



# Identifying the potential for resource and embodied energy savings within the UK building sector



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## ABSTRACT

The EU building sector is widely acknowledged as a primary source of anthropogenic emissions, contributing directly to climate change. Recent studies estimate the sector to account for approximately 40% of primary energy use and 50% of extracted materials within the European Union. The Energy Performance of Buildings Directive 2010/31/EU requires efficiency improvements to be implemented in all new EU buildings, with a requirement that from 2020 all new buildings constructed should be “nearly energy zero”. From this stance the embodied energy of a building, when taking a full life-cycle perspective, is gaining importance and will become a more dominant issue to tackle when striving for sector-wide reduction in the coming years. This research took the UK as a case study and investigated where reduction measures are most suited to reduce material and energy consumption. The study proposes four reduction measures strategically focusing on hotspots of excessive consumption. The findings demonstrate that significant reductions can be achieved for the UK building sector's annual material and embodied energy consumption in the short to midterm, with projections estimating resource and embodied energy savings respectively of 4.7% and 6.4% by 2020 and 9.3% and 28.6% by 2030.

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## 1. Introduction

Reducing both absolute energy and resource consumption are vital components of the European Union's (EU) sustainable growth strategy to 2020, with a major objective outlined as a 20% decrease in EU primary energy use [1]. The 2020 strategy of the European Commission (EC) promotes resource efficiency as one of seven flagship initiatives required towards creating a more sustainable Europe [2]. The building sector is widely acknowledged to be a major contributor to both energy and resource consumption throughout the EU [2]. The EU's Roadmap for a Resource Efficient Europe labels the sector responsible for approximately 40% of primary energy use and 50% of all extracted materials [3], qualifying the sector of essential interest for reduction efforts up to 2020 and strategies for longer term goals to 2050.

The combination of renewable energy for production and the use of renewable resources for application as building materials provide an ideal solution to issues relating to overexploitation of fossil resources. However, under practical circumstances, a sectoral transition to a situation in which renewable materials are

the prominent choice for developers is at least decade's away [4]. This is especially the case within the construction sector where requirements such as physical strength play a pivotal role in the selection of materials used. Therefore, resource and energy efficiency improvements are increasingly important challenges for the building industry and provide the most realistic opportunity to reduce consumption within a shorter time frame considering the EU's ambition to move to a competitive low carbon economy by 2050 [5].

The World Business Council for Sustainable Development projections state that current efforts in resource efficiency require a 4–10 fold increase in order to sustainably meet growing demand, with significant improvements needed by 2020 [6]. For the building sector this increased efficiency should focus on reduction across the complete life-cycle of buildings to achieve the maximum potential. Resource efficient construction provides a systemic approach that adds to the potential of other ambitions such as building related energy and emissions reductions, considering material and energy flows over the lifetime of a building. However, to date, firm legislation to reduce resource consumption is absent in all major EU policies. End-use energy efficiency within the building sector is better understood and is believed to hold the largest potential due to a mature range of cost effective efficiency technologies and measures [1,7]. EU legislation tends to focus solely on achieving

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efficiency improvements during the operational phase of a building and is governed by the Energy Performance of Buildings Directive 2010/31/EU. According to a recent report from the European Environmental Agency, UK is mentioned as one of the countries that needs to strengthen its policy package in order to achieve stated energy savings targets [8]. The current UK policy package needs additional measures to reach short term targets and future ambitions. In this paper, the UK is taken as a case study. The influence of the building sector on consumption is emphasised for the UK, where the current situation displays a shortage in housing and an imminent population growth [9,10], driven largely by high fertility and net immigration rates. This places further pressures onto the 2020 target.

There is substantial yet undetermined potential to further reduce consumption in the building sector via implementing best practice reduction measures that focus on the life-cycle stages outside of the operational phase alone [11]. In the case of reducing primary energy consumption this involves targeting the embodied energy (EBE) of a building, which is the energy required to construct the building and the production of its constituent materials. Although the energy used in the operational phase of a buildings life-cycle is currently agreed to be the dominant factor [12–14], the opportunity for savings potential within this phase is under deep investigation, with the deployment of technological advances including energy efficient heating and lighting appliances already factored into the European Energy Efficiency Directive 2012/27/EU [7]. As a consequence of the increased efforts to create a greener use phase, the ratio of embodied to operational energy has increased from 20:80 to 40:60 for an average UK building, with predictions that EBE will soon be the dominating factor [15]. Furthermore, when measured over a longer time-span, EBE is projected to be the dominating factor for a buildings LC energy requirements, especially for low-energy buildings [13]. When considering resource efficiency, understanding and reporting of quantitative material consumption is not adequate within the EU building sector or within the UK's. This is observed as widely fluctuating resource and associated EBE performance levels throughout the EU zone and between manufacturers and individual site projects for some of the key building materials per m<sup>2</sup> floor space created [16].

A range of best practices and innovative methods are available to bring about reductions in both resource and associated EBE from the EU average. These efficiency improvements may be achieved through the implementation of a range of reduction measures at sector-wide level, calling for a harmonisation of performance levels. There exists a body of research that identifies a variety of opportunities and details the physical reductions possible. These approaches include; material substitution, best available technology, resource light construction, and prefabrication, among others. However, from a review of the related literature these best practices remain almost exclusively at small scale, with their effects on resource and energy efficiency unexplored if they were to be implemented at sector-wide scale.

The primary purpose of this research is to provide a first assessment of the savings potential for natural resources used as construction materials and energy in the form of EBE. This includes identifying the current hotspots of excessive use within the building process and calculating the mitigation potential available. The results obtained from the research allow the development of a series of realistic and achievable time bound quantitative targets for sector-wide physical reductions which are further placed into national context, as seen for energy consumption in the operational phase. These targets are set for annual reductions achievable by the year 2020 in line with other targets and by the year 2030, to explore the importance of a longer term strategy. The outcomes of this study provide UK policy makers with an alternative additional pathway to greening the sector. Findings are presumed to

be indicative of those available in all member states (MS) with a comparable building practice to the UK.

## 2. Methods

### 2.1. Identifying consumption of resources and EBE

The consumption of each material investigated is often reported for the UK as whole (national consumption per annum), but not exclusively for the building sector. Extensive desk based research allowed for the sector's annual consumption to be identified and tracked over the historical period 2000–2010. This data was primarily gathered from Eurostat's Prodcom Database in combination with sector specific reports detailing the percentages of national consumption used for building production alone, carried out in a manner consistent with other generators of resource flow data. The materials selected for investigation in this study were chosen due to their dominant use in the sector by quantity and incorporation into the buildings envelope. The materials investigated are; aggregates, aluminium, cement articles, bricks, copper, glass, ready mixed concrete, steel, and timber.<sup>1</sup> The EBE of each material investigated was taken directly from the Inventory of Carbon and Energy (ICE) [17], considered to be the most up to date reference, providing an average figure for materials consumed within the UK. Total EBE used for each material was identified by:

$$EBE_{i,y} = Q_{i,y} \times EBEV_i \quad (1)$$

Where:

$EBE_{i,y}$  = Embodied energy (MJ) of a specific material ( $i$ ) in year  $y$   
 $Q_{i,y}$  = The quantity (kg) of a specific material ( $i$ ) used for new buildings in year  $y$   
 $EBEV_i$  = Specific embodied energy (MJ/kg) of a material ( $i$ )

#### 2.1.1. A process based LCI analysis

The ICE database, selected for use as a reference for the EBE quantities relating to each material investigated, set the system boundary for life cycle energy analysis as cradle-to-gate [17], thus, not accounting for transportation to site and energy used during assembly into the building.

Additionally, within the ICE dataset, EBE is quantified using processed-based analysis during the LCI phase of each materials LCA study. This approach itineraries the inputs and outputs within the defined system boundaries, in this case using multiple site specific data which reflects the real system being studied and eventually averaged to give an estimation of the average UK production LC [17]. This process-based approach however requires a cut-off criteria at which point the energy requirements located in higher upstream orders for the product system are no longer accounted for. This is commonly referred to as truncation error due to the system not being completely modelled. The effects of this in relation to the EBE assigned to building materials has been discussed in previous studies [18–20] and suggest even the most extensive process-based inventories do not capture a sufficient level of system completeness.

An alternative method within LCA is the input–output (IO) approach which uses aggregated sectorial level transactions data to account for complex inter industry relationships and shows the fate of products in the market, whether they leave the system to meet the supply side demand or take part in further production. However, the level of sector aggregation has an influence on the results

<sup>1</sup> The annual consumption by the UK building sector for each material investigated is provided within the Supplementary Electronic Material.

[21]. The IO method suffers from the aggregation error and assumes all products within the same sector have identical energy intensity per unit of monetary value [22]. Since process details of a sector are missing it limits the use of IO frameworks as a LCA tool [23].

Combining the approaches from purely process-based LCA tool as performed for the construction of the ICE database with the IO framework results in a hybrid LCA model enhancing the suitability for economic-environmental LCA by integrating sector and process level data, significantly extending the system boundaries of the study. However, such hybrid assessments are not currently common practice among LCA practitioners and are not embedded within the practitioners standards ISO 14041 [24]. This is highlighted in Moncaster and Symons' study [25], which suggests that EBE compliance, measured using the TC350 standards within the UK building sector may be substantially underestimating the total EBE.

Conventional process-based analysis quantities for EBE pertaining to the building materials investigated is considered of suitable scope for the intended purposes of this study, especially considering the ICE database is tailored to the UK market. However, it must be acknowledged that the reported figures taken from the ICE database may be to an extent under-reporting the total associated EBE, the effects of this onto the result of this study are discussed within sub-section 4.1.

## 2.2. Identifying trends in building activity

The quantitative consumptions of each material were compared to the building activity for each year over the historical period 2000–2010. One of the few building activity indicators recorded for the UK is the number ( $N$ ) of households built per annum, provided by the Office for National Statistics [26]. The total floor space created in the building sector for both residential and non-residential is needed to accurately assess the intensity of material use, thus the following two assumptions are needed: (1) the average size of a UK residential property ( $\alpha$ ) held static throughout the period at 2008 levels, which is 91 m<sup>2</sup> according to the Enerdata database [27]; (2) the percentage of newly constructed residential floor space ( $\beta$ ) accounting for 75% (versus non-residential at 25%) as reported in the Building Performance Institute's UK country profile [28]. For the analysis the following formulas was used:

$$A_{\text{res}_y} = N_y \times \alpha \quad (2)$$

$$A_{\text{tot}_y} = A_{\text{res}_y} / \beta$$

Where;

$A_{\text{res}_y}$  = Total new residential floor space (m<sup>2</sup>) created in year  $y$

$N_y$  = Number of new residential building in year  $y$

$\alpha$  = Average floor space of a UK residential property (91 m<sup>2</sup>)

$A_{\text{tot}_y}$  = Total new residential and commercial floor space (m<sup>2</sup>) created in year  $y$

$\beta$  = % of floor space for residential properties (75%)

## 2.3. Identifying the areas of concern (hotspots) for resource and embodied energy consumption

Using the compiled data on total volume of each material used for new residential and non-residential buildings and the known building activity, expressed as total floor space created, the trends for amount of material and associated EBE required to construct a theoretical 1 m<sup>2</sup> residential and commercial floor space were identified. By using a relative unit of 1 m<sup>2</sup>, fluxes and trends in individual material use can be analysed over the 2000–2010

period. The identified trends were carried forward into projections to 2020 and 2030. This was calculated as follows:

$$Q_{\text{spec}_{i,y}} = Q_{i,y} / A_{\text{tot}_y} \quad (3)$$

$$EBE_{\text{spec}_{i,y}} = EBEV_i \times Q_{\text{spec}_{i,y}}$$

Where;

$Q_{\text{spec}_{i,y}}$  = the quantity (kg) of a specific material ( $i$ ) used per 1 m<sup>2</sup> of new building in year  $y$

$EBE_{\text{spec}_{i,y}}$  = Embodied energy (MJ) of a specific material ( $i$ ) in year  $y$  per 1 m<sup>2</sup> of new buildings in year  $y$

The quantitative amounts of material used and the associated EBE needed to create 1 m<sup>2</sup> new floor space for each individual material were compared. This provides a preliminary assessment to identify where the hotspots for concern exist, for both resource and EBE consumption. Additionally, a review of the supply chain for each material when incorporated into a building was conducted and aided in assessing the cumulative energy and material demand, including where relevant, information surrounding waste streams and opportunities for material substitution, plus insight into the likely occurrence of future use in the sector. This analysis provided information for selection of appropriate reduction measures to investigate, indicating where reduction efforts would be most effective.

## 2.4. Scenario construction

The data collection and analysis of the period 2000–2010 forms a 'historical scenario' and identified what resource and EBE consumption for the UK building sector actually took place over this period. When projecting forward, three separate scenarios were developed to provide a degree of sensitivity analysis as to the expected consumption levels to 2030. The three exploratory scenarios differ with respect to assumptions on *population growth* and/or *demolition rates* of existing buildings. The building activity is assumed to have a direct relationship with population growth and assumes floor space per capita remain at levels reported during 2000–2010. The amount of each material used per 1 m<sup>2</sup> floor space follows a linear trend from that determined during the historical period. A literature review revealed there is little available reliable data on the expected future EBE efficiency gains for the production of the investigated materials. Therefore, the study assumes the values remain fixed for creation of building material per kg (a so-called frozen technology perspective), but will change per 1 m<sup>2</sup> new floor space created due to the projected changes in absolute quantity used per 1 m<sup>2</sup>. They are constructed as follows:

**Scenario A** projects an average of  $22.7 \times 10^6$  m<sup>2</sup> floor space is constructed per annum, based on the extrapolated rate of new construction in 2000–2010. Whereas the demolition rate remains static at the levels observed between 1996 and 2004, 0.1% of total building stock [29].

**Scenario B** projects an average of  $27.9 \times 10^6$  m<sup>2</sup> floor space is constructed per annum during the period 2010–2020. As population growth slows after 2020 this is reduced to an average of  $24.3 \times 10^6$  [m<sup>2</sup>] per annum over the period 2020–2030. The demolition rate remains fixed at 0.1%. This scenario follows the population projections projected by the Office for National Statistics [30].

**Scenario C** projects an average of  $31.8 \times 10^6$  m<sup>2</sup> space is constructed per annum during the period 2010–2030. This scenario follows the *Energy Trends 2030–update 2009* projections [31]. The rate of new building construction is highest within this scenario due to assumed demolition rate being 0.4% of the total housing stock per annum, in accordance with UK's ambitions to replace the ageing building stock [32].

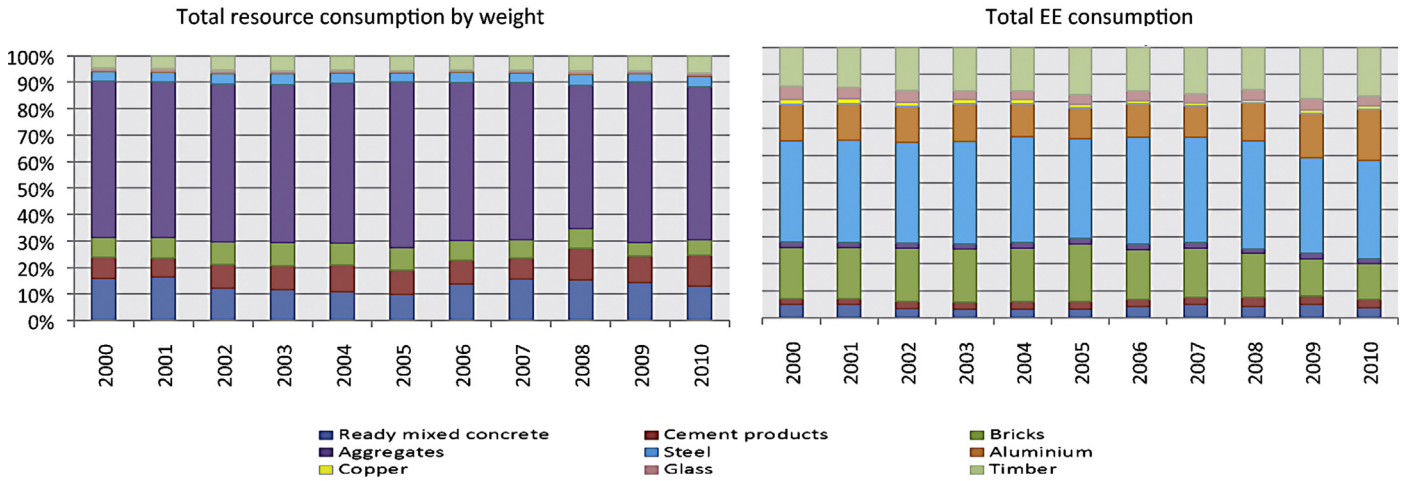


Fig. 1. Contribution of resources to quantity and associated EBE use in the UK building sector, expressed as % of total use.<sup>2</sup>

Additionally, a high and medium deployment rate for each of the reduction measures is explored under each scenario. The deployment rates are created based on a literature review of the attached industries and similar transitional periods from similar technologies/strategies.

### 2.5. Selection of reduction measures and assessment of their potential

A review of current case studies/literature was carried out, to identify reduction measures operating at small to local scale that aim towards reducing consumption in the hotspots identified. The focus of this research is to identify two crucial data inputs needed, namely:

1. The quantity of resources saved per tonne of material produced expressed per m<sup>2</sup> of floor space [kg/m<sup>2</sup>]
2. The amount of EBE saved per tonnes of material used [MJ/tonne] which may then be expressed per m<sup>2</sup> of newly constructed floor space.

The reduction potential for each measure (resource efficiency, EBE) is calculated as follows:

$$R_{\text{tot},i,y} = R_{\text{spec},i} \times A_{\text{tot},y} \times \eta_i \quad (4)$$

Where:

$R_{\text{tot},i,y}$  = Total reduction (tonne or MJ) by a specific measure ( $i$ ) in year  $y$

$R_{\text{spec},i}$  = Reduction (tonne/m<sup>2</sup> or MJ/m<sup>2</sup>) by a specific measure ( $i$ ) achieved per m<sup>2</sup> of new floor space constructed

$\eta_i$  = Annual deployment rate for a specific measure ( $i$ )

The reduction potential of each measure is then calculated up to 2020 and extended to 2030 for both high and medium deployment assumptions and under each of the future scenarios explored. The reductions are calculated as the difference in consumption in both resource use and EBE after implementation, compared to no

implementation. The total cumulative potential for each measure was calculated as follows:

$$R_{\text{tot},\text{cum},i} = \sum_{y=2010}^{2020/30} R_{\text{tot},i,y} \quad (5)$$

Where:

$R_{\text{tot},\text{cum},i}$  = Total cumulative reductions over the period 2010–2020/30

## 3. Results

### 3.1. Analysis of consumption trends over the historical period 2000–2010 (identifying consumption hotspots)

The consumption of major building materials within the UK building sector and their respective EBE was obtained for the period 2000–2010. A comparative analysis of the results for individual materials is provided below in Fig. 1, used to identify the most prominent areas of concern in terms of overall consumption by the sector. Additionally, comparative analysis was performed to identify the trends in absolute consumption over the period compared to the total floor space constructed and per 100 m<sup>2</sup>. This served to highlight the trends in resource efficiency over the period and concluded that the composition of the average 100 m<sup>2</sup> building remained almost static over the period. Furthermore, negligible improvement in resource efficiency was observed. The full analysis is available within the supplementary electronic material.

From Fig. 1 it is seen that aggregates are the most dominantly used material within the UK building sector, consistently representing >50% of total material use, due to the heavy use within the foundation structure of modern buildings. However, a literature based assessment of the corresponding supply chain revealed there only to be scope available to reduce the use of virgin aggregate consumption within the sector, through exploiting opportunities existing in the downstream phases of the materials life-cycle, mainly via recycling pathways attached to the; glass, cement, concrete and brick industries [33]. This is already being carried out to near maximum potential in the UK with ~30% of all aggregates being produced from recycled sources [34], this is limited by annual demolition and reclamation. In general the ratio of each of these key materials remains fairly static over the period, suggesting building techniques and design have remained fairly constant. More radical alternatives to common building construction tend to be privately

<sup>2</sup> N.B 100% of materials displayed in Fig. 1 refers only to the building materials under investigation.



funded projects and take place on small-scale meaning they did not significantly affect material fluxes at national level.

Besides aggregates, the remaining consumption hotspots have attached commercially available processes or technology that may be scaled up to achieve reductions in resource or EBE consumption or both. The findings are prioritised, based on absolute consumption levels for both materials by quantity and associated EBE, with selection following the principle that tackling the hotspots will harvest the largest savings, with cross-cutting measures introduced where possible. In order of largest contribution for EBE these are then 1.Steel, 2.Aluminium, 3.Bricks, 4.Timber, 5.Cementitious material; and for resource use by quantity 1.All resources combined, 2.Cementitious materials, 3.Bricks.

A literature review of the supply chain for each of the major consumption areas identified that the largest opportunity for reductions are commonly observed within the manufacturing stage, where the highest energy inputs are typically observed and waste production is most excessive, a typical finding within life cycle assessments. The review identified some opportunities for reduction measures in the downstream phase, but typically found no significant level of absolute resource reduction to be possible in the extraction or demolition phases. It is necessary to communicate that transportation is not covered in this study due, to large variances between building projects and it does not have a direct effect on material consumption, additionally, energy required for transportation typically contributes only a small percentage of total embodied energy [35]. The foremost current issues found and the acknowledged hotspots are briefly outlined below in Table 1, presented alongside the identified opportunities within each materials supply chain, indicating where reduction potential is present throughout the life-cycle stages assessed in this research. The final column indicates where each reduction measures (1–4) targets.

### 3.2. Proposed reduction measures (1–4)

A collection of 4 reduction measures were investigated that specifically target one or more of the opportunities identified in Table 1. This section provides the reader with a general description of each measure (1–4) including the quantitative reduction potential at a fixed relative level i.e. (kg/100m<sup>2</sup>) or (MJ/kg). For details of the calculations and factored assumptions used to provide the quantitative reduction potentials, the reader is referred to the supplementary material.

#### 3.2.1. Reduction measure 1 – timber frame and clad walls (as a substitute for conventional masonry construction)

The conventional UK building consists of walls comprising an inner skin of concrete blocks (articles of cement) and an outer skin of brick work. The use of these materials accounts for the vast majority of their application within the sector and is consequently a suitable area to focus when aiming to reduce consumption. Combined, these materials accounted for roughly 17% of key material use within the sector by quantity and 21% of the associated EBE per 100 m<sup>2</sup> new floor space constructed over the period 2000–2010.

The reduction measure investigated is the proposed substitution of the conventional masonry walls with timber frame and clad structures, a lighter weight alternative that is able to meet the tensile strength and insulation levels embedded in current UK building regulations. This alternative method uses prefabricated module components built offsite reducing construction waste [36], and additional EBE savings are observed due to significant reductions in absolute quantity of material used.

The reductions were calculated at 26.5 tonnes per 100 m<sup>2</sup> that is brought about by a substitution of 13.5 tonnes of concrete blocks and 24.3 tonnes of bricks, with 11.25 tonnes of timber. This

translates to [247GJ/100m<sup>2</sup>] reduction in EBE an equivalent of ~30% decrease from the average observed during 2000–2010.

#### 3.2.2. Reduction measure 2 – use of best available technology to lower EBE in the metal industry

As seen in Fig. 1 the EBE of metals constituted >50% of the total used for building production, of which the vast majority is accounted for by steel and aluminium production. Using recycled sources offers large energy reductions (~95% for aluminium production and ~74% for steel). However, recycling of these metals is already >96% in the UK [37], further scope to reduce consumption through this path is limited. A review of both of the metals supply chains identified the manufacturing step to be the largest energy consumer and exposed a range of best available technologies that are commercially available to reduce this demand.

Worrell et al. (2008) [38], **calculated** the energy reductions that may be obtained throughout a number of industrial production processes including steel and aluminium manufacture when deploying the world's best available technology. They analysed the major energy consuming processes in each manufacturing chain and the results are compared to the values for the average steel and aluminium used in UK buildings as reported in ICE [17]. When assuming the same product types and the percentages of recycling being static for the UK, the levels of best practice represent opportunity of savings equivalent to 36.0 [MJ/kg] (23%) for aluminium production, and 13.5 [MJ/kg] (43%) for steel used in buildings.

#### 3.2.3. Reduction measure 3 – reducing EBE of cement through best available technology and fly ash replacement

An in depth literature review of LCA studies surrounding the ready mixed concrete and articles of cement supply chain revealed cement to be the component most largely responsible for EBE, even though by weight it represents only a small fraction. Portland cement is the most common type used in the UK, with an EBE content of 5.02 [MJ/kg] [17], far higher than that of the subsequent building products, ready mixed concrete 0.95 [MJ/kg] and articles made of cement 0.67 [MJ/kg] [17].

Worrell et al. (2008) showed that implementation of best available technologies during the Portland cement production chain can lower energy requirements to ~3.35[MJ/kg]. The majority of the savings derive from technologies implemented during the clinker making process which is responsible for ~90% of the EBE demand [38]. This represents a reduction from the UK average equivalent to 1.67[MJ/kg] (33%). In addition to these technologically induced reductions, fly ash (a waste product of other industrial processes) may be added to the cement mixture up to 35%. The inclusion of this fly ash effectively reduces the ratio of clinker needed, thus, the EBE is lowered [38]. When this approach is combined with the aforementioned best available technology, Worrell et al. reports reduced energy requirements of 2.44 [MJ/kg], increasing total savings to 2.58 [MJ/kg] (51.4%) from the UK average. This reduction in EBE required for cement production translates to:

- For ready mixed concrete at a ratio of 1:2:4 (cement, sand, aggregate) provides a reduction of 0.37 [MJ/kg], thus the UK average falls from 0.95 to 0.58 MJ/kg (39% reduction).
- For articles made of cement. At a tensile strength of 10 MPa provides a reduction of 0.24 [MJ/kg], thus the UK average falls to (0.67–0.24) 0.43 [MJ/kg] (36% reduction).

#### 3.2.4. Reduction measure 4 – decreasing waste production within the construction phase

The building sector is a large contributor to UK waste production [39]. A significant proportion of this waste arises from the constructional phase of a buildings life-cycle, where variations in

**Table 1**  
Summary of identified areas to tackle with greatest reduction potential.

Material	Current Issues	Opportunities/specific areas to tackle	Measure
<b>Aluminium</b>	<ul style="list-style-type: none"> <li>• Abundant material so likely to continue being used</li> <li>• Very high embodied energy</li> <li>• Quantities used are already very low</li> </ul>	<ul style="list-style-type: none"> <li>• <u><b>Reduce energy used in the manufacturing process especially electrolysis step.</b></u></li> <li>• Increase recycling (small potential)</li> <li>• Substitute for less energy intense material</li> </ul>	<b>2 and 4</b>
<b>Steel</b>	<ul style="list-style-type: none"> <li>• Abundant material so likely to continue being used</li> <li>• High embodied energy</li> <li>• Quantities used are relatively high</li> </ul>	<ul style="list-style-type: none"> <li>• <u><b>Reduce energy used in the manufacturing process especially BOF method and converting iron ore to pig iron</b></u></li> <li>• Increase recycling (small potential remaining however large quantities used so could be significant)</li> <li>• Substitute for less energy intense material</li> </ul>	<b>2 and 4</b>
<b>Bricks</b>	<ul style="list-style-type: none"> <li>• Negligible amounts of waste during upstream phases</li> <li>• Brick use appears to be declining over the period</li> </ul>	<ul style="list-style-type: none"> <li>• The firing and kiln phases of manufacture are the most energy intense and efforts to reduce this are key</li> <li>• <u><b>Can be substituted by timber</b></u></li> <li>• Techniques to lower quantity of clay needed or embodied energy in brick composition (e.g. soil brick)</li> <li>• Scope for reuse of bricks and increased recycled content</li> </ul>	<b>1 and 4</b>
<b>Ready mixed concrete</b>	<ul style="list-style-type: none"> <li>• Large Quantities used with no suitable replacement</li> <li>• Low embodied energy</li> </ul>	<ul style="list-style-type: none"> <li>• <u><b>Amount used should be reduced</b></u></li> <li>• <u><b>Embodied energy of the cement contained within the concrete is the only area of significance to tackle for EBE</b></u></li> <li>• <u><b>Recycled material potential is large but can only be used as aggregates</b></u></li> </ul>	<b>1, 3 and 4</b>
<b>Articles of cement</b>	<ul style="list-style-type: none"> <li>• Substantial quantities used and appears to be increasing</li> <li>• Low embodied energy</li> </ul>	<ul style="list-style-type: none"> <li>• <u><b>Embodied energy of the cement contained within the concrete is an area of significance to tackle for EBE</b></u></li> <li>• Pre-cast articles save energy in the construction phase</li> <li>• Also uses mechanical drying which is energy intense and this should be reduced</li> <li>• Can potential replace a % of bricks to reduce overall quantity and EE</li> <li>• <u><b>Can be partly substituted by timber</b></u></li> </ul>	<b>1, 3 and 4</b>

\* Tackled by investigated reduction measures 1–4.

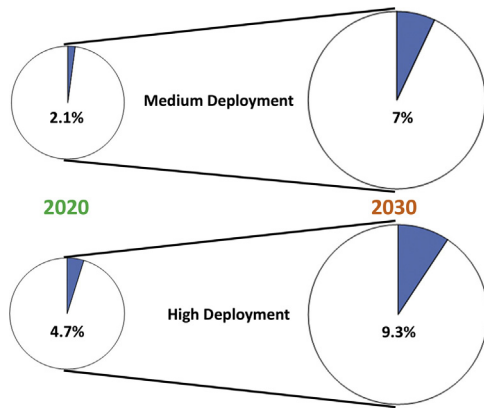


Fig. 2. Projected resource reduction in the target years 2020 and 2030.

onsite activities dictate the amount of waste occurring. This waste is often in the form of unused materials, damaged materials and inefficient building techniques. The efficiency in waste minimisation from site to site can vary dramatically depending on the procedures that have been put in place and willingness of the project leaders to reduce waste streams. The Building Resource Establishment's (BRE) SMART waste programme [39] has created a benchmark for waste production at a relative 100 m<sup>2</sup> for all building types. This study for BRE incorporates cases from 17 of the UK's 20 leading building contractors and shows the waste production achieved from an average 100 m<sup>2</sup> construction and additionally when performed under best practice conditions. Best practice measures under such systems involve going beyond the current average UK performance which largely focuses on meeting legal obligations [40]. Implementation of effective waste management site plans include, efficient design, improvement in material logistics, use of offsite construction and eliminating the over ordering of materials [40].

Using the data collected by BRE's waste smart programme and applying it to a theoretical 100 m<sup>2</sup> built floor space (both residential and non-residential combined) produces 18.8 tonnes of waste during the construction phase alone. After implementation of effective waste systems this may be reduced to <4.7 tonnes, representing a saving of 14.1 [tonnes/100m<sup>2</sup>] newly built floor space.

### 3.3. Identifying the reduction potential at sector scale for the UK in target years 2020 and 2030

#### 3.3.1. Projected efficiency of annual resource consumption in the target years

The projections for the percentage of resource consumption avoided due to implementation of the investigated measures are displayed below in Fig. 2 for the future target years assessed. The results represent the average findings between the three scenarios explored under both ascribed medium and high deployment rates, providing guidance for what may be achieved at national scale.

The results presented in Fig. 2 show that significant reductions in annual resource consumption are possible and can be achieved through the application of just two measures (1 and 4). The findings highlight the importance of evoking a long term approach as large increases are seen between the two target years. A stronger implementation strategy is observed to double savings in the short term by 2020 but becomes less important by 2030 as the measures reach full maturity, this is demonstrated by the relative decrease between the two modelled deployment rates. To put these reductions into context for savings at a project level, after implementation in the year 2020, 13.7 tonnes of resources are avoided for every 100 m<sup>2</sup> of floor space created, by 2030 this increases to 25.3 tonnes.

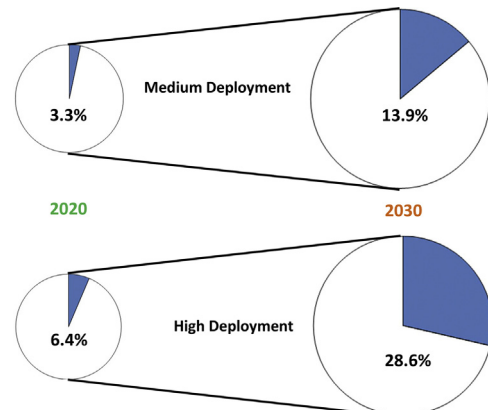


Fig. 3. Projected EBE reduction in the target years 2020 and 2030.

#### 3.3.2. Projected efficiency of annual EBE consumption in the target years

The efficiency gains projected for EBE consumption used for new building production after implementation of the measures are displayed below in Fig. 3.

Fig. 3 shows that significant efficiency gains for annual EBE consumption may be achieved in the short to mid-term. The results once again highlight the importance of long term policy support, with 2030 reductions much larger. Greater levels of reduction are observed for EBE than resource consumption by quantity, with the high deployment rate adopted producing positive notable contributions towards overarching EU targets. The projected reductions would result in avoidance of 61 PJ of EBE in the building sector and attached value chains per 100 m<sup>2</sup> new floor space constructed in 2020 and 269 PJ in the year 2030

#### 3.4. Absolute cumulative reduction potential during the investigated periods

The absolute cumulative resource and EBE reductions attributed to each reduction measure and when combined is reported in Table 3. The provision of cumulative reduction potentials provide insight into the total reductions possible during the time periods assessed, which has implications when assessing the accessible potential remaining within the sector for contributing to the national decrease required to meet the legally binding 2011 Carbon Budget Order. Furthermore, it is considered good practice to additionally analyse the cumulative potential as the choice of one target year alone may lead to an over-representation of any subsequent reductions achieved due solely to a lower rate of building activity within that year. The ranges in values presented in Table 2 are due to the sensitivity analysis carried out, including changes in build rate and deployment rate of the measures themselves. Typically (scenario A – medium deployment) provided the least absolute savings, whilst (scenario C – high deployment) produced the largest, due to the technique of linking deployment potential as a percentage of total new construction deployed in this research. This approach assumes that the demand for the measures will dictate their implementation to a greater degree than possible supply side constraints.

#### 3.4.1. Cumulative reductions in resource consumption

Measures 1 and 4 both hold resource reduction potentials for the UK building sector. Measure 4, which targets the reduction of a wider range of building materials (being a cross cutting measure) is observed to hold a larger potential than that of measure 1. When combined as a package they provide significant savings compared to no implementation.

**Table 2**  
Absolute cumulative reduction potential from measures 1–4.

Deployment rate	2013–2020				2013–2030			
	Resource [Mt]		EE [PJ]		Resource [Mt]		EE [PJ]	
	Med	High	Med	High	Med	High	Med	High
<b>Measure 1</b>	1.9–2.9	2.7–4.2	18–27	25–39	11–14.4	18–23.4	103–133	169–217
<b>Measure 2</b>			16–24	28–45			102–132	240–308
<b>Measure 3</b>			2.4–3.8	5.8–9.3			19.7–25.2	61.7–79.4
<b>Measure 4</b>	3.7–5.9	9.1–14.6			26.1–34.7	42.4–57.8		
<b>Combined measures</b>	<b>6–19.0</b>		<b>36–93</b>		<b>37–81</b>		<b>225–604</b>	
<b>% of cumulative use avoided</b>	<b>1.05–2.3%</b>		<b>2.1–3.5%</b>		<b>2.8–4.8%</b>		<b>5–11.8%</b>	

The cumulative reduction potential projected over the period 2013–2020 indicate a maximum of 8.9 Mtonnes of the total material requirement for new building production under medium deployment could be avoided. This is roughly double under high implementation for each building rate scenario. This difference highlights the value of pursuing an aggressive approach with policy support when aiming to stimulate the measures incorporation by the sector. The maximum reductions projected under high deployment up to 2020 identify 2.3% of the resource consumption may be avoided. Whilst 2.3% may not immediately appear as a promising result, it is worthwhile to recall that the sectors sheer consumption at ~50% of all extracted material in EU nations<sup>4</sup> would mean a national reduction of material demand for the UK of ~1.2%. Furthermore, in the year 2010 to construct an average sized UK house (91 m<sup>2</sup> floor space) required 299 tonnes of the materials included in this research. Thus, the 18.8 Mtonnes saved is equivalent to the quantity required to build 63 thousand average UK house sized buildings.

The projections over the period 2013–2030, show when the measures are allowed a longer time frame to establish themselves within the sectors practices, a large increase in the cumulative savings potential is observed. When allowed a 17 year timespan up to 2030, a maximum of 81.2 Mtonne or 4.8% of the total resources projected under no implementation is saved under high deployment. This is the equivalent of the total current material requirement to construct 272 thousand average UK house sized buildings.

#### 3.4.2. Cumulative reductions in EBE consumption

The projected EBE reduction potentials displayed in Table 2 derive from the implementation of measures 1, 2 and 3. Measures 1 and 2 provided the largest potential with similar contributions, whilst measure 3 accounted for <14% for all scenarios explored.

Over the short-term future 2013–2020, a cumulative reduction of 36–93 PJ of EBE may be realised varying on the degree of expansion to the UK building stock, representing a saving of 2.1–3.5%. As a primary objective of this research gravitates towards providing absolute energy savings that may be achieved by expanding current efforts that focus on the operational phase alone, a comparison of measures currently being undertaken is drawn. The replacement of a UK boiler (UK average efficiency = 60% [41]) by a category A 90% efficient boiler. The average UK house uses 42.2 GJ primary energy annually for heating purposes [41], the boiler replacement then provides annual savings of  $(42.2 \text{ GJ} \times 0.3)$  12.66 GJ. The savings projected under high implementation (93 PJ) is equivalent to the energy savings experienced if 1.05 M households were to switch

boilers throughout the entire period, so essentially installation must be complete in the base year.

When a longer term perspective 2013–2030 is taken, significant increases in cumulative reduction are identified, with projected avoidance of 471–605 PJ representing 10.3–11.8% of the total EBE required under all building rates investigated. This increase is attributed to the fact measures 1–3 are projected to observe increased diffusion into the sector as they approach maturity. The maximum reduction potential projected would require efforts in the operational phase equivalent to 2.81 M switching boilers for the entire period.

#### 3.5. Policy implications

A review of the UK building sector's reporting identified no suitable quantitative targets for resource and EBE reductions in life-cycle stages outside of the operational phase. No targets for resource consumption in the sector were found. Sector wide energy targets are part of the EU's 2020 strategy, the EC endorsed the Energy Efficiency Directive 2012/27/EU and in doing so set indicative targets for energy efficiency improvements across all major energy consuming sectors including the building sector. This target of a 20% decrease whilst suitable for reductions in the operational phase is unsuitable for reductions brought about by tackling EBE, due to the use of absolute primary energy consumption per annum in the target year as the indicator. Therefore, reduction measures implemented in the operational phase can achieve savings from the BAU projections in the target year for the whole existing building stock (or part thereof which the measure is implemented upon, for example low energy light bulbs in X% of buildings). However, savings in initial EBE can only be realised in new building production within the target year, thus subsequent savings are vastly overshadowed and would appear insignificant to measures implemented during the operational phase, providing a skewed portrait of the importance of tackling EBE. Therefore, an ideal target would concentrate on resource use and EBE for new building production alone to provide a true reflection of the reductions possible.

The results of this research show that through the implementation of a handful of purposely targeted reduction measures significant cumulative and annual resource consumption savings can be achieved within the UK building sector, in line with the ambitions of the European Commission's flagship initiative for a resource efficient Europe. The results may be used to provide a guideline for the setting of provisional targets, previously not

**Table 3**  
Contribution to UK national energy efficiency.

	UK gross inland energy consumption		Saved in target year	
	Reported in [Ktoe]	Converted to [PJ]	[PJ]	% of total energy consumption projected
2020	208, 829	8743	23	0.26
2030	204, 549	8564	72	0.85



possible due to a lack of quantitative understanding surrounding the sectors consumption behaviour. The projection for annual resource consumption indicates a decrease of 4.7% is achievable by 2020 and 9.3% by 2030. Acknowledging that there further remain additional opportunities for reduction, not discussed within this paper, the study concludes provisional targets may be set at:

- 5% resource efficiency gains by 2020
- 10% resource efficiency gains by 2030

The successful achievement of these targets would require ambitious and immediate action, through which the high deployment rate proposed is adopted. In the Roadmap for a Resource Efficient Europe the following milestone is identified:

**“Milestone: By 2020 the renovation and construction of buildings and infrastructure will be made to high resource efficiency levels. The life-cycle approach will be widely applied; all new buildings will be nearly zero-energy and highly material efficient.”** EC Roadmap to A Resource Efficient Europe COM (2011) 571 final. Pg18

If a 5% increase in resource efficiency is classed as “high resource efficiency levels” then this milestone for the building sector is possible if supported by policy at the level required to attain the high deployment scenario used in this report. Anything above 5% would need a radical change to the way current buildings are designed and seems an unlikely occurrence considering the composition and total material use per m<sup>2</sup> of new floor space remained almost static over the past decade.

As no existing targets for national resource consumption are in place, to provide insight into what the projected savings mean at UK level, the nation's domestic material consumption (excluding fossil fuels) is used. No projection for the UK's Domestic material consumption exist however a review of this indicator over the past decade indicated it remained fairly stable at an average of 428 Mtonnes [42]. Assuming this level remains static up to 2030 the annual resource saving in the year 2020 is equivalent to 1.2% of the DMC and 1.6% by 2030. It is highly probable that the EC's ambitions, although not yet quantitatively stated would supersede this amount, thus reduction opportunities present in the sector cannot solely satisfy the reductions required at a national level.

Reductions for the projected EBE use are observed to hold a comparatively larger scope. The findings indicate a maximum of 6.4% annual reduction in EBE required is achievable by 2020 and a notable 28.6% by 2030. The proposed quantitative targets for EBE reductions are then.

- 7% embodied energy efficiency gains by 2020
- 30% embodied energy efficiency gains by 2030

These targets once more require a high deployment rate to be undertaken and the addition of measures that acquire savings within areas not considered as hotspots in this report, which may hold less potential but may still be beneficial. It appears that a long term strategy is essential to create a meaningful impact, highlighted by the much larger reductions possible by 2030. To provide insight into how the observed future savings potentials could contribute to the national energy savings, projections of the Gross Inland Energy Consumption for the UK have been taken from the *EU Energy Trends–update 2009* projection [31] and are almost identical to that of the Department of Energy and Climate Change 2012 primary energy consumption projections [43].

As seen in Table 3 the percentage of the total national energy consumption avoided from the *EU Energy Trends – update 2009* projections are at first glance unimpressive (i.e. <1% in both target years). From a national perspective it is clear that the energy

savings potential available from opening up the building sector to reduction measures in life-cycle stages outside of the operational phase is not realistically going to have a large effect at a national level. Especially not in the short term, contributing a maximum efficiency improvement of 0.26% to the EU 2020 target. However, it must be remembered that the reduction measures put forward by this research are only affecting newly built construction in the target year, which is less than 1% of the entire building stock and this is impressive considering the whole sector accounts for 40% of total national energy use.

#### 4. Discussion

Decisions and assumptions deployed throughout the research have an inevitable effect on the accuracy of the results obtained, which may have led to the exaggeration or underreporting of the reduction potential projected. The deployment potentials explored for each measure were largely based on the assessment of similar technological or behavioural transitions performed in various sectors. However, the research would benefit from a deep cost benefit analysis of each proposed measure and would lead to a clearer understanding of the timescale in which savings may be realised. This is under the remit that stakeholders predominantly base their decision on whether to implement measures on economic viability, with assumed prioritisation towards more financially attractive ventures.

The incorporation of a ‘frozen’ technology perspective, embedded within the ‘no implementation’ baseline for the EBE requirements for production of building materials was applied. This technique means that autonomous improvements in the energy efficiency of material production are not factored into the results produced. Ultimately, this means that the (no implementation) projections for future periods may over-report the EBE demand, thus the savings potentials reported for energy are likely to be slightly lower than projected. One way to avoid this would be to incorporate the projected energy requirements for building product production up to 2030. However, since separate manufacturers often display varying energy requirements for the same product and there being no readily available projection of these expected efficiency gains, it was not possible to account for the effect of autonomous efficiency improvements in the related manufacturing industries during the analysis at present. Within the boundaries of this study, one could expect that building materials production (especially of metals) are becoming less energy intensive in general through increased technological efficiency. However, the efficiency increase, although quantitatively unknown, is expected not to influence the prioritisation of measures selected, as the expected discrepancies are not large enough to cover the differences among the materials. This is further complicated by many of the materials requiring import and the sourcing of future supplies to the sector can only be guessed at.

The inclusion of projections into the cumulative reduction potentials over the investigated periods allows for a more accurate reflection in terms of efficiency improvements for the sector. This is imperative to include, as efficiency targets that focus on a specific future year do not tell the full story. This is due to the fact that building activity largely governs the total consumption and by viewing an isolated year alone may lead to incorrect assessment of the sectors improvements if the new building construction level in the specific target year is low.

The method provides an approach that may be replicated for other EU MS and indeed for additional and forthcoming reduction measures that are not discussed in this paper. For energy savings, the measures explored promise real opportunity for the EU building sector as a whole and it is predicted similar levels of efficiency gains can be achieved in most MS due to the choice of materials

investigated being consistently used in buildings throughout the EU. The replacement of conventional walls by timber structures would have a significant effect for many MS, however would be more limited in countries such as Norway and Sweden which already have >90% of the total building stock constructed this way [44]. Measure 2 and to an extent measure 3 are more international measures which means their implementation would by default affect the whole of the EU due to import of the affected materials. The results obtained from this research then serve to act as an example of what may be achieved for the EU building sector as a whole if these measures were to be adopted as harmonised EU standards throughout the building sector and associated value chains.

In order to capitalise on the opportunities for reductions that exist in the building sector outside of the well documented operational phase, the development of an annually/biannually updatable database that reports on sector-wide consumption at national scale is required. This could be additionally paired with a separate database that provides quantitative information regarding new and existing best practices that influence the sector's consumption. It is presumed this development would entail an increased interaction between associated industries, which may benefit through the production of a knowledge sharing platform. The addition of financial projections surrounding the costs for implementation for such measures would provide policy makers with direction, incentive and the information required to develop informed strategies regarding the sustainability of the sector.

#### 4.1. Further considerations

The use of the ICE database [17], discussed in section 2.1.2 means that a cradle to gate assessment of the EBE data is taken. This means that the energy required during the building assembly and that at end of life (EOL) are not fully accounted for. Even though the scope of this study is relatively small in relation to an average building's life-span, it should be noted that the omission of these life-cycle phases may change the results to an extent, even though the embodied energy of the materials from recycled sources has also been taken into account. For instance, the disposal process of concrete will inevitably increase the overall EBE. Alternatively, timber may be recaptured and used within the power generation sector, meaning EBE quantities associated to the material are reduced. The study would benefit from further investigation and inclusion of these EOL possibilities for each of the materials. Furthermore, the operational phase of the building's life is not assessed within this study which from an operational energy perspective is not an issue due to the building requiring no more energy after introduction of a measure than before, due to for instance, identical thermal insulation properties. However, the issue of recurrent EBE, the additional EBE required for physical maintenance and replacement of materials will affect the absolute EBE quantities relating to a building life-cycle. This is relevant for measures where the durability and service life of the substituting material is less than its conventional counterpart. A relevant example of this would be timber facade needing replacement more frequently than bricks as seen in measure 1. Whilst this material substitution indeed reduces the initial EBE, it can conversely lead to the increase in recurrent EBE and thus absolute EBE of the building. Previous case studies carried out [45,46] highlight the importance of recurrent embodied energy over various life spans and indicate similar quantities as initial EBE requirements. Thus, the inclusion of a service life comparison would need to be included for the exploration of scenarios that extend past the 2030 projections outlined in this paper. The omission within the <20 year period currently assessed is thought to be minimal, but should be incorporated within the study due to its importance in selection of initial materials when conducting a life-cycle assessment.

Previous studies [47,48] highlight the popular argumentation for the integration of aggregated IO data within the process-based LCI inventory approach to form a hybrid assessment. A case study carried out by Crawford [48] indicates that on average the use of process based LCI data alone could lead to under reporting of the absolute EBE for buildings by 64% and for building products by 79%. The projections for EBE determined by this study then are likely to be underestimating the absolute EBE savings that are possible due to incomplete system boundaries. For example, the omission of capital goods within the upstream production phases could lead to considerable differences between the two approaches, especially for material substitution measures. Combining the process based data available through data sets such as the ICE, with the UK's IO tables which are publicly available and reported by the *Office For National Statistics* [49] would arguably improve the level of accuracy in terms of system completeness via adapting a hybrid LCA approach.

## 5. Conclusion

The EC's Energy Efficiency Plan highlights the building sector has the largest savings potential available for energy reductions. However, efforts currently focussing on the operational phase alone are currently unable to meet the 20% reductions needed by 2020, thus the contribution of these findings may hold an additional role even though they are not enough to bridge the discrepancy. The findings become of greater importance when looking further ahead, if the embodied: operational energy requirements for buildings will shift from 80:20 to 60:40 or greater EBE will become the priority area to tackle for future building stock, mainly due to advancing efficiency gains in the operational phase, including the use of renewable energy. With longer-term targets in mind the World Business Council for Sustainable Development predicts a need to reduced resource consumption levels to just 10–25% of current levels by 2050. Under the reduction measures explored in this research, the savings potential available in the building sector is unable to meet these targets.

The paper has identified the physical consumption of the major resources used within the UK building sector. The results obtained provide quantitative insight into where areas of currently excessive use reside and the reduction potentials accessible through actions that are commercially available at present. These results suggest there is scope to reduce consumptions of both resource and associated EBE within the sector outside of the operational phase, which may additionally provide economic benefit, producing a more sustainable and competitive sector. The results produced from this research provide important information for UK and EU policy makers with regards to directing the strategies of building design, construction and manufacturing processes throughout the supply chain of the building sector. The provision of these savings projections provide further aid in future tasks surrounding the monitoring and review of performance of implemented measures compared to the maximum savings potential and any future defined targets.

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