reducing embodied energy. Local contractors/suppliers, minimising material use or intensity, and modular construction were highlighted as the key reduction techniques that can be used to help achieve future targets concerning embodied carbon in residential developments. The study contributes significantly to understanding the current state of embodied energy use in affordable housing and provides new insights on how to deal with embodied energy if we are to meet future energy targets.

Keywords: affordable housing; carbon emission; case study; embodied carbon; embodied energy; sustainable construction; United Kingdom; zero carbon

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1. Introduction

Rapid urban development and population growth have gradually increased energy demand [1] and carbon footprint [2], with the United Kingdom (UK) emerging as one of the top fifteen carbon emitters per capita [3]. In 2019, the UK became the first major economy in the world to enact laws to put an end to its contribution to global carbon emissions by 2050 by setting a target to bring all greenhouse gas emissions to net zero by 2050 (Department of Business, Energy & Industrial Strategy and Skidmore, 2019). Various studies indicate construction and the built environment have the highest potential for reducing energy [4,5]. With buildings contributing up to 40% of the global energy consumption annually [6], it is considered one of the critical areas for improvement in meeting the UK Government's 2050 greenhouse gas reduction target [7]. Furthermore, the residential sector produces almost half of the built environment's greenhouse gases [8]. Therefore, there is a critical role to be played by the residential sector in meeting the carbon reduction targets.

The energy usage of a building can primarily be categorised into operational and embodied energy [9]. The Building Research Establishment [10] defines embodied energy as "total primary energy that has to be sequestered from stock within the earth to produce a specific good or service". Under normal circumstances, operational energy outweighs embodied energy in buildings. However, depending on the composition of a building, embodied energy can range up to 60% of the total energy spent, especially when the operational energy requirement is low [11]. Understanding the relationship between operational and embodied energy is imperative to reducing the overall carbon [9] due to its Pareto optimal nature [12]. Reports from the United Nations Environment Programme advise that construction, including manufacturing, accounts for between 10–20% of a building's total energy consumption [13]. Similar studies by [14] postulate 10–30%; however, [15] reduces the range to between 25–30%. In addition, the embodied energy range is highly dependent on the operational requirements and can vary between 9% and 38% when conventional systems are used [16]. Despite varying percentages based on different case studies, the consensus of the literature would suggest that Leoto and Lizarralde's [11] statement is accurate. When considering construction, refurbishment, and demolition over 50-years, the total energy consumption figures alter to 45% and 55% from embodied energy and operational energy, respectively [17,18].

Although a plethora of research [19], legislation and design considerations [16] have been conducted, there is a stronger focus on operational energy over embodied energy [19]. However, an emerging argument within literature is that embodied energy is more important over the life cycle of a building as operational energy can be reduced post-construction, unlike embodied energy [20]. However, embodied energy has received significantly less consideration than operational energy, both in practice [21] and within academia [22]. Consequently, some appraisal systems consider only operational energy and exclude embodied energy from calculations [16]. However, as operational energy is reduced through increased government intervention and improved design, the significance of embodied energy is expected to grow [23,24]. This is demonstrated in a study by Azari and Abbasabadi [25], which confirms embodied energy has gained focus in recent years due to the current trend of reduction in operational energy. BRE [20] claim that embodied energy should be prioritised as, unlike operational, it cannot be reversed once installed. Thus, embodied energy in buildings requires further attention, especially in the residential sector.

Multiple studies express the criticality of improving affordable housing to meet 2050 energy targets, primarily due to the social and affordable residential sector producing over half the carbon within the residential sector [26–28], suggesting that affordable housing can present additional pressures with most housing associations working with Small, Medium Enterprises (SME), subjecting poor knowledge, workmanship, and project fragmentation. Furthermore, they state that the complexity of ageing tenants often causes rebounding issues with operational energy, increasing the importance of embodied energy. A key issue with affordable housing is that costs need to be kept to a minimum to keep the prices 'affordable'. This presents a significant opportunity and a challenge to innovate and develop low-cost and low-carbon solutions. While there is no universal definition of affordable housing, it is identified as 'housing of any tenure that is judged to be affordable to a particular household or group by analysis of housing costs, income levels, and other factors in a House of Commons briefing paper [29]. Affordability here is a subjective term, as it depends on the income, savings, disposable income, etc of a household. The definition of the House of Commons identifies affordable housing as 'subsidised housing that meets the needs of those who cannot afford to secure decent housing on the open market either to rent or buy' [30] provides a more applicable explanation of affordable housing. According to research commissioned by the National Housing Federation [31], it was projected that England will need about 340,000 new homes to be built per year over the 15 years between 2018–2033, of which 145,000 were expected to be affordable homes (including 90,000 for social rent, 25,000 for shared ownership and 30,000 for intermediate rent). This represents over 40% of the new-built homes. To fulfill the 2050 carbon reduction targets, it is recommended to evaluate carbon emissions from the residential sector by considering its contribution to over half of the carbon emission of the built environment [8]. Therefore, the category of affordable homes too will need to achieve carbon reduction targets if the wider carbon reduction targets are to be met.

This research seeks to assess the importance placed by both the client and design team on embodied energy in the low-cost affordable residential sector to determine areas for improvement in reducing embodied energy. To help achieve this goal, we calculate the embodied energy produced by three separate single-family residential designs in a selected affordable housing development. This will enable highlighting the most embodied-carbon-significant building elements in social housing. With the help of primary research with project stakeholders, we seek to provide a set of improvements to create efficiency between embodied and operational energy in social housing. The study is significant for understanding the existing level of embodied energy and exploring strategies to lower the total carbon impact of social housing.

2. Materials and Methods

A report by the UK Green Building Council [9] revealed that embodied energy levels were not governed by legislation. Embodied energy has not been included within Part L of the building regulations [32,33], despite the government showing commitment to reducing environmental impact [16]. The Committee on Climate Change [34] has reported to Parliament that new policies are required; however, previous studies have highlighted that housebuilders believe that policies do not enforce the same degree of rigour as legislation [35].

Although the Home Quality Mark (HQM) is not enforced legally, some councils are creating a policy whereby any developments, where feasible, should use the HQM [36]. The HMQ is a new national standard for housing in the UK created by BRE [20]. Five percent of the total credits available are for the environmental impact of materials, enforcing life cycle assessments, and environmental product declarations to be supplied [37]. However, there is limited literature available determining the uptake of the HQM standard, with HQM's website stating that there are only around twenty-six sites providing feedback [38]. The Building Research Establishment (BRE) has incorporated life cycle assessments into their material category, making it harder for companies to reach good, excellent, and outstanding certifications on buildings without reviewing embodied energy [20]. There is no confirmation on the number of homes being tested under the guidelines following the last 2012 BRE digest. The European Union (EU) has included embodied energy as a core indicator within the EU framework for building assessments [9]. The companies Act 2006 (Strategic and Directors' Reports) Regulations 2013 require companies whose shares are traded on a stock exchange to report their GHG annually [39].

Several industry organisations are working with the Greater London Authority to enforce new guidelines for embodied energy, with a requirement for specific schemes to report and meet targets of both embodied and whole life carbon emissions [40]. Furthermore, as part of the RIBA's 2030 Climate Change Challenge, they declared that embodied energy should be reduced by around 50–70% before offsetting with a benchmark of 300 kg CO_2/m^2 in domestic buildings [41]. However, there is no indication of the repercussions of not following this procedure and how it will be policed. LETI-2020 [24] has a different set of domestic guidelines aiming to reduce embodied energy to 500 kg CO_2/m^2 from 2020 and 300 kg CO_2/m^2 in 2030 from the current baseline of 800 kg CO_2/m^2. Also, there is no confirmation whether LETI's guidelines are nationwide or applicable to only domestic properties within the London area.

The client or end-user has a significant influence on a buildings' carbon footprint through purchase decisions, which can similarly extend through to the supply chain [42].

Farmer [43] confirms this, recognising the need for clients to enforce change if governmental intervention is absent. When designing buildings, both economic and environmental criteria should be discussed [44]. A cost-saving of 30–50% has been revealed from Anglian Water due to tracking embodied energy [9], which is in line with WRAP's [45] proclamation that a financial benefit can be made with embodied energy reductions. Conversely, the [46]estimates the cost to reduce GHG emissions to net-zero at around 200 £/t CO^2e. With the UK emission levels at 460 $MtCO_2e$ in 2017 [47], this implies a cost of 96 billion £ to the UK to achieve net-zero.

Hendrickson et al. claim calculating embodied enables parties to address cost-effective strategies through a profound understanding [42]. The parameters for calculating the environmental performance of buildings are outlined within BS EN 15978:2011 [48]. However, the guidelines are not comprehensive, which led to the BRE guides [37]. Other guidelines include the RICS Whole Life Carbon Assessment [49], BS EN 15804:2012, the Life Cycle Assessment (LCA) framework, and ISO14040:2006 [50].

Due to the broad system boundary definitions available to estimate embodied energy, there are high levels of uncertainty when compared to estimating operational energy [25]. Additionally, D'Agostino et al. argue that throughout research on embodied energy, methodologies are deficient in both description and consistency, causing "scarce research repeatability and data quality" [51]. Furthermore, uncertainty can be amplified with Hendrickson et al. [42] claiming that companies often focus less on the supply chain in their emission calculations, which could be due to the limited availability of data [25]. Bhardwaj [52] revealed that transportation could be the most uncertain element within embodied energy as significant variations come from 'manufacturing location, carriage weight, distance travelled, and transportation type used' [53]. Therefore, transportation cannot be included unless named suppliers are specified for the study [54]. However, it is also argued that transportation should never be discounted from studies as it accounts for between 5% and 20% of total embodied impacts [54,55].

3. Embodied Energy Reduction Techniques

Ali et al. [56] compiled six strategies for reducing embodied energy throughout the production of buildings. These strategies include more efficient use of space [57], extending the life cycle of buildings [58], using fewer materials or materials of lower energy intensity [59], reduction of waste [60], recycling [61], and re-use [62]. Various research also highlighted a plethora of embodied energy reduction techniques related to the built environment [6,63,64]. Among them reducing waste, recycling and re-use, refurbishing existing properties, mitigation of energy-intensive materials, and increasing the longevity of materials were discussed in detail.

3.1. Reducing Waste

A study by Glass et al. [64] revealed circa one-third of all construction and demolition waste could be traced back to poor design. Eliminating waste is imperative as resource scarcity will pose a greater global threat to construction than any other industry, causing costs and programmes to increase [65]. Furthermore, WRAP [45] opines a carbon reduction of around 6% can be obtained domestically by reducing the waste of bricks, blocks, in-situ concrete, insulation, and timber by 50%. Quale et al. [66] found that modular housing reflected a reduction in embodied energy of between 20–70%. This is substantiated by Baldwin et al. [67], Wang et al. [68], and Jaillon et al. [69], who argue that traditional construction methods cause the highest waste, consequently causing unnecessary embodied energy in construction [64].

3.2. Recycling & Re-Use

Several studies suggest that replacing steel with timber would be beneficial in reducing embodied energy and greenhouse gases [63,64]. Despite timber having a lower initial embodied energy, changing the connection method of steelwork enables re-use and reduces the overall lifecycle energy [65]. This also extended to using cement replacement concretes in a study carried out by Dusicka et al. [70]. Hotza et al. [2] consider reducing embodied energy by designing lightweight, efficient structures from recycled materials. Furthermore, WRAP [45] highlights the re-use of existing materials as a vital reduction technique, either by reclaiming materials from demolition or importation from another site. WRAP [45] suggests a potential 12% can be saved using reclaimed bricks on external walls. However, there is no clarification on the site or typology of the house these calculations are based upon.

3.3. Refurbishment of Existing Properties

Andersson et al. [71] extend re-use theories, opining that it is “essential” to renovate existing building stock and re-using existing structures to reduce embodied energy as most energy is embedded into the shell. Schwartz et al. [3] add that new-build properties only become more efficient after a 50-year life span when compared to refurbishment. In contrast, Preservation Green Lab [72] indicates a potential saving of between 4% and 46% for a refurbished property over 75 years compared to a new build. Unlike previous arguments, Davies and Osmani [73] suggest that new-build housing omits around half the carbon annually to existing homes. However, despite Davies and Osmani being reputable academics receiving 2783 and 1908 citations from published articles, respectively, they fail to state the boundaries of the calculations, which increases the complexity of comparing theories. Nonetheless, some properties are ‘hard to treat’ [28] and can be uneconomical to refurbish [74], whereby demolition and re-constructing are considered the most effective option [75].

3.4. Mitigation of Energy Intensive Materials

Loukaidou et al. [6] claim a distinct correlation between a building’s envelope and energy consumption, with up to 50% of energy embedded [44]. Furthermore, studies including [76] and [24] conclude that 80% of energy can be traced to the substructure, foundations, and ground floor, confirming arguments that building materials are the greatest contribution to embodied energy. Abegaz and Taffeze [77] attribute the energy to mass fill concrete and rebar, which averages 13% wastage. To negate this, replacing non-load-bearing concrete with hempcrete has successfully reduced embodied energy in other studies [78]. However, Barbour [79] advises that despite increasing use, its accessibility to the product is still limited and can cause an increase of 8–12% in project costs. Another study also stated that in many scenarios, a building could reduce its quantity of steel by circa 19% while maintaining structural and architectural requirements [80].

3.5. Increasing the Longevity of Materials

Azari and Abbasabadi [25] suggest that one of the critical strategies for reducing embodied energy in construction is to increase the durability of materials. Increased material longevity would decrease the overall lifecycle of embodied energy [81] by reducing recurrent energy [25]. Furthermore, if materials could be re-used after demolition, energy savings of up to 95% could be made [82].

3.6. Other Techniques

One of the less common techniques raised within literature is project collaboration. Papachristos et al. [83] suggest that a carbon reduction of 37% can be found when project partners align. However, this article does go on to say that it is a consequence of replacement products and not collaboration in isolation. This technique is also discussed in [24] and [43]. Similar results can be found with urbanization [1] due to efficient deliveries and project coordination. However, Tan and Wang [84] suggest that minimal research has been completed on the onsite construction in isolation which can be reduced substantially despite the overall impact of this element. LETI [24] suggests that other techniques could include reducing structural requirements through reduced building weight, increasing knowledge on reduction strategies, calculation methods, and material recording, which is in line with the UK Green Building Council. Hossain et al. [85] found that locally sourcing materials could reduce the overall energy effects by around 28%, in line with Bhardwaj [52], claiming that transportation has the greatest impact on embodied energy. Further, the built environment's carbon footprint is extensively affected by the demand for construction materials worldwide. While more innovative methods include using bio-materials and living technology in housing to minimise material usage and embodied energy, their use at a commercial scale is still in infancy [86].

4. Research Method

An exploratory, single case study design assessed embodied carbon in affordable housing. An exploratory study can be identified as the initial investigative stage of a more rigorous study to follow. The case study approach allows for a detailed investigation of the issues of concern [87]. The case study project selected was a typical low-cost, affordable housing project. Multiple housing designs within the project were analysed for their embodied carbon. As Yin [88] has explained, studying a single case is appropriate if the single case represents a common case, as in the project chosen here. Rather than selecting an exemplary project with targeted action to reduce embodied energy, a typical housing project has been selected as this would provide a better account of the general situation on new-build affordable housing. The houses in the development are intended either to be socially rented or sold on a shared-ownership basis. The study was subjected to methodological triangulation to increase accuracy. Initially, embodied carbon was calculated to identify embodied carbon significant building elements and critical areas for improvement. A total of three common house types used in the case study development were used for this embodied carbon calculation. Secondly, semi-structured interviews were conducted with the selected members of the project team.

An exploratory approach was adopted in undertaking semi-structured interviews with the key members of the project design team. Face-to-face interviews were carried out in the interviewees' board room. Reasons for conducting face-to-face interviews were to have a great rapport between the interviewer and interviewees, to monitor body language, which helps with the flow of the interviews, and to identify any limitations related to the responses. Semi-structured interviews queried the respondents, which allowed key questions to be answered and probed the respondents on any new themes emerging from the discussion. Accordingly, five well-experienced members of the project design team were interviewed. Table 1 presents the profile of the interviewees.

Table 1. Profile of Interviewees.

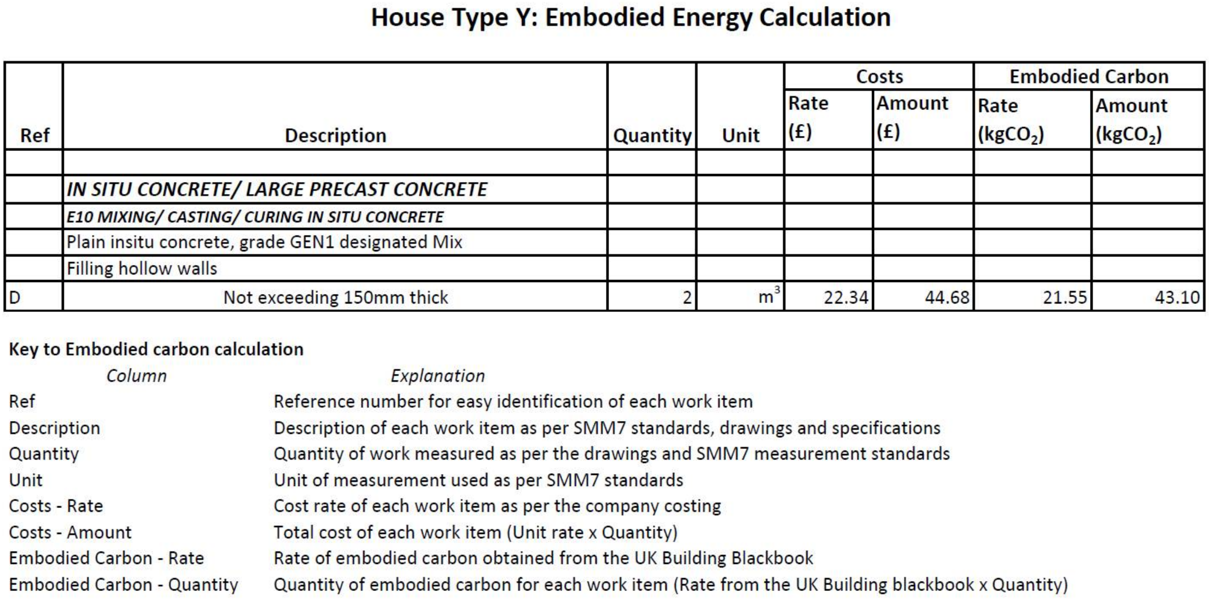
No.	Team	Interviewee Code	Designation
1	Project Design Team	A	Lead Project Quantity Surveyor
2		B	Head of Delivery, Social Housing Provider
3		C	Managing Director for Project Quantity Surveyor
4		D	Design and Build Manager—Contractor
5		E	Project Delivery Manager—Social Housing Provider

The interviews were recorded and transcribed via true verbatim. This allowed a natural flow of conversation without breaks for writing or forgetting vital information. Moreover, interview transcripts were reviewed as a validation technique. Interviewees had the opportunity to read and clarify any statements made during the interviews, and this enhanced the accuracy of the data.

After that, themes on drivers, barriers, and reduction techniques were developed. Non-probability sampling was selected since there is no probability attached to the unit of measurement [89]. The purposive sampling technique, which comes under non-probability sampling methods, was selected as the most suitable sampling technique to select interviewees since there is no probability attached to the population unit, and selection relies on the researcher's judgment [89]. Lastly, project documents, including contract documents, were examined to extract further information.

The main building elements such as substructure, superstructure, roof, internal partitions, and finishes were considered to calculate the embodied energy. The external works were not included within the calculation as this would be divided equally amongst the houses in the development and could not be effectively measured with the resources available. The take-off was carried out as per the Standard Method of Measurement 7 (SMM7) format and transferred to a bill of quantities where the carbon rates were applied. SMM7 was selected as the measurement guide due to it being the standard used in the case-study project and also because of its compatibility with The UK Building Black book [90], which is one of the limited resources produced in a bill of quantity format [91]. To select the most appropriate carbon database for this study, an exercise was completed whereby the databases were accessed, and a set of identical searches were completed. Other alternatives such as Ecoinvent, Inventory of Carbon and Energy, WRAP, Greenbook Live, and Eco Platform were considered, but the UK Building Black book was selected as the most suitable tool to obtain carbon data due to the compatibility with the method of measurement used in the project [92]. This allowed taking account of both materials and operations, a benefit not offered by most of the databases considered. No allowance for wastage will be added as it is already accounted for within the carbon rate [90]. The UK Building Black book presents embodied carbon of building work adopting a cradle-to-end of construction approach, excluding transport. Therefore, the calculations are based on cradle-to-end of construction, and embodied carbon of transport is not included. While transport is not included, [93] found that embodied carbon calculation arrived at using the Black book was considerably higher than cradle-to-grave calculations arrived at using BRE Green Guide. As commented by [93], while there can be disparities between the results produced by different construction carbon counting tools, the Black book is commonly used to calculate embedded carbon in construction work. Figure 1 presents an example of how embodied carbon for each work item was calculated to provide a better understanding of the calculation involved. The stepwise calculation followed is identified below for ease of reference.

- Each work item involved in the project was identified, and quantities of each work item were measured/quantified as per the SMM7 measurement standards, according to the project's drawings. (This step has already been completed by the project team).
- Then the embodied carbon rate for each work item was obtained from the UK Building Black Book.
- Embodied carbon quantity of each work item was calculated by multiplying the quantity of work by the unit rate of embodied carbon.
- Quantities from all work items were then enumerated to arrive at the total embodied carbon for each house type.



House Type Y: Embodied Energy Calculation

Ref	Description	Quantity	Unit	Costs		Embodied Carbon	
				Rate (£)	Amount (£)	Rate ($kgCO_2$)	Amount ($kgCO_2$)
	IN SITU CONCRETE/ LARGE PRECAST CONCRETE						
	E10 MIXING/ CASTING/ CURING IN SITU CONCRETE						
	Plain insitu concrete, grade GEN1 designated Mix						
	Filling hollow walls						
D	Not exceeding 150mm thick	2	m^3	22.34	44.68	21.55	43.10

Key to Embodied carbon calculation

Column	*Explanation*
Ref	Reference number for easy identification of each work item
Description	Description of each work item as per SMM7 standards, drawings and specifications
Quantity	Quantity of work measured as per the drawings and SMM7 measurement standards
Unit	Unit of measurement used as per SMM7 standards
Costs - Rate	Cost rate of each work item as per the company costing
Costs - Amount	Total cost of each work item (Unit rate x Quantity)
Embodied Carbon - Rate	Rate of embodied carbon obtained from the UK Building Blackbook
Embodied Carbon - Quantity	Quantity of embodied carbon for each work item (Rate from the UK Building blackbook x Quantity)

Figure 1. Example of Embodied Carbon Calculation.

5. Results and Discussion

5.1. Embodied Carbon

Within the case-study project, 3 house types were selected for carbon calculation and analysis; two detached (Types Y and Z) and one semi-detached property (Type X). These properties have been selected as they were the most common properties in the development. UK Building Blackbook can be recognized as one of the most common tools used for carbon calculations in the UK [92]. Therefore, the UK Building Blackbook was used for embodied energy calculation in this study. Table 2 reflects the results of the embodied energy calculations. When comparing the results against the targets set by the industry, the case study houses are substantially below the baseline figure of 800 kg CO_2/m^2. Nevertheless, only two of the three properties fall within the LETI (2020) target of 500 kg CO_2/m^2. Moreover, all of the properties within the study would fail to meet the RIBA or 2030 LETI target of 300 kg CO_2/m^2, meaning a reduction of 53%, 40%, and 32% is required for property types B, C, and E, respectively, to fall within these targets.

Table 2. Embodied Carbon Calculations.

House Type	Gross Internal Floor Area (GIFA)	Total		Total (m^2)	
	(m^2)	(£)	(kg CO_2)	(£/m^2)	(kg CO_2/m^2)
Type X (3 Bedroom semi-detached property)	91	77,491	58,073	850	637
Type Y (3 bedroom detached property)	99	76,937	49,331	779	499
Type Z (4 bedroom detached property)	137	88,592	58,727	648	429

According to the embodied carbon calculation, the main work sections (as per SMM7) that contributed to embedded carbon were Masonry work, Building fabric sundries, concrete, and linings/sheathing/dry partitioning (Please see Table 3). Building trades/elements of brickwork and blockwork have contributed to the high embodied carbon levels of Masonry work, whereas insulation work has contributed to the high embodied carbon levels in the building fabric sundries work section. Embodied energy on brickwork, blockwork, concretework, insulation, and partitioning/dry lining is generally in line with what has previously been reported by Arrigoni et al. [44]. However, varying from

Monahan and Powell's [76] calculations, these could be due to the relatively larger floor area, construction methods and materials used in the current development, and also the carbon calculation methods used

Table 3. Contribution of each work section towards the overall embodied carbon level.

Work Section	**Contribution of Each Work Section to Overall Embodied Carbon**		
	Type X	**Type Y**	**Type Z**
Groundwork	1%	1%	1%
Concrete	18%	13%	13%
Masonry	43%	47%	43%
Structural/Carcassing metal/timber	2%	2%	2%
Cladding/Covering	1%	2%	2%
Waterproofing	1%	1%	1%
Linings/Sheathing/Dry partitioning	9%	12%	11%
Windows/Doors/Stairs	2%	2%	0%
Surface finishes	4%	3%	4%
Furniture/Equipment	0%	0%	1%
Building fabric sundries	18%	14%	19%
Disposal systems	0%	0%	1%
Meachanical/heating/cooling/refrigeration systems	2%	2%	2%

The project team and project document analysis highlighted three solutions as practical techniques for reducing the embodied energy of the project; reducing wastage, opting for timber windows in-lieu of u-PVC, and loft space utilisation. Therefore, the study calculated and analysed the feasibility of the proposed three techniques. Among various embodied energy reduction techniques, reducing wastage was identified as an achievable solution. It was suggested that onsite wastage could be reduced from 10% to 5% in the first instance and to 0% eventually. Table 4 shows the potential cost and energy-saving, relating to a 5% reduction. However, it is important to understand that these calculations do not include reduced skip charges and transportation due to less material waste and packaging. And this is not impacting the U Value or operational capacity of the building.

Table 4. Reduction of Waste by 5% Embodied Carbon Forecast.

Element	**House Type X**		**House Type Y**		**House Type Z**	
	(£)	**(kg CO_2)**	**(£)**	**(kg CO_2)**	**(£)**	**(kg CO_2)**
Brickwork	−0.33%	−0.91%	−0.37%	−1.16%	−0.33%	−1.02%
Blockwork	−0.47%	−0.61%	−0.34%	−0.31%	−0.31%	−0.27%
Concrete	−0.35%	−0.86%	−0.15%	−0.41%	−0.45%	−1.23%
Insulation	−0.39%	−1.05%	−0.29%	−0.95%	−0.47%	−1.43%
Cavity Closers	−0.12%	−0.47%	−0.34%	−1.39%	−0.05%	−0.37%

Another solution was to install timber windows instead of u-PVC. As shown in Table 5, this technique can influence a substantial reduction within the element which also has a large effect on the building's whole embodied energy count, however, at an increased cost. While the cost of the building element will increase substantially, the cost impact of the whole building was a 2.9% cost increase on average. This technique does not impact the U Value or operational capacity of the building, though the cost impact may affect the practicality of implementation in affordable housing units.

Table 5. Exchange of PVC to Timber Windows.

Element	House Type X		House Type Y		House Type Z	
	(£)	**(kg CO_2)**	**(£)**	**(kg CO_2)**	**(£)**	**(kg CO_2)**
Windows	126.87%	−72.45%	178.94%	−73.59%	48.97%	−43.13%
Effect on House Type	2.66%	−0.73%	2.69%	−2.85%	3.36%	−0.96%

The last suggested improvement in the evaluation was utilising the loft space as GIFA, as shown in Table 6. The insulation had been designed within this building, lines within the roof rather than at ceiling level, meaning there was no additional insulation. The calculations used usable floor space only and included the additional embodied energy to install the stairs and the Velux windows. Although this method did not reduce the total embodied energy, it will bring down the embodied energy per square metre of gross floor area—thus contributing to achieving the LETI [24] target. It will also provide additional floor space in these affordable housing units, catering to much larger households.

Table 6. Loft Space Utilisation.

House Type	Original GIFA	Revised GIFA	Original Embodied Carbon		Revised Embodied Carbon	
	(m^2)	**(m^2)**	**(kg CO_2)**	**(kg CO_2/m^2)**	**(kg CO_2)**	**(kg CO_2/m^2)**
X	91	101	58,073	637	58,114	91
Y	99	121	49,331	499	49,372	99
Z	137	158	58,727	429	58,768	137

5.2. Drivers for Reduced Embodied Energy Implementation

Drivers for reducing embodied energy were discussed in the exploratory semi-structured interviews. The requirement of implementing proper legislation was identified as a key driver by 4 of the interviewees. Interviewees cited that proper regulation is essential to drive the industry to implement embodied energy reduction techniques in affordable housing. Further, if there is appropriate legislation, it will enhance the data standard given by the contractor for the development. Interviewee B suggested that enforcing change through regulation is the most effective way to allow a clear direction for reducing embodied energy. Moreover, environmentally conscious social housing providers and their policies regarding life cycle costing for components, sustainable materials, global warming potential of materials, waste management plans, and removal of waste were recognised as a driver by Interviewee A. Further, the interviewee mentioned introducing various sustainability aspects in their housing plans. According to the client's requirement, they are ready to fulfill it to reduce embodied energy and achieve the sustainability requirements. All participants highlighted and agreed to recognise the client as the biggest driver in this process. Interviewee A highlighted the client's involvement by saying, "the client is definitely the biggest driver; without the client, you cannot implement any policies. Everything has to be passed through the client, as any changes could affect their KPIs, and we may not be aware of that". Further, Hendrickson et al. [42] also emphasised the client's control in purchasing decisions which significantly affects when purchasing sustainability materials.

There is limited literature focusing on the local authorities as a driver. However, it is discussed widely in the interviews. Four participants recognised the local authorities as a driver which involves funding or planning permission targets in affordable housing. Interviewee C stated that through the involvement of local authorities, organisations could gain competitive advantages regarding embodied energy. Moreover, there is a developing theme throughout responses that affordable housing providers could be driven through enforced targets placed on funding acquisition, with three out of five discussing the criticality of funding on development success. Interviewee B implied that low embodied energy products could be inflated in costs due to high demand due to improved design efficiency. This contrasts with literature that shows a positive correlation between reduced embodied energy and reduced project costs. Likewise, participants denote embodied energy minimisation as a by-product of cost-saving initiatives. While other design changes had caused an increase in both cost and energy, supporting the correlation further. Accordingly, the summary of drivers and barriers for reduced embodied energy implementation are presented in Table 7.

Table 7. Drivers, Barriers and Techniques for Reduced Embodied Energy Implementation. √

		Sub-Category	Frequency of Occurrence within the Interview	Interview Reference				
				A	B	C	D	E
Drivers		Regulation	26	√	√	√		√
		Organisational	10	√	√	√	√	√
		Client	15	√	√	√	√	√
		Financial	38	√	√	√	√	√
		Local Authorities	15	√	√	√		√
		Public Demand	13	√	√	√	√	
		Programming	7		√	√		√
		House Typology	7		√	√	√	√
		Collaboration	4		√	√		√
		Market Demand	1		√			
		Technological	1			√		
Barriers		Operational Energy Prioritisation	31	√	√	√	√	√
		Operational energy reduction leading to increased embodied energy	1			√		
		Knowledge/Skill	20	√	√	√	√	√
		Lack of Effective Estimation Techniques	5		√	√		√
		Design Preference	4	√	√			
		Material Production Potential	1	√				
		Contractor	8	√	√	√		√
		Culture	3	√	√			
		Carbon Offsetting	5		√	√		
		Transportation	5		√			√
Embodied Energy Reduction Techniques	RT1	Material Longevity	0					
	RT2	Minimising Material Use or Intensity	7	√	√	√	√	
	RT3	Reducing Waste	1		√			
	RT4	Recycling and Re-use	3	√			√	
	RT5	More Efficient use of Space	2	√	√			
	RT6	Local Contractors/Suppliers	17	√	√	√		√
	RT7	Modular Construction	6	√	√	√	√	√
	RT8	Regeneration of Current Stock	1		√			
	RT9	Site Organisation	1			√		

5.3. Barriers to Reduced Embodied Energy Implementation

The semi-structured interviewees were also consulted on barriers to reducing embodied energy in affordable housing (See Table 7). Interviewee B revealed a current trend of shifting the government's interest from sustainability concerns to other financial requirements due to the current situation in the world, especially the housing shortage and the resultant demand for affordable housing. Therefore, meeting the housing demand has gained special attention other than the sustainability requirements, which directly affect the reduction strategies of embodied energy. Interviewees A and C confirmed that they are not conscious of the value of reducing embodied energy. The absence of proper discussion with the design and construction team regarding the reduction of embodied energy was also revealed concerning their organisation.

Home Quality Mark (HQM) can be recognised as one of the most popular platforms created to serve the UK's housebuilders and the householders who buy and rent new houses [36]. Harper [36] highlighted the concern given to the embodied energy in this platform. However, Interviewee A confirmed that the HQM platform is not currently followed in their organisation. In addition to that, Interviewee B highlighted that the unawareness of local councils regarding embodied energy and net-zero carbon could affect the reduction of embodied energy. Furthermore, Interviewee B stated that site constraints dictate the level of remediation work regarding embodied energy and highlighted the inherent focal disparity between academics and professionals when discussing financial barriers regarding embodied energy, especially when it comes to affordable housing.

Interviewee A postulated the increase in cost from these design changes derives from a lack of knowledge, whereas Interviewee B implied that generally, contractors need to "protect profit margins" which Interviewee A stated as an incentive to drive costs down to comply with competitive tendering suggesting that the initiatives may not be fully implemented. The theme of profit retention remains throughout, where there is a consensus that housing providers build in line with other providers and market demand as consumers would not pay an inflated price for a similar standard finish house, especially in affordable housing. Interviewee A said that when previous initiatives such as Passivhaus were implemented, there was little to no uptake from customers, which is potentially due to consumers not understanding the critical nature of the energy crisis, consequentially creating a lack of consumer focus. There are varying arguments throughout the interviews over whether the consumer dictates the market with purchasing power or whether they are subject to market conditions as they are limited to a finite number of properties due to the housing crisis. It is consistent throughout that programme implications are key considerations for reduction implementation, and therefore a programme reduction would likely incentivise embodied energy reduction. Farmer [43] discussed programming overruns concerning industry fragmentation which Participant B proclaims is a barrier to sustainability. Participant C expands, suggesting that without specifying efficiently at the brief stage, the design team fails to ensure contractual compliance. Therefore, despite having sufficient technology to make the development carbon neutral, the development fails to meet targets.

Moreover, Interviewee B stated that reductions in embodied energy are considered a low priority option in affordable housing as operational energy is not reduced to net zero. Interviewee A also agreed by stating, "I believe operational energy has the greatest importance placed upon it. I think there are increased checking parameters. An example of this is U Values. Depending on build quality, U values are forecasted and then checked to certify it has been completed to that standard and will perform in the required way. This is a requirement for the SAP ratings". Despite gaining focus, literature states that embodied energy has been excluded from many energy calculations. The knowledge gap was also mentioned as a barrier to reduced embodied energy implementation, and 3 of the interviewees discussed knowledge either directly or indirectly during the study, suggesting that embodied energy "is misunderstood" and "training" and "skills" would impede implementation. And also, Interviewees C and E showed a lack of knowledge in certain aspects, such as measuring energy consumption and definitions of key terms, respectively.

Literature findings highlighted that the wide system boundaries and poor methodology contribute to the high levels of data uncertainty with embodied energy compared with operational energy [25]. One participant raised a concern regarding the commerciality of using offsetting to reduce the overall consumption of buildings. The RIBA suggests that a reduction of 50–70% on embodied energy should be made before offsetting, although no information is provided on the policing of this. Offsetting operational energy may not be achievable in some scenarios, with literature suggesting that Passivhaus properties can take up to 80 years to offset.

5.4. Techniques for Reducing Embodied Energy

Literature findings and all interviewees except Interviewee D consistently stated that local labour and the supply chain would provide a reduction in embodied energy, with discussions on travel distance increasing (Table 6). This development has an 85% local labour initiative, whereby site staff has to provide postcodes for record purposes. However, Interviewee E raises the issue that the main contractor's main office is 50 miles from the site, suggesting that there is substantial transportation for the supply chain, which conflicts with previous comments. Although, there is no confirmation that any calculations are being carried out with the data. Interviewee B suggests that companies may begin to procure within the UK due to Brexit, further minimising embodied energy with reduced delivery distances.

Interviewees A and B introduced new concepts to minimise wastage and material usage through efficient utilisation of space, which is also a theme within the literature. The concepts included timber-framed walls in place of blockwork and the utilisation of loft space to minimise house extensions by users. Interviewee B and literature both highlighted material waste as contributing to embodied energy. However, the literature primarily focuses on designing off-site waste, whereas interviewees highlighted onsite waste protocols through site management logistics. Another method of efficiently reducing material wastage is a modular construction which Interviewees C and D opine could reduce embodied energy and increase sustainability which is in line with the 70% reduction statistics in literature [66]. There are conflicts about whether the cost and programming impacts are positive as this would impact implementation (Interviewees A and B). Furthermore, recycling and re-use are key techniques to reduce embodied energy throughout primary and secondary data.

Sources within the literature express the vitality of renovating existing properties before demolishing and rebuilding [64]. However, Interviewee B suggested that regeneration schemes are not initiated as they are unfeasible. Furthermore, there are arguments in the interviews as to whether regeneration schemes can achieve the required number of homes per year to solve the housing crisis. Interviewee C suggests that one of the methods to minimise embodied energy is being utilised onsite and consists of efficiently organising the site to allow minimum plant movement. Material longevity was also raised as a material reduction technique within the literature, although it was absent from transcripts.

Table 8 highlights the compatibility of embodied energy reduction techniques with identified drivers and barriers. According to the analysis presented in Table 8, five drivers, namely regulation, organisational, client, financial, and local authorities, can trigger the implementation of all the nine embodied energy reduction techniques. As in the above, the enabler 'programming' helps deploy all the techniques except RT6: local contractor/supplier. RT1, RT2, and RT9, being material longevity, minimising material use or intensity, and site organisation can be implemented with the aid of 'public demand'. Even though the 'market demand' is not triggered by the reduction techniques such as RT3, RT4, RT5, RT6, RT7, and RT8, it supports implementing the reduction techniques of material longevity, minimising material use and intensity, and site organisation. On the other hand, implementing all the embodied energy reduction techniques can be limited due to barriers such as 'operational energy prioritisation', 'operational energy reduction and increases the embodied energy, 'transportation', and 'contractor'. But, the lack of an effective estimation technique was not identified as a barrier to implementing any of the reduction techniques. Carbon offsetting and knowledge/skill could be barriers to some implementation options.

Table 8. Compatibility of Techniques with Drivers and Barriers Present on Development.

Drivers and Barriers	**Embodied Energy Reduction Techniques**								
	RT1	**RT2**	**RT3**	**RT4**	**RT5**	**RT6**	**RT7**	**RT8**	**RT9**
Drivers									
Regulation	√	√	√	√	√	√	√	√	√
Organisational	√	√	√	√	√	√	√	√	√
Client	√	√	√	√	√	√	√	√	√
Financial	√	√	√	√	√	√	√	√	√
Local Authorities	√	√	√	√	√	√	√	√	√
Public Demand	√	√	X	X	X	X	X	X	√
Programming	√	√	√	√	√	X	√	√	√
House Typology	X	√	X	X	√	X	√	√	√
Collaboration	√	X	√	√	X	X	√	√	√
Market Demand	√	√	X	X	X	X	X	X	√
Technological	√	X	√	√	√	X	√	X	√
Barriers									
Operational Energy Prioritisation	√	√	√	√	√	√	√	√	√
Operational energy reduction leading to increased embodied energy	√	√	√	√	√	√	√	√	√
Knowledge/Skill	√	X	X	X	X	X	X	X	√
Lack of Effective Estimation Techniques	X	X	X	X	X	X	X	X	X
Design Preference	X	X	√	√	√	X	X	√	X
Material Production Potential	√	√	√	√	√	X	√	√	√
Contractor	√	√	√	√	√	√	√	√	√
Culture	√	√	√	√	√	X	X	√	X
Carbon Offsetting	X	√	X	X	X	X	X	√	X
Transportation	√	√	√	√	√	√	√	√	√

6. Conclusions

This study assessed the importance placed by both the client and the design team on embodied energy in the residential affordable housing sector to determine areas for improvement in reducing embodied energy. The study calculated the embodied energy consumption of three affordable housing units. The results revealed that all three housing units are substantially below the baseline target of 800 kg CO_2/m^2. Although the current target is satisfied, only two out of three properties fall within the LETI 2020 target of 500 kg CO_2/m^2. On the other hand, all three housing units would fail to fulfill the RIBA or LETI target of 300 kg CO_2/m^2. On one hand, caution should be exercised when interpreting the embedded carbon calculations for these 3 properties due to limitations in the embodied carbon calculation method adopted here, including the UK Building Blackbook and the Bill of Quantities from the project. The data, however, shed light on the general level of embodied carbon in typically affordable housing units in the UK. The key observation here is that much still needs to be done to achieve 'best practice' standards and to help achieve future national and industry targets concerning embodied carbon.

Therefore, the study explored drivers and barriers for reduced embodied carbon implementation and embodied carbon reduction techniques to bring them in line with the targets above. Accordingly, 11 drivers and 9 barriers were recognised, and 9 reduction techniques were proposed and checked for compatibility. The sub-categories of 'financial' and ‘regulation’ were recognised as the top two drivers, and ‘client’ and ‘local authorities’ were highlighted as sub-categories next in line. On the other hand, ‘operational energy prioritisation’ was the most significant barrier to reducing embodied carbon. The study findings on potential reduction strategies and the potential of key enablers and barriers can be exploited to reduce embodied carbon in new-build affordable housing units. Thus the research facilitates UK building stakeholders to mitigate embodied carbon in the residential housing sector, especially affordable housing. The findings reveal that further work is required to future-proof the affordable housing sector in line with the targets set for the decade ahead. Any improvements will positively contribute to the net zero-carbon agenda as the work required to offset embodied energy will be reduced. Further research is required to better understand the financial and operational impacts of the strategies suggested.

This research answers the demand for methodological pluralism in research on embodied energy. Research on embodied carbon is mostly calculative and seeks to quantify embodied energy. This research, however, offers an alternative viewpoint, complementing the embodied energy calculations with qualitative research. The approach adopted not only provided a quantitative account of embodied carbon in the case study project but also shed light on drivers and barriers to reducing embodied carbon and potential strategies for reducing embodied carbon in typical affordable residential development.

As with every research, this research also possesses some limitations. The embodied carbon calculations were based on the Bill of quantities already prepared for the project, and although spot checks have been performed throughout the process, there can be some uncertainty on the accuracy of dimensions. If there were errors in the bills, these would have caused an incorrect reading when calculating the embodied energy. Furthermore, the rate book used for the study (UK Building Black book) has limitations that will have impacted the accuracy of embodied carbon calculations. While the embodied carbon calculations may carry limitations, they present a good account of current rates of embodied carbon in residential developments. Apart from that, although continually stressed the anonymity of the study, there were signs that one or few of the participants were expressing signs of Halo Effect Bias. The researchers believe this may have occurred due to a pre-existing professional relationship.

Based on the results of this paper, the study proposes several research directions in the field of embodied energy. The present study was undertaken as an exploratory study to obtain a general account of the state of affairs in terms of embodied carbon in residential developments, particularly affordable housing, and as a precursor to a more detailed study to follow. Further research can now be undertaken reflecting on the limitations of this exploratory research and to explain the observations further. Future research can be undertaken to evaluate the effect on the buildings from cradle to end of construction. This would allow an analysis of whether a higher initial embodied energy assists in the reduction of the whole life energy when looking at replacement and maintenance of the building. A further recommendation is to include multiple case studies to arrive at more generalisable findings. This would enable the understanding of the drivers and barriers in the housing sector and whether different sectors produce and maintain buildings with a different approach. This may also highlight whether the form of the contract assists in its ability to monitor and reduce embodied energy. Measuring the building works from scratch ahead of carbon calculations rather than relying on an already developed bill of quantities may also improve the accuracy of findings.

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