A comparison of the lifecycle cost and embodied energy of buildings

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Executive summary

When assessing the energy impact of a new building, it is important to consider both the energy consumed by the building during its occupancy and the energy consumed in its design and construction. The sum of these two quantities represents the *lifecycle embodied energy*. The purpose of this report is to investigate whether this quantity is related to the cost of a building.

The money that is spent on a building throughout its lifecycle can be broadly broken into three components: materials (such as steel or concrete), human labour (including architects and bricklayers) and direct energy consumption (including heating during occupancy and diesel for on-site equipment). The energy content of direct energy consumption can be easily measured, and there exist a number of studies seeking to quantify the embodied energy of a range of building materials. However, few attempts have been made to establish the embodied energy of human labour. This report devises a methodology that can be used to estimate the intensity of embodied energy within human labour.

We estimated the cost and embodied energy associated with the design, construction and occupancy of a school and an office, based on a previous study by the Concrete Centre and Arup. These quantities were compared and certain variables, such as the structural method and utility prices, were controlled in order to estimate their respective impacts.

The key conclusion from this report is that we found no general proportionality between cost and embodied energy across the whole building lifecycle. However, when the lifecycle is broken down into smaller components a relationship between cost and energy does exist. The ratio between the two quantities – the £/kWh rate – varies between these components. For labour, we estimated this rate to be 83p/kWh, while direct energy consumption costs only 4p/kWh.

We propose that the £/kWh rate for a given construction material is a function of the relative quantities of direct energy and labour that are required to manufacture it. Further research should be carried out to investigate this.

Therefore, a building developer seeking to build a low energy building will not necessarily achieve this by simply seeking to minimise lifecycle costs. A more dominant factor is the proportion of human labour involved compared with automated processes consuming energy directly. Generally, our study concludes that minimising human labour in the building design, construction and maintenance will both reduce costs and embodied energy. However, such a policy would have societal impacts that require consideration. Additionally, although the energy consumption of the building may be lower, it may be the case that the UK's overall energy consumption will rise as a consequence.

Acknowledgements

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1 Introduction

When new buildings are being designed there is now an increasing desire for them to be 'low energy'. This can refer to the building's performance during occupancy or can refer to the energy consumed by the people and processes required to design and construct it. The latter is often known as 'embodied energy'. This report is interested in both types of energy consumption and will refer to them jointly as the 'life-cycle embodied energy'. This definition includes energy consumed in the design, construction and occupancy periods of the building, both directly in the form of gas, electricity and diesel, and indirectly in the form of energy embodied within materials and human labour.

The current definition of 'embodied energy' is very limited; in particular the energy consumed during the design process and in on-site activities is rarely included. Chapter 2 explores how the boundaries can be expanded to account for these activities.

The embodied energy associated with human labour is rarely accounted for, yet a huge proportion of the cost goes into paying people to work on the design, construction and maintenance of a building. Chapter 3 looks at how labour can be accounted for by exploring the relationship between money and energy consumption on a macroeconomic scale, in order to establish a kWh/£ rate to convert labour spending to embodied energy.

This report will consider whether there is a proportionality between the cost of a building and the energy embodied within it. If a strong correlation exists, it would conclude that the most energy efficient building over any given timescale would be the cheapest to construct or run over that timescale. To explore whether this concept can be applied directly to construction materials, chapter 6 features a small study on the relationship between the embodied energy and cost of a range of building materials.

In order to consider the cost of energy over the occupancy period of the building's lifecycle, it is necessary to know the price of gas and electricity over several decades. This is clearly impossible to predict with confidence. However, chapter 4 explores the trends in domestic gas and electricity prices over the last 30 years and considers the effects of continuing these trends on future prices.

The comparison of the cost and energy consumption associated with a building's lifecycle will primarily be based on a 2008 study by the Concrete Centre into the cost of constructing a school, an office and a hospital using up to eight different structural techniques. Chapter 5 will begin by estimating the cost and energy consumption of the school at the design, construction and occupancy stages, based on an average of the construction methods.

In order to assess the impact of varying the construction method, estimates of cost and energy will also be calculated for the most expensive and least expensive construction methods. Additionally, estimates will be calculated for alternative scenarios assuming different energy price inflation rates. Finally, the cost and embodied energy for the life cycle of an office building will be estimated in order to highlight any differences to the school.

1.1 Units

To provide consistency when comparing different buildings, all calculations of cost and energy over the building lifecycle will be per square metre (m^2). This is consistent with the approach taken by the Concrete Centre study.

Energy will generally be referred to in terms of kilowatt-hours (kWh). Although this is not a standard SI unit (such as the joule), it is a familiar and well-used measure of energy. It refers to the quantity of energy consumed by a 1000 watt appliance (for example, a fan heater) over the period of an hour. Gas and electricity bills measure domestic consumption in kWh, making it a familiar unit of energy for the general public; a 40W light bulb consumes approximately 1kWh in a 24 hour period.

When this report refers to energy it is in reference to the quantity measured at the point of consumption. Due to energy being delivered along inefficient supply lines (electricity generation and transmission, for example), a kilowatt-hour of energy consumed as heat or light in a building is not equivalent to a kilowatt-hour of primary energy inputted at the power plant.

2 'Life-cycle embodied energy' – what's in it?

'Embodied energy' is now a common phrase, although the energy consumption that is taken into account for it can vary. In building construction, the whole design stage itself is seldom considered, and for the construction stage, gate-to-site activities are not usually covered, such as transportation of materials to site, and energy use on site. Ideally, all energy consuming processes should be accounted for, but since this is not feasible, a boundary must be drawn around what practically can be.

Each design stage broadly breaks down into:

- Direct energy consumed through electricity, gas and petrol
- Energy consumption attributed to materials
- Energy consumption attributed to labour

Direct energy use and its cost are simple to account for, and one can be estimated with the other, since the price of energy is established and known.

The embodied energy of materials can also be broken down into four categories:

- Direct energy use
- Transportation
- Labour
- Raw materials

Of course some materials have a number of stages of production, and it would be possible to track back the 'raw materials' element over the stages of processing, but this is impractical and too complex for calculation.

Accounting of energy attributed to labour is rarely considered in embodied energy and will be discussed in the chapter 3. It is important to note that our attempt to account for it is included in each life-cycle stage, but not within the embodied energy of materials, i.e. to manufacture them.

The definition of 'life-cycle embodied energy' set out in the introduction could have also included the final stage of a building's life-cycle – the process of demolition. However it was estimated that the contribution of demolition would be relatively insignificant, as well as creating the possibility of double-counting recycled materials.

3 Embodied energy of human labour

When we consider the embodied energy of a building, we immediately think about the energy such as gas, diesel and electricity directly consumed by machinery to manufacture, process and transport building materials, and then that required to actually construct the building on site.

Less obvious is the energy attributed to human labour. For example, a construction worker needs transport to get to the site. He also needs to use physical energy on site, so of course he needs to eat. What about a project designer, before the building is even constructed? She'll need to sit in an office and probably use a computer, with adequate light, plus heating and cooling to work in.

All of these things require energy, and most of them consume it directly, apart from food which is a product so one might try to account for its embodied energy from a number of processes.

Where do we draw the line? If the building project is paying for all these workers, should we account for their personal energy use too? Their pay through working on the project allows them to have heat and electricity in their homes, take holidays, buy all sorts of 'stuff' such as computers, iPods, food and whatever else goes into an affluent Western lifestyle.

3.1 Existing approaches in accounting for energy of labour

The Simons Group (1) developed a methodology to assign the emissions associated with design offices, site transport, site equipment etc. to the building project.

The Simons Group research draws a relatively tight lifestyle boundary to calculate the embodied emissions of labour. For example, in the design stage the emissions of the design office over 12 months is evenly divided between the employee-hours worked in the office, then assigned on a pro rata basis to the building projects under design.

In terms of transport, this approach accounts for transport of designers to and from meetings, but not from their home to place of work. It also does not account for the indirect emissions of the employees' lifestyles.

3.2 Establishing the labour rate

3.2.1 Approaches to calculating a labour rate

We believe that as much energy as possible should be accounted for in terms of labour, not only transport and building energy use in order to allow the workforce to operate over the design and construction periods, but also personal energy use which is paid for by the building project. The former is more straightforward to estimate, whereas the energy people use personally is much more complicated to account for.

How can we estimate how much energy people use at home, what holidays they take, and what stuff they buy? A quicker way might be to simply take someone's salary – if they're paid more, they can afford to consume more, so use more energy. Perhaps we can take someone's salary, multiply it by some kWh/£ factor, and make an estimate of their energy consumption. However, how much does this salary and energy consumption relationship hold?

3.2.2 Relationship between salary and energy consumption

The travel activities of households and individuals in Oxfordshire were studied (2) in order to compare the results against socioeconomic factors. Figure 1 illustrates the relationship between the salary earned by an individual and the amount of energy they consume through personal transport. There is a clear trend to indicate that personal energy consumption in transport is higher among people who have a higher income. Those with an income greater than £40,000 per year consume more than four times as much energy through transport than those earning less than £10,000 per year.

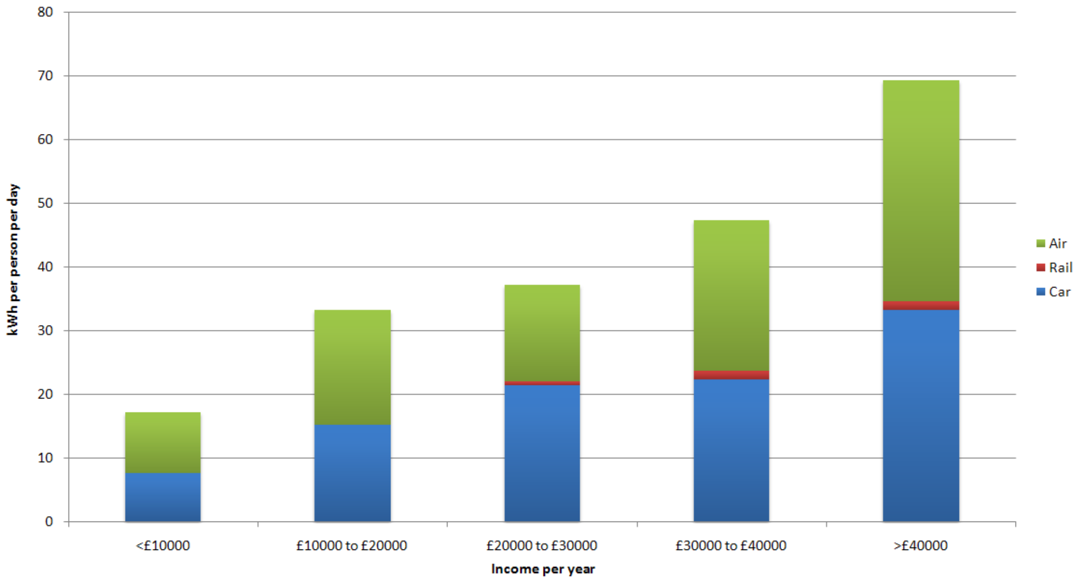


Figure 1: Income vs travel energy[1]

[1] Based on CO_2 emissions vs income (2). The non-CO_2 effects have been excluded as these are dominated by the additional global warming impact of aviation emissions at altitude. The remaining CO_2 emissions for the three dominant modes of transport (air, rail and car) have been converted to kWh by using the following emissions factors: Car 0.24 $kgCO_2/kWh$; Air 0.24 $kgCO_2/kWh$; Rail 0.537 $kgCO_2/kWh$.

The consumption of gas and electricity by consumers in the USA was compared with their household income (3). Figure 2 illustrates the relationship between household income and household consumption of electricity and gas. Again, there is a clear trend to suggest that those with the means to spend more money on electricity and gas actually do so. The highest earners in these samples consumed 70% more gas and more than double the electricity compared with the poorest households.

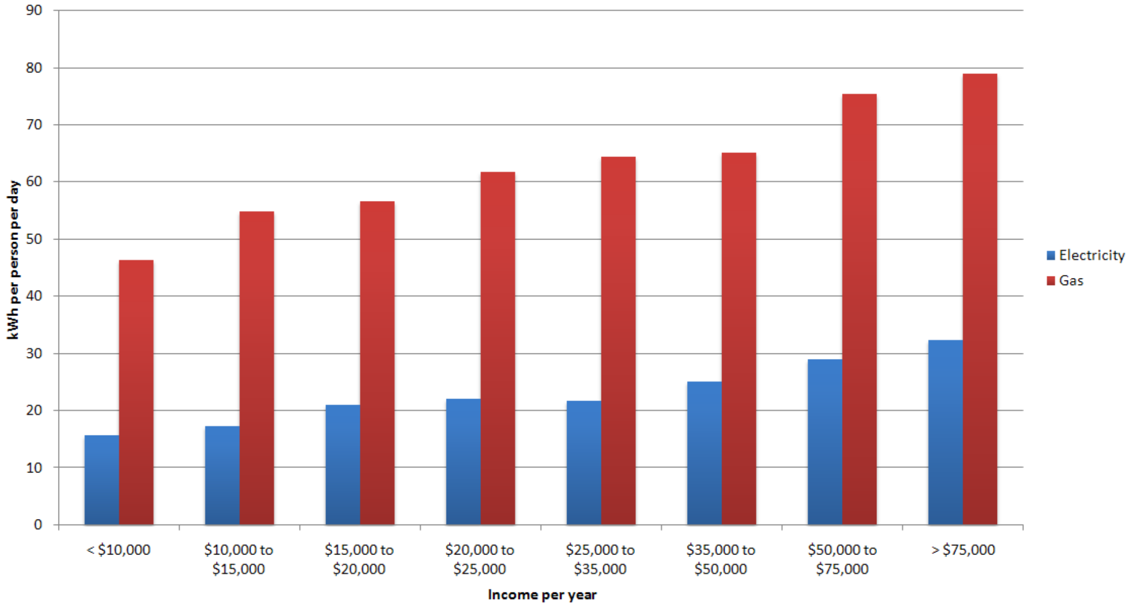


Figure 2: Household income vs utility consumption

Figure 3 shows that domestic consumption and transport account for 67% of final energy use in the UK (4 p. 27). We have demonstrated above that these sectors enjoy a proportional relationship between income and energy consumption, so can we assume that the same is true of the remaining one-third of our energy consumption?

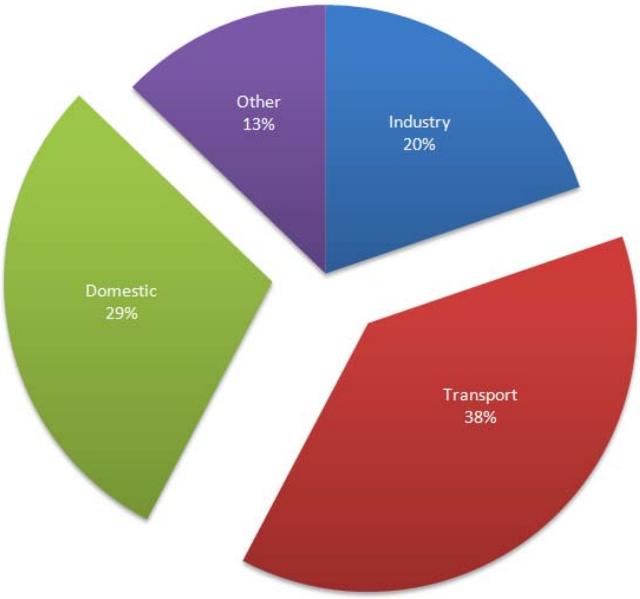


Figure 3: Final UK energy consumption by user (2008),

3.2.3 Relationship between income and energy consumption

The median household salaries in each of the UK's 646 parliamentary constituencies (5) have been compared against the estimated average household energy consumption in each constituency (6)[2]. Figure 4 illustrates the relationship between these two values, with a clear trend that higher incomes are associated with higher energy consumption (the correlation between the two data sets is 68%).

[2] The data measured CO_2 emissions per household. These have been converted to energy consumption in kWh by multiplying them by the UK's ratio between energy consumption and carbon emissions.

In 2008, the UK energy consumption was 164,974,000 TOE (4). This equates to 2.7 TOE per person, or 31,453 kWh per person.

UK CO_2 emissions in 2008 were 628.3 million tonnes(17), which is equivalent to 10.3 tonnes per person.

Therefore, the ratio between energy and CO_2 emissions in the UK in 2008 was 3054 kWh/tonneCO_2.

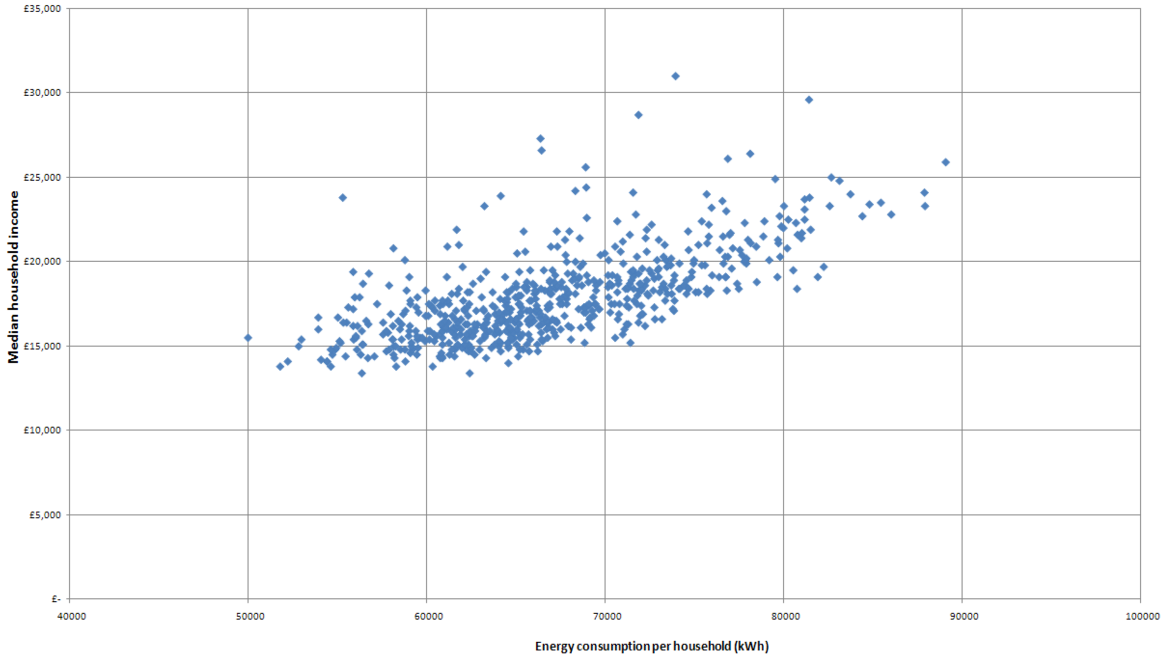


Figure 4: Household energy consumption vs household income for every constituency in the UK

3.2.4 Comparing GDP with energy consumption

The Gross Domestic Product (or GDP) of a country is a measure of the wealth of that nation and is calculated in a standard way for all countries. If we take the UK's GDP in 2008 and divide it by the UK population for the same year we can estimate how much money each man, woman and child would have earned in 2008 if our wealth had been distributed evenly.

Similarly, the International Energy Agency provide estimates of how much energy has been consumed by each country in a year. By dividing this number by the population we can estimate the average person's energy consumption per year.

If there is a relationship between personal wealth and energy consumption, the ratio of the GDP per person and the energy consumption per person should be similar all over the world. To investigate this, the two sets of data (7) have been plotted against each other for all the countries of the world (Figure 5).

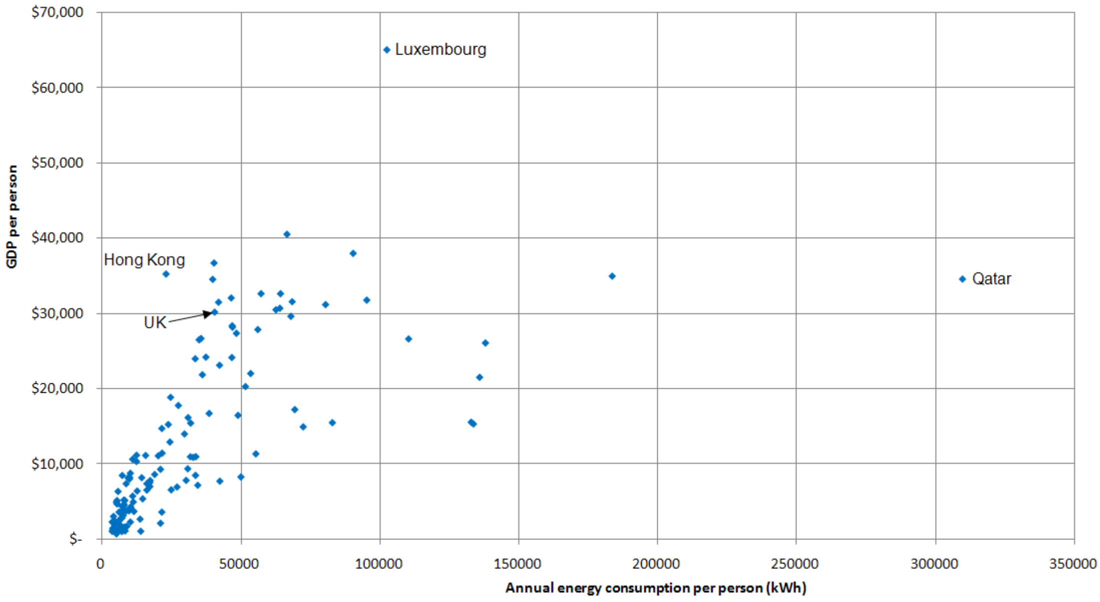


Figure 5: Energy consumption per person vs GDP per person for every country

There are clearly outliers on the chart, such as Qatar and Hong Kong, who have very similar GDP per person to the UK, but wildly different energy consumptions. Oil-rich Qatar consumes more than 13 times as much energy as Hong Kong in pursuit of generating roughly the same amount of money.

However, on the whole there is a clear trend that rich countries consume more energy than poor countries (the correlation between energy consumption and GDP per capita is 66%). This further supports our assumption that salary is proportional to energy consumption, although with the caveat that the precise relationship between the two quantities varies between countries.

3.2.5 Determining the ratio

If this is the case, we could calculate the embodied energy of labour by determining a rate of kWh/£ and applying it to the cost of that labour.

To estimate the kWh/£ we can take a ratio of the UK's total energy consumption to GDP for the same year. The equivalent of 165 million tonnes of oil were consumed in energy by the UK in 2008 (4). Divided equally across the population, this equates to 2.7 toe[3] per person. Converted to kWh, this is 31,000 kWh per person per year (or 86kWh/person/day).

According to the IMF the UK's GDP in 2008 was US$2.65 trillion (8), which is equivalent to GB£1.6 trillion. Divided equally among the UK population of 61 million, this is approximately £26,000 per person. This figure includes all money generated within the UK, including that owned by companies and individuals based overseas, but since the economic activity occurred within the UK it is fair to assign this activity to the energy consumed within the UK.

To calculate a labour rate of energy consumed per pound spent, the energy consumption per person was divided by the GDP per person to give a rate of 1.2 kWh/£.

[3] Tonnes of Oil Equivalent. According to the IEA/OECD: 1 toe = 41.868 GJ.

3.2.5.1 A caveat

86kWh per person per day only includes energy that is consumed within this country. It does not include the energy consumed by a Chinese manufacturer to build that person's television, which they have effectively outsourced for China to worry about.

Is it reasonable to ignore this inconsistency? As a result of buying televisions from China, the UK's energy consumption is lower than if the TVs had been manufactured in the UK, but so too is the UK's GDP because British people are sending their money to China. Similarly, the UK manufactures cars to be sold overseas; this increases both energy consumption and GDP.

If we assume that the cost of the televisions and the cars are roughly in proportion to their energy footprints, they (and everything else we trade) should cancel each other out in energy if they cancel out in money. Actually, the UK spends more money importing than it makes from exporting (a trade deficit), so it is likely that it imports more embodied energy than it exports. However, this imbalance is equivalent to less than 5% of GDP[4] (9), so we have assumed it to have a similarly small impact in energy terms and chosen to ignore it.

3.2.6 What does 1.2 kWh/£ mean?

1.2 kWh is the amount of energy consumed for every pound generated by the UK economy, including the energy embodied within goods and services.

By inverting 1.2 kWh/£ to 83p/kWh, the figure now represents the amount of money generated for each unit of energy consumed.

If we use data from the IEA for estimates of GDP and energy consumption (7), the UK stands at $0.74/kWh[5], whereas Hong Kong has the highest $/kWh figure at $1.52, while Iraq has the lowest at $0.07. This can be read both as an indicator of the efficiency of the economies at converting energy into money and of the cost of energy within the country. Hong Kong has a strong financial services sector, which is able to create wealth while consuming less energy. Oil-rich middle eastern economies, on the other hand, have little need for energy efficient economies because they can afford to consume cheap fossil fuels in vast quantities. Additionally, service-based economies such as the UK tend to have higher $/kWh rates than manufacturing-heavy countries such as Germany and China.

3.2.7 Comparing the labour rate to utility prices

When compared to the cost of domestic gas or electricity, a labour rate of 83p/kWh seems very high. This illustrates the high cost of human labour relative to raw energy, although it must be stressed that the labour rate refers to the embodied energy associated with the labour, not the thermodynamic work that can be done for 83p. Modern humans are incredibly inefficient from that perspective, requiring food, transport, entertainment, clothing and so on in order to output a relatively insignificant quantity of thermodynamic work[6]. As industrialised economies have

[4] Total exports in 2007: £204 billion; total imports in 2007: £281 billion. Therefore the trade deficit in 2007 was £77 billion. As a proportion of 2007 GDP (£1.68 trillion), this is 4.6%.

[5] This does not correspond with the previously derived 83p/kWh above because the IEA data uses different boundaries for estimating national energy consumption compared to the UK Department of Energy and Climate Change.

[6] The recommended daily intake of calories for an adult male is 2500. This is equivalent to less than 2.5 kWh per day, so even if he required no energy to breathe, digest food or pump blood, the maximum amount of work he could do in a day would be less than the electricity consumed by a single 100W lightbulb over the same period. A labourer earning £12 an hour who performs 1 kWh of physical work (i.e. consuming 1000 calories more than a non-manual worker) during his eight hour shift is costing his employer £96/kWh – nearly 1000 times more than the cost of an equivalent quantity of electricity.

become more reliant on fossil fuels to do the thermodynamic work, so the role of human labour has shifted towards decision making.

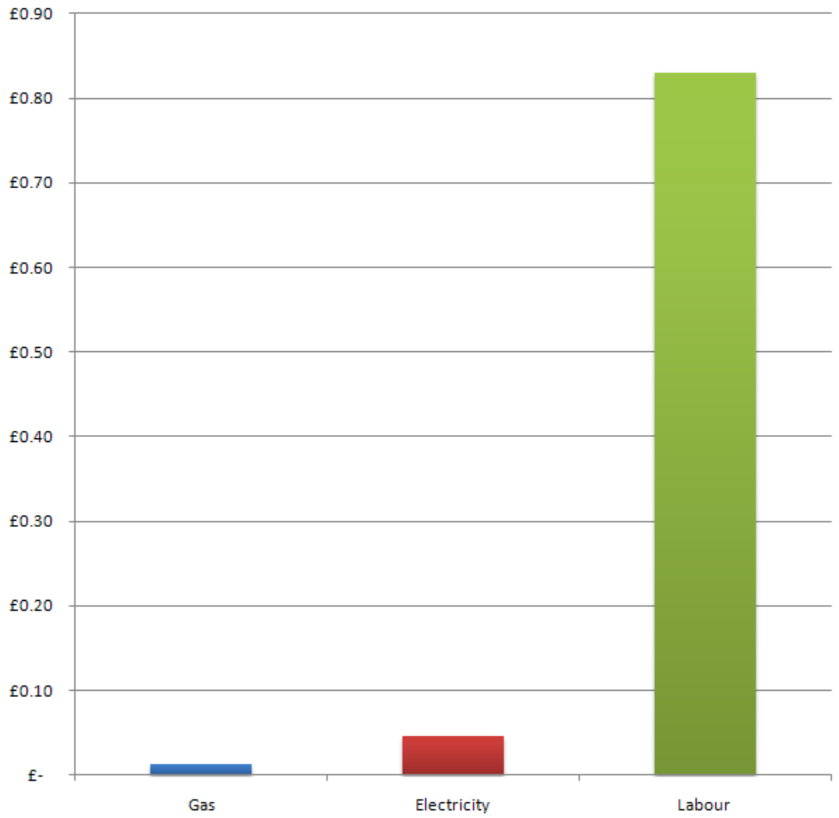


Figure 6: Comparison of the labour rate with gas and electricity prices

3.2.8 Testing the labour rate

The amount of energy required to live an affluent western lifestyle has been estimated to be 195 kWh/day by Professor David MacKay (10). A labour rate of 83p/kWh suggests that this affluent western lifestyle would require a salary of £59,000. This is significantly higher than the median salary for a full-time worker in the UK of £25,000 (11), although this may be explained by MacKay's description of it as an "affluent" lifestyle, as well as the large margins of error acknowledged in both this report and MacKay's.

We can also look at estimates of energy embodied in products. The following table shows the estimated embodied energy in a number of products, which we have divided by our labour rate of 1.2kWh/£ to give a cost estimate.

Table 1: Estimated embodied energy and cost of products (10)

Item	Embodied energy kWh	Cost estimate
Aluminium can	0.6	£ 0.50
PC	1800	£ 1,494.00
AA battery	1.4	£ 1.16
The Independent (newspaper)	2	£ 1.66
House	83950	£ 69,678.50
Car	76000	£ 63,080.00

In most cases, this estimate is reasonably close to the real price, although there is clearly something wrong with the car estimate.

Perhaps the cost of a product is a function of the ratio between direct energy consumption and labour during the manufacturing process. Modern car manufacturing is famously dominated by robotics and other automated techniques, so if we assume that no human labour at all is used in the manufacture of a car we could multiply 76,000 kWh by the price of electricity (4.7p/kWh according to chapter 4.4) and get £3,572, which is much closer to the price of a car.

The idea that the cost of a product is a function of the ratio between direct energy consumption and labour used during manufacture will be further explored in chapter 6.

3.3 Discussion

If we accept that the embodied energy of human labour is 1.2 kWh/£, how useful is this knowledge to a building designer? At first glance, it would appear that the cost of human labour is much higher than electricity, so budget-minded designers should favour automation over employment.

However, this simplistic analysis misinterprets the definition of the embodied energy within the labour rate. For every pound spent on a person's services, 1.2 kWh are consumed by that person across their lifestyle, so it is wrong to say that a machine performing 1.2 kWh of thermodynamic work is equivalent. Neither the person nor the machine are 100% efficient.

It is simple to calculate the efficiency of a machine; it is a ratio of the useful output power to the input power. For an electric drill, this is around 60%. However, the efficiency of a human performing thermodynamic work (as opposed to making decisions) varies according to their salary, because a higher salaried worker has more embodied energy associated with his lifestyle than one on a lower pay, but can perform a similar amount of thermodynamic work[7].

A labourer earning £15,000 per year (12) has an embodied energy, according to the 1.2 kWh/£ labour rate, of 68.4 kWh/day. His metabolic rate (the calories required to stay alive) is approximately 2000 calories per day, and the recommended intake for an adult male is around 2500 calories per day. On the basis that his strenuous work requires him to eat more than the average, we will assume he expends 1000 calories during his eight hour working day. This is equivalent to 1.16 kWh/day; as a proportion of his embodied energy, this equates to an efficiency of 1.7%.

If the thermodynamic work required for a project is 10 kWh, an 800 watt electric drill would consume 16.6 kWh at a cost of £1.08, taking 20 hours. However, the labourer would have an embodied energy of 590 kWh at a cost of £489, taking 67 hours to do the same work (see Figure 7).

[7] As a society with access to cheap forms of energy, we do not place a high value on people who perform significant thermodynamic work in their jobs. In fact, the relationship between salary and thermodynamic work is perhaps inverse, with labourers among the lowest paid and doctors, lawyers and bankers earning many times more. Our economy places a much higher value on the specialist skills and knowledge of the professionals than it does on the labourers' ability to convert their food into physical work.

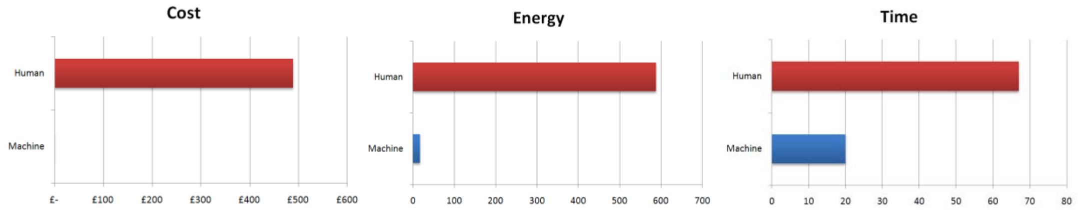


Figure 7: A comparison of the cost, embodied energy and time taken for a human and a machine to perform 10kWh of work

It is clear, therefore, that replacing a human with a machine can reduce the cost, embodied energy and duration of a project. However, if the wider economy becomes richer as a result of this additional automation, it is likely that overall energy consumption would increase, regardless of the reduction in the building's individual energy footprint.

Additionally, the societal implications of substituting employment with mechanisation may be significant and should be carefully considered before agreeing on a policy. This is beyond the scope of this project.

4 Electricity and gas price assumptions

4.1 Projecting energy prices

Due to uncertainty surrounding future energy policy and resource availability, it is not possible to make confident forecasts of electricity and gas prices. The data available (13) provides electricity and gas prices dating back 30 years, while the occupancy stages of the buildings in this study last 60 years, so it is clear that any projection will have a large scope for error. However, in order to estimate the costs associated with direct energy consumption over the occupancy stage, it is necessary to select an inflation rate for energy prices.

4.2 30-year trend

Figure 8 illustrates the prices of electricity and gas over the period 1980 to 2009. The prices have been normalised to a scale where 100 is equal to the 1990 price, and adjusted for inflation using annual RPI (Retail Price Index) data. There is no obvious visible trend to the data, with rising prices in the early 1980s, followed by a steady decline in the 1990s before a very steep rise in the final five years of data.

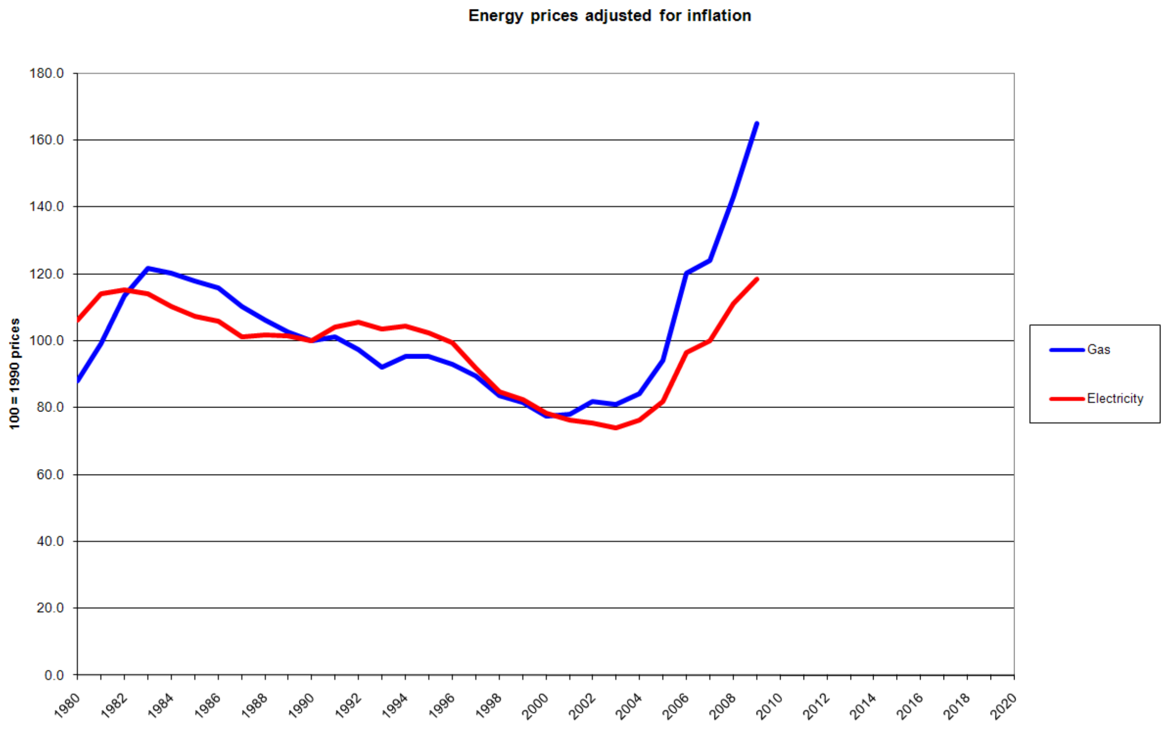


Figure 8: Normalised electricity and gas prices 1980 to 2009, adjusted for inflation

Exponential curves were fitted to each set of data in order to establish a typical percentage year-on-year increase between 1980 and 2009. For the purpose of projecting the prices beyond 2009, it was assumed that they would immediately regress to the trend line before continuing at that rate. The dashed lines in Figure 9 show the forecasted years from 2010 to 2020. It is assumed that the gas price decreases in real terms by 0.1% per year while the electricity rate falls at a rate of 0.9% per year.

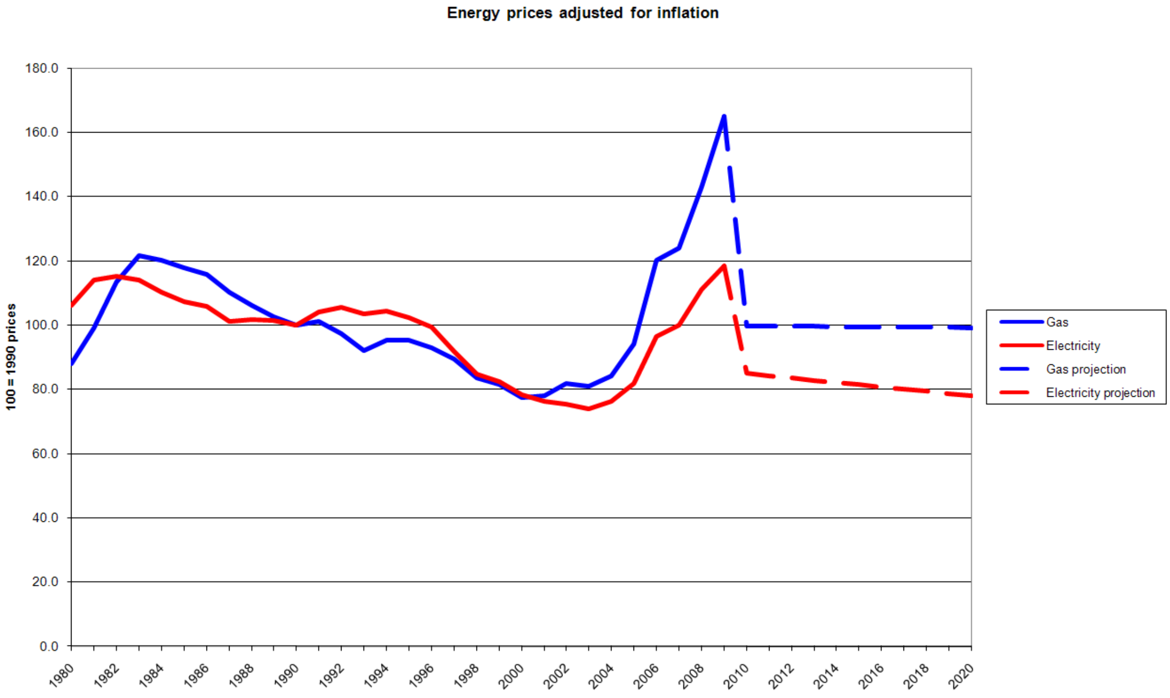


Figure 9: Normalised electricity and gas prices projected to 2020, adjusted for inflation

Over the last three decades, relative to the rate of general inflation, gas and electricity prices have, on average, fallen slightly year-on-year. Although prices are currently at a high (gas prices are 60% higher than in 1990), this forecasting model has chosen to assume that they will immediately regress to the mean, leaving gas prices approximately equal to 1990 prices and electricity prices around 20% cheaper by 2020.

It is perhaps to be expected that energy prices should be closely related to general inflation, since an increase in the price of fuels is likely to cause transport and manufacturing costs to increase, and therefore the cost of other goods.

However, to assume that the next 10, 30 or 60 years will be similar in energy price terms to the previous 30 years may be foolish. In the last 30 years, the UK has developed an oil and gas industry, before more recently becoming reliant on imported fuels again. Looking forward, the UK is likely to spend a significant amount of money on nuclear, renewable and carbon capture power stations, in order to replace elderly generators and also to decarbonise the energy supply in order to meet climate change obligations.

4.3 10-year trend

What would happen if prices were to continue to rise at the same rate as they have since 2000? In real terms, gas prices have risen by 113% in the last decade, with electricity prices increasing by 51%. Figure 10 illustrates the results of this model: after an initial slight regression to the mean, the prices of both fuels rise exponentially, leaving gas prices four times higher than under the 30-year forecast model and electricity prices two and a half times higher. The increases are equivalent to 9.1% per year above inflation for gas and 5.4% for electricity.

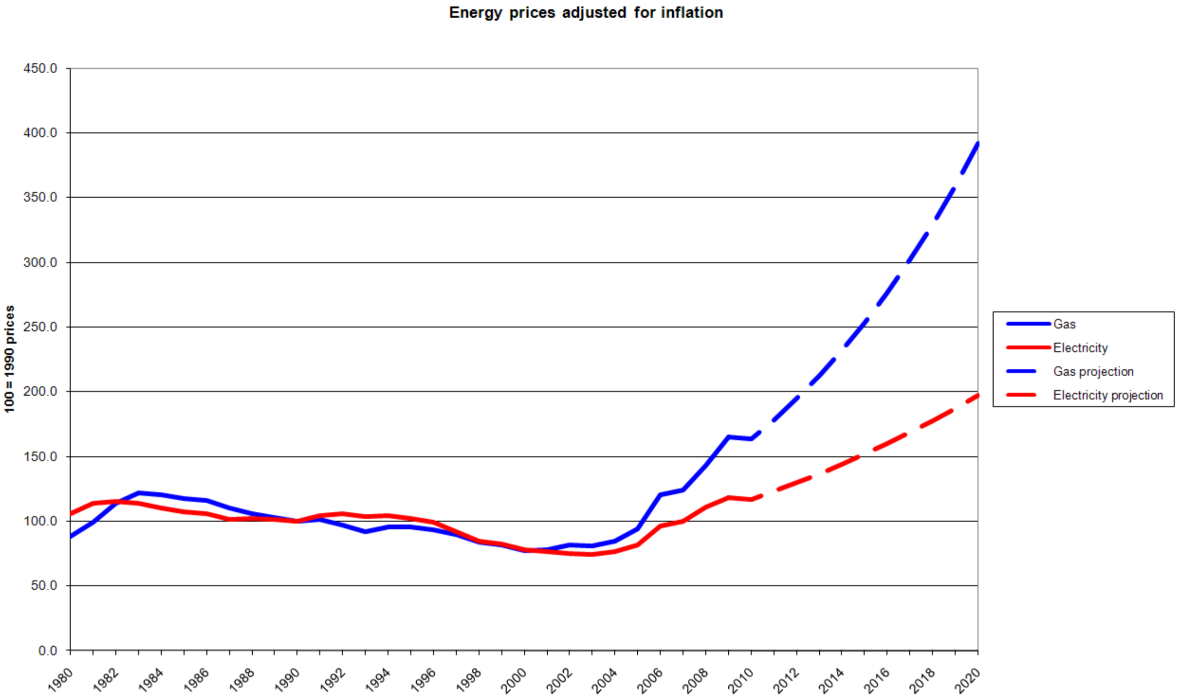


Figure 10: Normalised electricity and gas prices projected to 2020 based on trend between 2000 and 2009, adjusted for inflation

Are such sustained price rises possible? Higher prices would increase the feasibility of alternative energy sources, thus introducing additional supply to constrain prices. Additionally, as prices become unaffordable for consumers, their consumption is likely to fall which is also likely to have the effect of suppressing price rises. In short, the market may be effective in regulating energy prices to within a band of affordability.

It is unlikely that typical consumers would be able to afford such steep increases as forecasted over the 10 years above, let alone over the 60 year occupancy period of the buildings modelled in this report.

4.4 Assumptions chosen for this study

It is important to be aware that accurate long term forecasting of energy prices is impossible. However, in order to estimate the cost of the energy consumed by a building during its occupancy stage, it is necessary to make an assumption of the energy inflation rate over the coming decades.

Gas prices have, in real terms, fluctuated around a constant price for the last 30 years. Similarly, there has been significant variation in electricity prices over this period, but the underlying trend suggests that prices have been falling very slightly. The prospect of the UK investing in expensive nuclear and renewables capital projects suggests that this price decline may not continue.

Therefore, this project will assume that energy prices will increase at a rate equal to general inflation. In other words, a 0% real terms increase in both gas and electricity prices. Figure 11 illustrates the impact of this model on the real £/kWh prices of gas and electricity, based on 2009 prices of 2p/kWh for gas and 6.5p/kWh for electricity[8]. This model outputs a constant price

[8] Sourced from energy survey project work by David Wheatley in Arup Building Performance and Systems group. Prices are an average over 2009 for a 12,000m^2 office building in London, consuming up to 600,000kWh and 200,000kWh of

from 2010 onwards, adjusted for inflation, of 1.2p/kWh for gas and 4.7p/kWh for electricity. These prices will be used throughout this report.

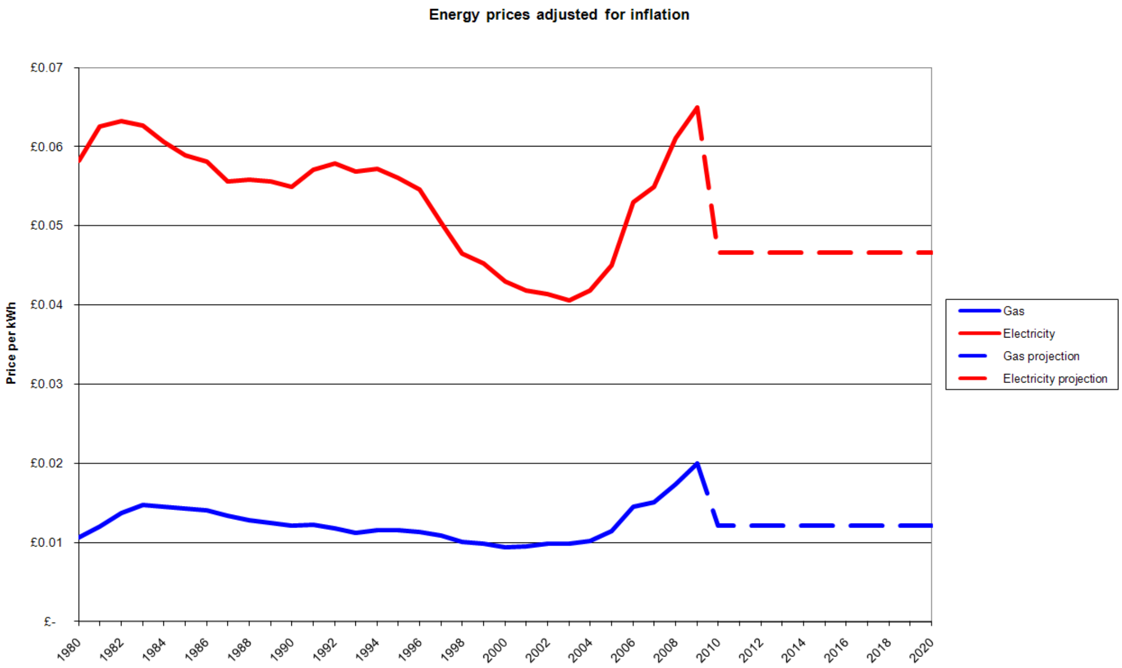


Figure 11: Projected gas and electricity prices in cash terms, adjusted for inflation

gas and electricity respectively per month.

5 Estimation of typical energy and cost for two building types

An estimation of energy consumption and cost over time was carried out for two building types: a school and a commercial building.

The projection of energy and cost over time was broken down to three stages: design, construction and occupancy. The design stage involves the work done by architects, design engineers, quantity surveyors, and any other body involved before the construction phase. Construction includes energy and cost in the production of materials ('cradle-to-gate'), plus that in transporting labour and materials to site and that used on-site ('gate-to-site'). The occupancy stage includes the embodied energy of the maintenance and upkeep of the building, in addition to the direct consumption of utility energy in the form of natural gas and electricity.

The two building types that have been modelled were each based on specific designs that were used in individual reports commissioned by the Concrete Centre to estimate their cost and embodied CO_2 (eCO_2) in construction. Sarah Kaethner and Frances Yang of Arup provided the research into the eCO_2 figures published. Data for 'cradle-to-gate' embodied energy in materials is widely available and well-established, and so current estimations of embodied energy in buildings often only covers this process stage. Kaethner and Yang expanded on this by researching embodied energy values for materials at the 'gate-to-site' construction stage. The eCO_2 figures were later converted into embodied energy for this project.

This work has been built on by adding the element of embodied energy of labour, and then making a full new estimate of embodied energy and cost for the design and occupancy stages, based on the specification of the buildings.

5.1 School

The design was a 1,400 place secondary school, with a total floor area of 13,500m² (14)

5.1.1 Design stage

The Concrete Centre's estimation for cost of construction of the building was used to make a valuation on the cost of design (i.e. the combined fees of the architects, engineers, quantity surveyors and other specialists. Based on a contractor's pre-stage cost plan[9] for a £21m new build school, we will assume that the cost of design represents 10% of the total fee. The Concrete Centre's average construction cost for the six superstructure types was £1,500/m². Therefore, the design cost is £167/m², equivalent to 10% of the combined design and construction cost of £1667/m².

The proportion of the design fee that is spent on operational energy use was based on Arup's own energy use, using figures for electricity and gas consumption at the Watford office. This equated to about £350 per employee per year[10]. For the whole company of around 10,000 people, it can be estimated that about £3,500,000 is spent per year on energy use, which is about 0.6% of a total turnover of £600m. This is a very small percentage, and applying it to the design fee of £167/m² gives just £1/m². The remaining 99.4% of the design cost (£166/m²) was assumed to be 'labour' which includes pay to staff and overheads, such as administration and maintenance staff, materials etc. Materials were not considered as a separate category for this

[9] Cost plan made by Laing O'Rourke on a new build school, design and construction cost totalling £21m.
[10] Average consumption per employee in the Watford office in the 12 month period between December 2008 and November 2009 was 7,053 kWh/person of electricity and 1,756 kWh/person of natural gas. At rates of 4.6p/kWh and 1.2p/kWh respectively this equates to £345 per employee per year.

stage since the contribution was expected to be insignificant in terms of cost, compared to the labour.

In the Arup Watford office, taking account of the split between gas and electricity consumption, the average price paid per unit of energy was 3.9p/kWh, assuming 4.6p/kWh for electricity and 1.2p/kWh for gas. The £0.84/m² of design fee attributed to designers' direct energy consumption could therefore buy 21.5kWh/m² of energy.

For labour, using the conversion rate of 1.2kWh/£ on the remaining £166/m² gives 199kWh/m².

In summary:

Table 2: Energy and cost for school over design stage

	Cost (£/m²)	Energy (kWh/m²)
Direct Energy	1.0	21.5
Labour	166	199

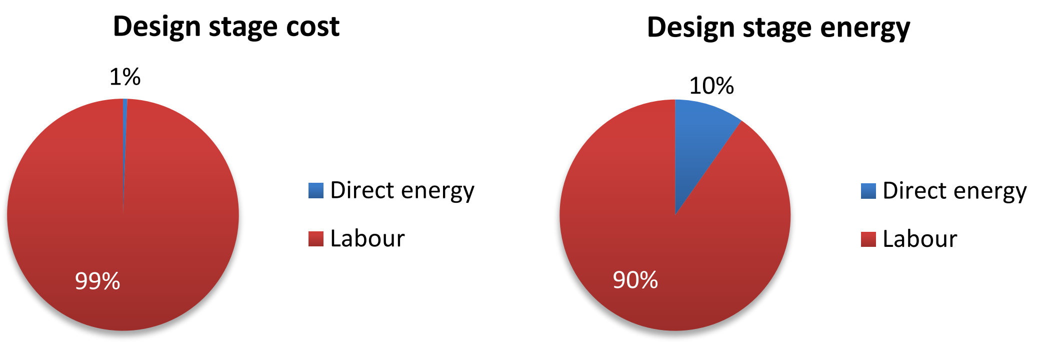


Figure 12: Cost and energy for school over design stage

5.1.2 Construction stage

The Concrete Centre study on the eCO_2 of construction of the school was converted to embodied energy for the purpose of this study. This was broken down into embodied energy in the following parts:

'Cradle-to-Gate'

- Construction materials up to the point of leaving the factory gate of final manufacture. Direct energy use and transportation were considered in the sources of this data, but human labour was excluded.

'Gate-to-Site'

- Construction materials from leaving the factory gate to being installed on-site. This includes the additional 'cradle-to-gate' embodied energy of extra material that is wasted on site, as well as the energy to transport all materials to site.
- Direct energy use on site. An estimation of the use of diesel in site machinery over the duration of construction was made.
- Labour. This was not considered in the Concrete Centre study and an estimation was made based on the projected cost.

Average values for the six superstructure designs were used for calculating the embodied energy and cost of each part of the construction process.

The Concrete Centre made a cost estimation for construction of the school, which was broken down into building elements and non-material items such as overheads and profit. However, the allowance in cost for labour to install each building element was incorporated into these values, and also the cost of direct energy on-site was not separated out either. In order to break down the cost into these preferred categories, the total construction cost was used to make an estimate of these.

The Arup Project Management Team was consulted for an estimate of the proportion of the construction cost of a building that typically makes up materials, labour and direct energy use on-site. A consensus was reached of about 60% labour and 40% materials without allowance for direct energy use. It was estimated that direct energy use on site would only take about 1% of the total cost, at the most perhaps 2%, so the latter upper bound value was used since it is still very insignificant. This was taken out of the labour allowance thus reducing it to 58%. Of the 40% of the cost allocated for materials, it was assumed only 1% was for costs from gate-to-site. The final breakdown of the costs for construction are:

- 58% Labour
- 39% Materials (cradle-to-gate)
- 1% Materials (gate-to-site)
- 2% Direct energy use

Using the 58% labour cost for construction, a value of embodied energy could be estimated for labour using the £1.2/kWh conversion factor, which gave 1030kWh/m^2.

Table 3: Energy and cost for school over construction stage

	Cost (£/m^2)	Embodied Energy (kWh/m^2)
Cradle-to-Gate		
Construction Materials	585	1297
Gate-to-Site		
Construction Materials	15	101
Direct Energy Use	30	299
Labour	855	1030

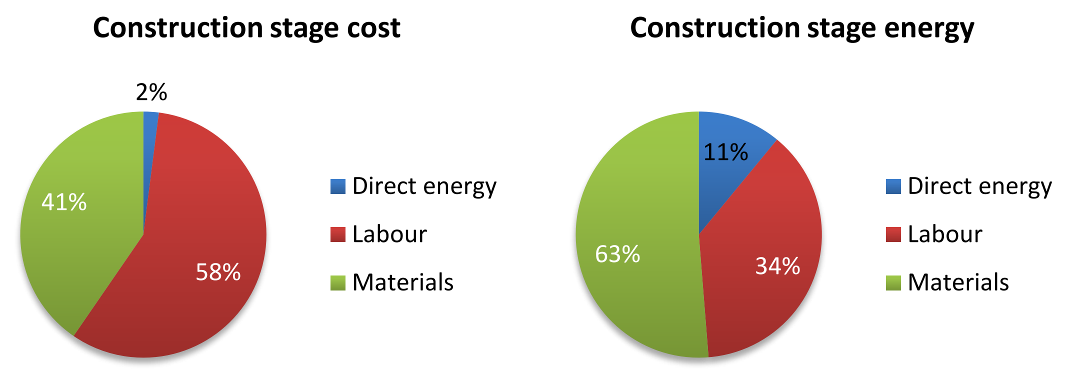


Figure 13: Cost and energy for school over construction stage

5.1.3 Occupancy stage

The duration of the occupancy stage was assumed to be 60 years, over which the quantity and cost of energy consumption was projected. This was made up of the direct energy consumption of gas and electricity, and also the embodied energy associated with the maintenance labour.

Three sources of typical energy consumption data are compared in Table 4. For the purposes of this study, the CIBSE Guide F recommendations have been followed, so the school will be assumed to consume 144 kWh/m² of natural gas and 33 kWh/m² of electricity per year.

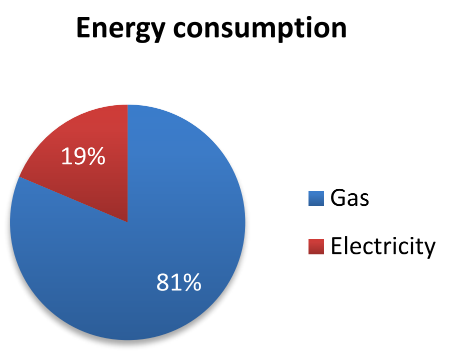
Table 4: Typical energy consumption data (kWh/m²/year)

	CIBSE Guide F, 2000		ECON 19 or 73		Arup Infrastructure Design Guide, 2003 (mid-value)	
	Fossil fuels	**Elec**	**Fossil fuels**	**Elec**	**Fossil fuels**	**Elec**
School (secondary)	144	33	173	28	150	25

The rate of utility consumption was assumed to remain constant throughout the 60 year occupancy period. This assumption relies on any increase in the use of energy-consuming equipment being offset by an increase in their efficiency. The prices of gas and electricity (1.2p/kWh and 4.6p/kWh respectively) are assumed to increase at a rate equal to general inflation (i.e. a 0% real terms increase), as described in Section 4.4. The energy consumption and associated costs are outlined in Table 5.

Table 5: Energy and cost for gas and electricity use in the school

	Gas	Electricity
kWh/m²/yr	144	33
kWh/m² over 60 yrs	8640	1980
£/m² over 60 years	103.68	91.08



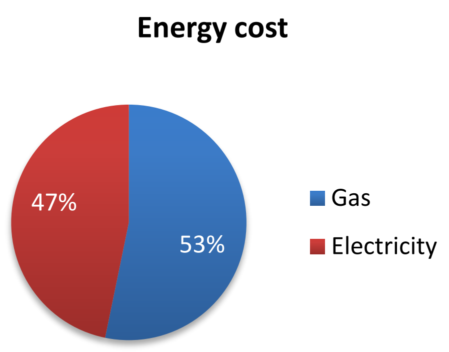


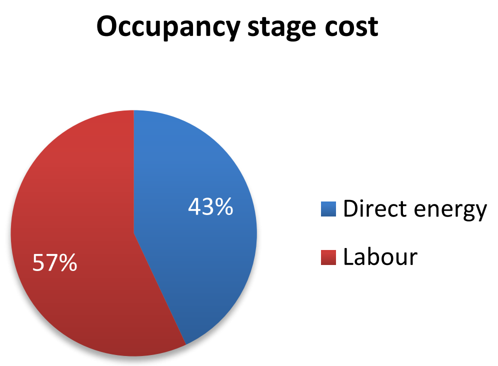
Figure 14: Consumption of gas and electricity in the school in terms of energy and cost

In order to estimate the costs associated with maintaining the school, it was assumed that two full-time caretakers would be employed on a salary of £14,000 per year alongside five part-time cleaners earning £6,000 per year. Therefore the total expenditure on maintenance is £58,000 per year or £4.30/m²/year.

By applying the labour rate from Chapter 2 we estimate the embodied energy associated with maintenance to be 5.2 kWh/m²/year. The cost and energy consumption over the 60 years is summarised in Table 6.

Table 6: Energy and cost of direct energy use and labour over 60 year building occupancy

	Cost over 60 years (£/m^2)	Embodied Energy over 60 years (kWh/m^2)
Direct Energy Use (elec and gas)	194.76	10620
Labour	258	312



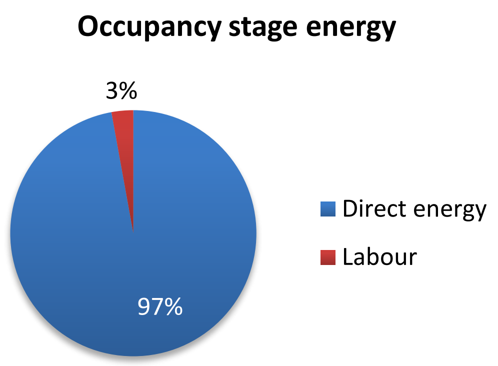


Figure 15: Cost and energy consumption over 60 year building occupancy

5.1.4 Results

Figure 16 shows the cumulative costs of direct energy, materials and labour in the design, construction and occupancy phases.

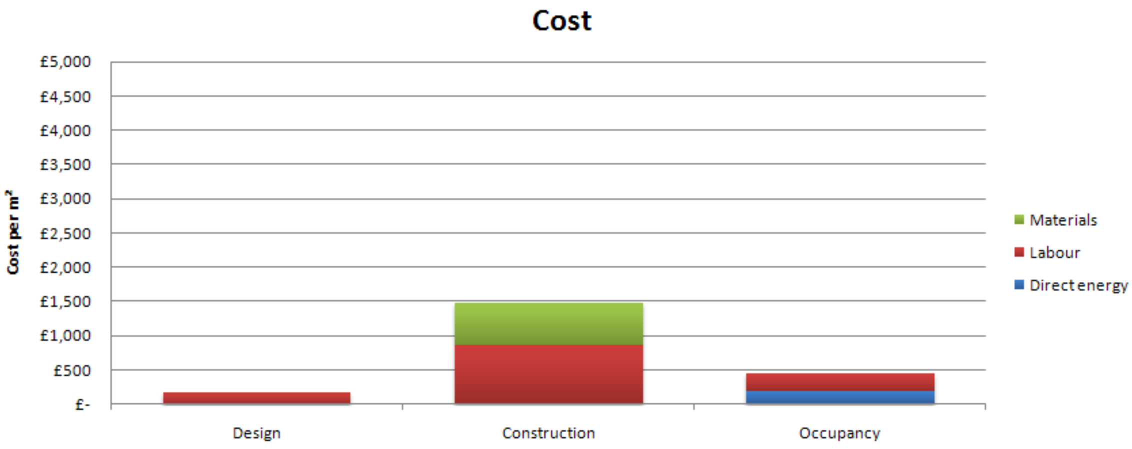


Figure 16: Cumulative cost of school, assuming average of construction types and 0% inflation-adjusted growth in energy prices

The cumulative energy consumption of direct energy, materials and labour over the three phases are shown in Figure 18. In terms of cost, it is clear that the construction stage is the most significant, but when energy is considered it is the occupancy stage that dominates consumption. Figure 18 illustrates the cumulative energy consumption over time, showing how quickly the embodied energy of the design and construction stages is overshadowed by the energy consumed during building occupancy.

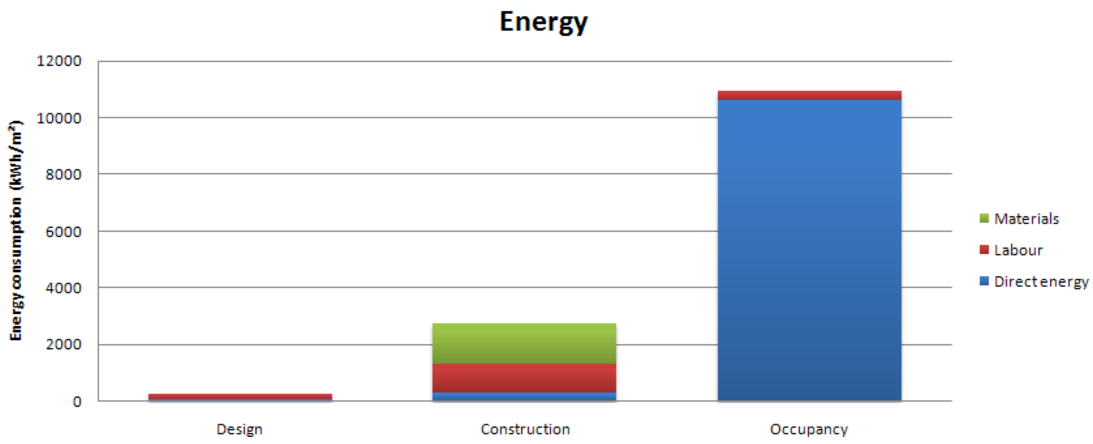


Figure 17: Cumulative energy of school, assuming average of construction types

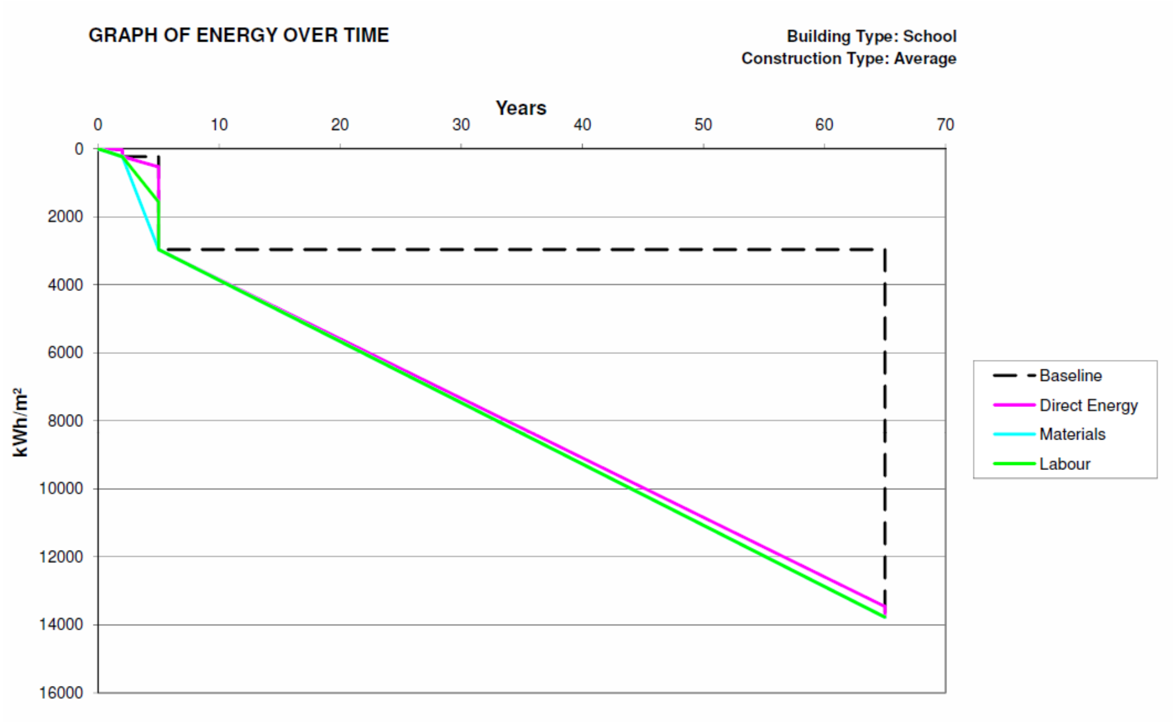


Figure 18: Cumulative energy vs time of school, assuming average of construction types

In order to illustrate the relative intensities of cost and energy within each phase, the overall consumption and spend of each phase have been plotted on cost vs energy log-log axes in Figure 19. The prices of gas, electricity and the labour rate have been plotted as gradient lines. From this graph it is clear that the occupancy stage is the most energy intensive, but that the gate-to-site construction stage is the most expensive.

The position of each marker relative to the price gradients illustrates the proportions of direct energy consumption and labour within each stage. The design, cradle-to-gate and gate-to-site stages lie close to the labour rate, indicating that they are dominated by human labour. In contrast with this, £/kWh of the occupancy stage lies close to the price of electricity, due to the dominance of the direct consumption of energy in this stage.

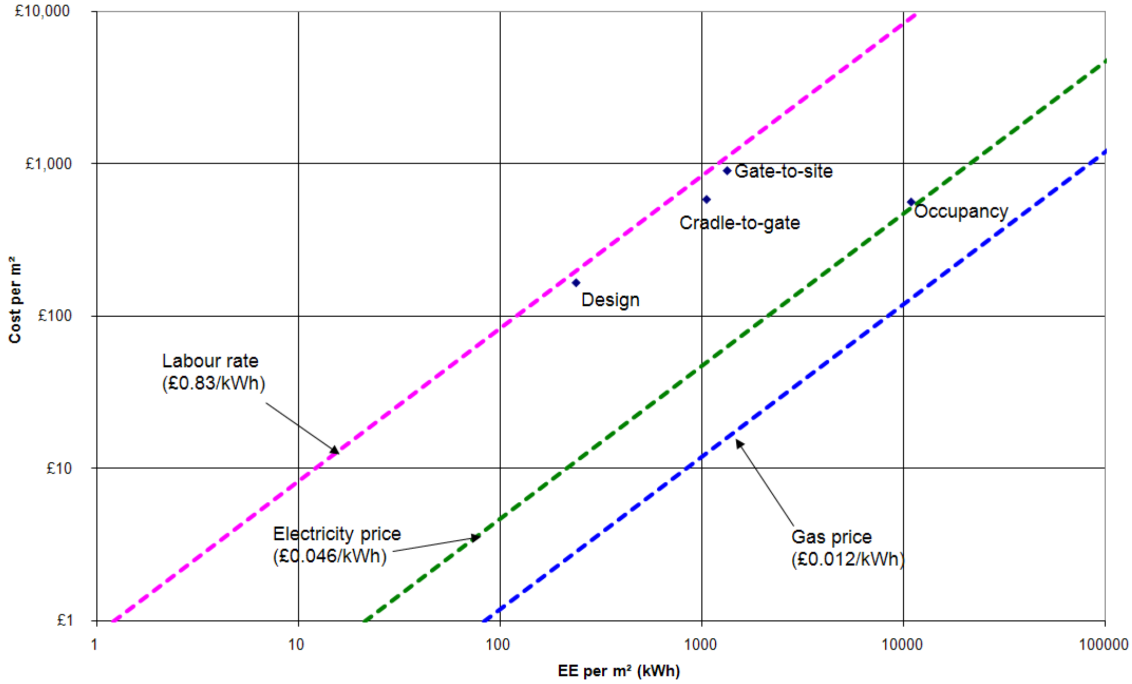


Figure 19: Embodied energy per m² vs cost per m² for each stage of the school's lifecycle

5.1.5 Alternative scenarios

There are multiple variables in the calculations, the variation of which may cause significant changes to the results. Firstly, the above calculations assume that the construction method used to build the school was based on the average of the six construction methods studied by the Concrete Centre.

Figure 20 and Figure 21 respectively illustrate the cost and energy consumption of the construction stage, comparing the average construction method with the Slimdek and PT flat slab methods.

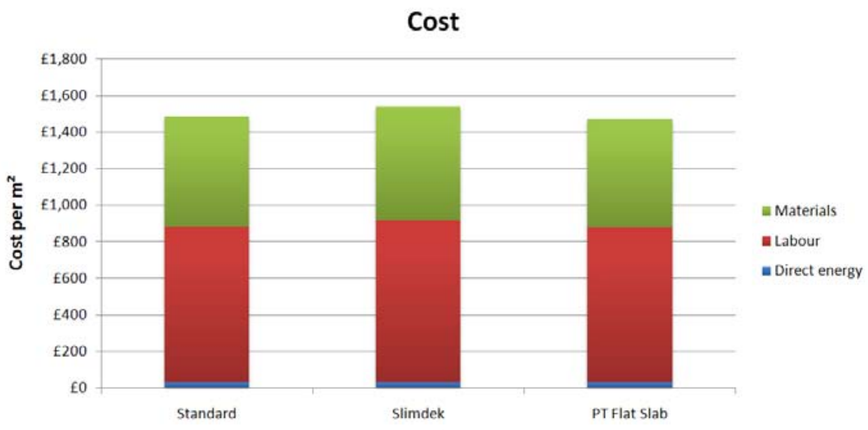


Figure 20: Cost of construction stage for average construction method, Slimdek and PT flat slab

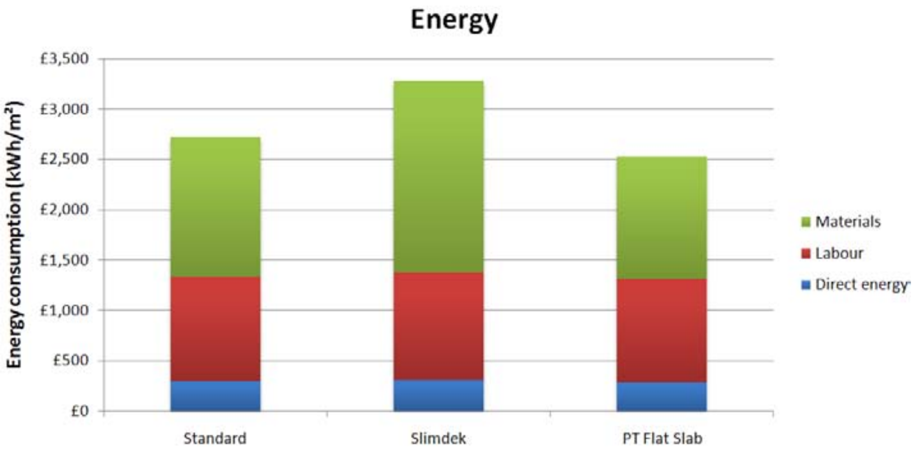


Figure 21: Embodied energy of construction stage for average construction method, Slimdek and PT flat slab

Finally, Figure 22 assumes an average construction method, but this time the inflation rate of the direct energy consumed in the occupancy stage is assumed to be equal to the inflation rate over the last decade (9.1% per year for natural gas and 5.4% per year for electricity). The impact of this is dramatic, causing the cost of the occupancy stage over 60 years to rise from around £500/m² to almost £5000/m².

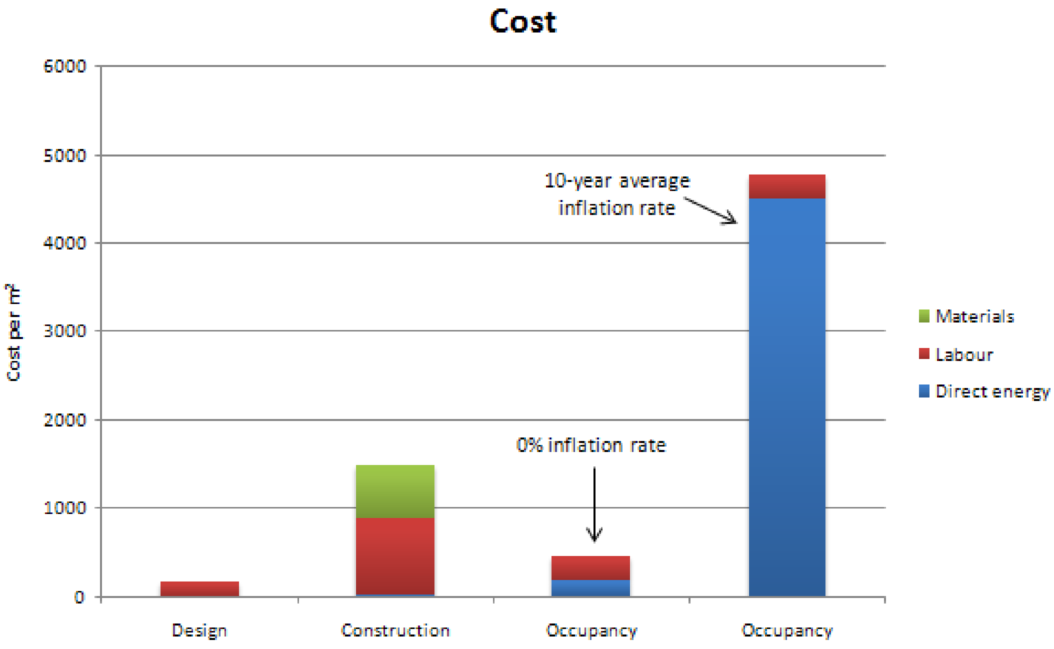


Figure 22: Cumulative cost of school, assuming average of construction types and energy inflation rate equivalent to the 2000 to 2009 trend

5.2 Office

The design was a 6-storey office building, with a total floor area of 16,480m² (14)

The calculation of energy and cost for each stage of the building life cycle was similar to that for the school. Detailed explanations for the same calculations will be omitted in this section, however any different calculations/assumptions will be expanded on.

5.2.1 Design stage

The Concrete Centre average estimated cost of construction for the eight building types was £1710/m^2. The design cost (assumed to be 15% of overall cost of design and construction) is:

(1710/(1-0.15)) x 0.15 = £302/m^2

Direct energy cost: 0.6% x 302 = £1.8/m^2

Labour cost: 99.4% x 302 = £300/m^2

Direct energy 1.8 / 0.017 = 105kWh/m^2

Labour energy 300 / 0.83 = 361kWh/m^2

Table 7: Energy and cost for office over design stage

	Cost (£/m^2)	Energy (kWh/m^2)
Direct Energy	1.8	105
Labour	300	361

5.2.2 Construction stage

Average values for the eight superstructure designs were used for the embodied energy of each part of the construction process.

The same cost breakdown used for the school was applied to the construction stage of the office.

- 58% labour
- 39% materials (cradle-to-gate)
- 1% materials (gate-to-site)
- 2% direct energy use

The total construction cost and associated embodied energy is broken down in Table 8.

Table 8: Energy and cost for office over construction stage

	Embodied Energy (kWh/m^2)	Cost (£/m^2)
Cradle-to-Gate		
Construction Materials	1056	667
Gate-to-Site		
Construction Materials	67	17
Direct Energy Use	231	34
Labour	1195	992

5.2.3 Occupancy stage

The embodied energy and cost over 60 years for the occupancy stage was again calculated, considering that associated with direct energy consumption, as well as maintenance labour.

As for the school, CIBSE Guide F was consulted to obtain typical kWh/m^2 values for fossil fuel and electricity consumption for an office. The values were 178kWh/m^2 and 226kWh/m^2 for gas and electricity respectively (see Table 9).

Table 9: Typical energy consumption data (kWh/m²/year)

	CIBSE Guide F, 2000		ECON 19		Arup Infrastructure Design Guide, 2003 (mid-value)	
	Fossil fuels	**Elec**	**Fossil fuels**	**Elec**	**Fossil fuels**	**Elec**
Offices (air-con, 'standard')	178	226	178	226	140	180

The same assumptions for the occupancy of the school were used for the direct energy consumption over the 60 year occupancy period of the office. The use of energy is considered to be consistent, and gas and electricity prices (1.2p/kWh and 4.6p/kWh respectively) are assumed to increase at a rate equal to general inflation (i.e. a 0% real terms increase), as described in chapter 4.4.

The energy consumption and associated costs are outlined in Table 10.

Table 10: Energy and cost for office gas and electricity

	Gas	Electricity
kWh/m^2/yr	178	226
kWh/m^2 over 60 yrs	10680	13560
£/m^2 over 60 years	130	648

In order to estimate the costs associated with maintaining the office, it was decided to make an estimate required for Arup's No.8 Fitzroy Street building in London which is of similar size (13,675m²). Chris Gray, Environmental Manager of the Arup London Estate was consulted. Since official figures of maintenance staff cover the whole of the London Estate, Chris advised on a broad estimate for the No.8 building. This was:

- Maintenance – 1 person working full time. There is also short term contracted maintenance on plant repair, however this will not be considered as it was not for the school.
- Cleaning staff – 1 supervisor and two cleaning staff working full time, plus 6 evening cleaners (4 hours per day)
- Catering staff were not considered for either the office or the school.

Since all maintenance staff are contracted from an agency, the exact hourly rate paid to the staff was not available from Chris Gray. Instead an estimate was made that for a London office the cleaning staff would have an hourly wage somewhere between minimum wage and the London Living Wage set by the Greater London Authority. This is £5.80 to £7.60 respectively (current rates in March 2010). Therefore an hourly wage of £6.70 was assumed.

The cleaning supervisor would be given a higher wage than this, so £10 per hour was estimated. It was estimated that the maintenance worker would be paid a higher salary, perhaps at around £30,000, so an hourly wage of £15 was assumed. All rates were increased by an additional 30% to pay the contracting companies. Table 11 contains a summary of the annual costs for maintenance and cleaning staff. By applying the labour rate from Chapter 2, the embodied energy associated with maintenance is estimated to be 13.4 kWh/m²/year.

Table 11: Summary of annual maintenance costs

	Hourly wage	Number of staff	Number of hours per week	Total annual cost
Maintenance staff full-time	£15.00	1	38	£29,640
Cleaners full-time	£6.70	2	38	£26,478
Cleaner supervisor full-time	£10.00	1	38	£19,760
Cleaners on evening shift	£6.70	6	20	£41,808
	TOTAL + 30% for contract company			£152,991
Cost per m² per year	£11.19			
Cost per m² over 60 yrs	£671			
Energy per m² per year	13.4	kWh		
Energy per m² over 60 yrs	805	kWh		

The cost and energy consumption of labour and direct energy over 60 years are summarised in Table 12.

Table 12: Energy and cost of direct energy use and labour over 60 year building occupancy

	Embodied Energy over 60 years (kWh/m^2)	Cost over 60 years ($£/m^2$)
Direct Energy Use (elec and gas)	24240	778
Labour	805	671

Figure 23 and Figure 24 respectively show the costs and embodied energy associated with each lifecycle stage for both the school and the office.

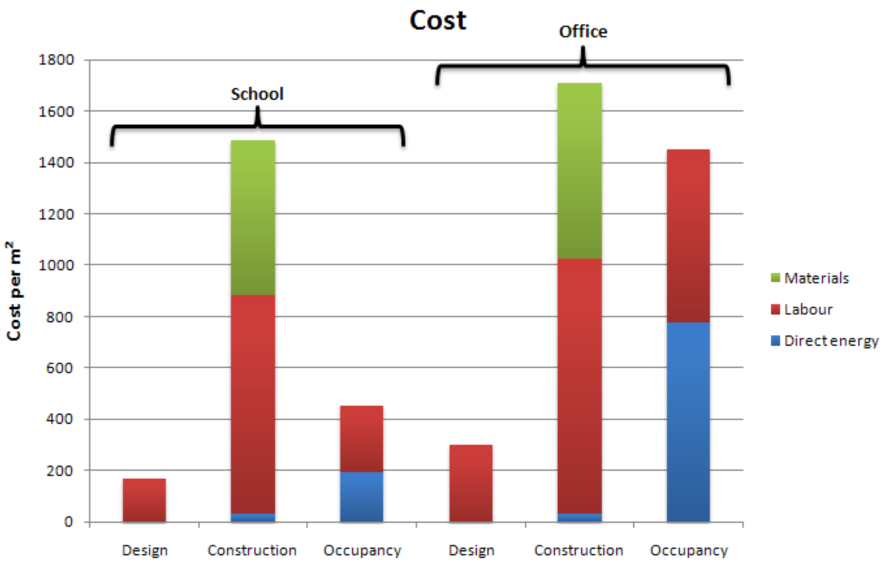


Figure 23: Cost of each lifecycle stage for school and office

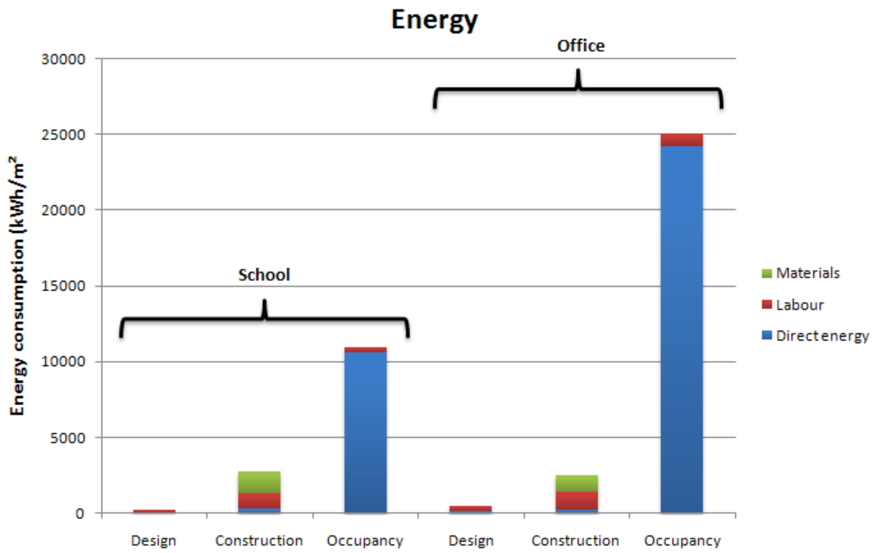


Figure 24: Embodied energy of each lifecycle stage for school and office

5.3 Results summary

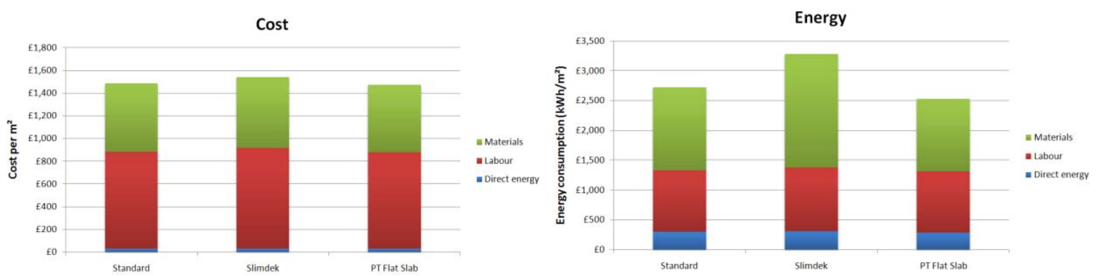


Figure 25: Comparison of cost and embodied energy during construction stage using different structural methods

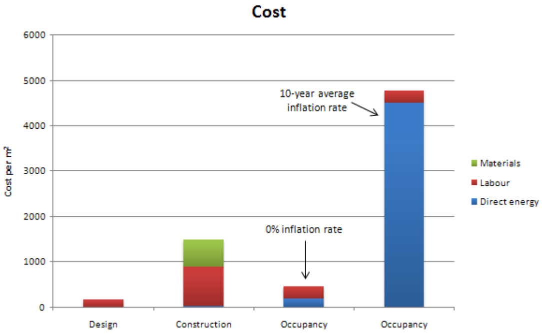


Figure 26: Comparison of lifecycle cost based on varying energy price inflation rates

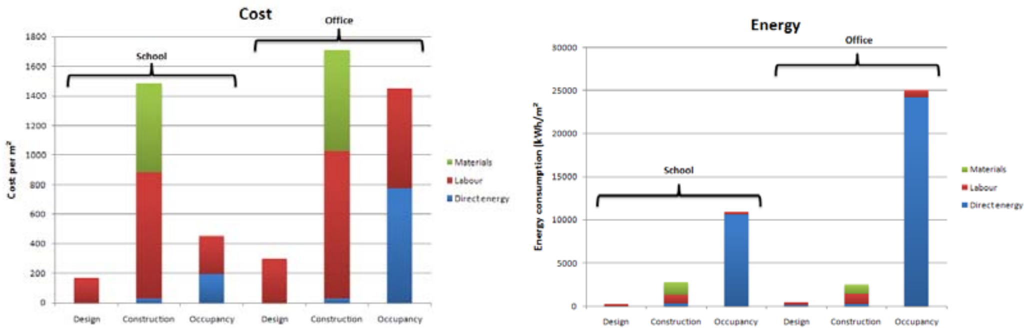


Figure 27: Comparison of lifecycle cost and energy for school and office

6 The relationship between cost and energy for construction materials

If there is a relationship between cost and energy throughout a building's lifecycle, it is possible that the construction materials, which make up a significant proportion of both cost and energy consumption, are also priced in proportion to their embodied energy.

6.1 Methodology

A range of construction materials were selected, specifically:

- Concrete wall
- Steel column
- Glass fibre insulation
- Medium-density fibreboard
- Granite paving
- Common brick wall
- Plywood
- Glass
- Aluminium

Estimates of material cost and cradle-to-gate embodied carbon dioxide (CO_2) were taken from the Blackbook (15). The units of measurement for these quantities varied, including per tonne, per cubic metre, per square metre and per linear metre. These varied units were converted into per tonne by multiplying them by a function of the density and dimensions of each material.

In order to remain consistent with the approach taken throughout this study, the estimates of embodied carbon dioxide were converted to embodied energy in kWh by using conversion factors from the University of Bath's 'Inventory of Carbon & Energy' (ICE) (16). Statistical error bounds for the data were also calculated.

The Blackbook did not include data related to aluminium, so a wide range of pricing data was sourced online, while the energy data were obtained from the ICE. The variation in pricing was incorporated into the error.

In order to check the accuracy of the Blackbook-derived figures, embodied energy data for the seven materials were also obtained from the ICE. The mean of the two energy data sets was then plotted against the cost data as in Figure 28; the error bars represent the range of the two data sets, also accounting for statistical errors.

Additionally, three lines of constant energy price were plotted onto the graph, representing a gas price of £0.012/kWh, an electricity price of (£0.047/kWh) and the labour rate calculated in Section 2 (£0.83/kWh).

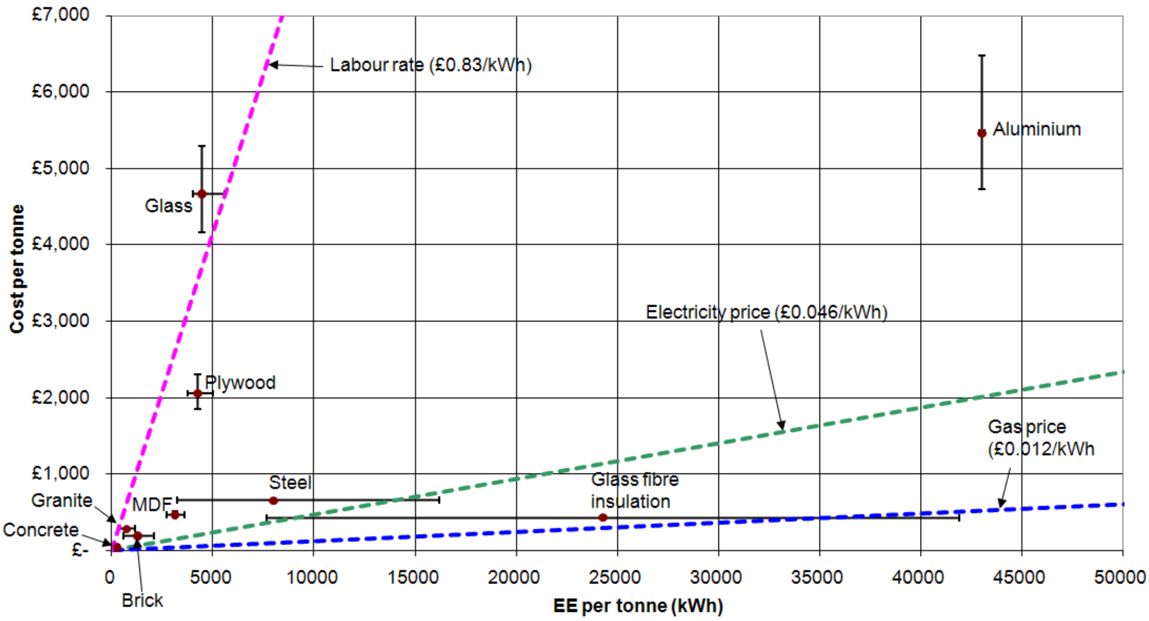


Figure 28: Embodied energy vs cost of construction materials

For clarity, the same points and lines were also plotted on a log-log axis, see Figure 29.

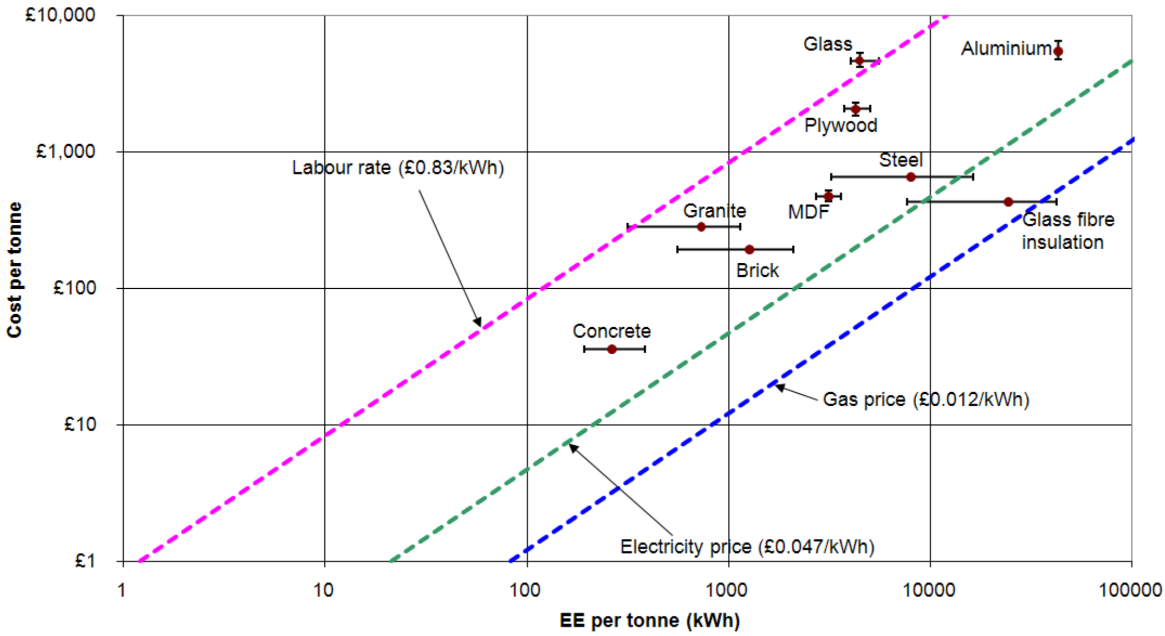


Figure 29: Embodied energy vs cost of construction materials (log-log scale)

6.2 Analysis

The graphs above appear to indicate that there is a positive correlation between the cost of a construction material and the energy consumed in its creation. The weakness of the correlation (calculated to be 59%) is such that it would be incorrect to conclude that there is a single £/kWh rate that can be applied to all construction materials.

It is perhaps notable that the materials broadly fall within the range of £/kWh between the price of natural gas and the labour rate established by this study. It could be hypothecated that the £/kWh of a given material is a function of the relative contributions of energy and labour in its creation.

For example, concrete and steel have £/kWh rates similar to the price of electricity, perhaps suggesting that the energy-intensive nature of steel and concrete manufacture dominate the cost. Conversely, granite and plywood £/kWh rates are closer to the labour rate of 83p/kWh, which may indicate that human labour plays a more dominant role in the cost of these materials.

To seek evidence to support or disprove this hypothesis would require further work. Specifically, a wider range of materials should be compared, with a focus on the nature of the cradle-to-gate manufacturing processes.

7 Conclusions

The results obtained in this study suggest that our initial hypothesis that the lifecycle cost of a building is in proportion to its embodied energy is false. However, proportionalities do appear to exist between cost and energy within certain boundaries of energy consumption. We chose to divide activities into labour, materials and direct energy consumption, assuming that proportionality existed within each of these sectors[11].

The embodied energy intensity of labour was estimated in chapter 3 using a methodology developed for this report. The distinction between this methodology and others is primarily in the size of boundary drawn around the energy associated with a worker. We chose to apportion energy related to a building according to the money paid to the worker for their involvement in the design, construction or maintenance. This led to a large boundary based on all aspects of a Western lifestyle being applied to estimate the embodied energy of human labour.

When compared to the energy intensity of electricity (4.7p/kWh = 21 kWh/£), our estimation for human labour energy (1.2 kWh/£) is much lower but, as explored in chapter 3.3, the two quantities are not directly interchangeable. To replace an automated process powered by electricity with a manual process powered by human labour would actually result in the process becoming both more expensive and more energy intensive.

The cost of consuming energy in the form of gas and electricity is subject to change. Our estimates of consumption over the occupancy stage of the buildings hinge on a projection of future energy prices that is impossible to verify. If prices fall over the long term, this quantity will become less significant, while rising prices could cause the occupancy stage to dominate costs.

The embodied energy of construction materials has been the subject of much prior analysis. Chapter 6 established that a correlation appears to exist between embodied energy and material cost, but that a single kWh/£ rate cannot be applied to all construction materials. Further work should be carried out to investigate whether the energy intensity of a material is a function of the proportions of direct energy consumption and labour used in its manufacture.

We explored these relationships across two hypothetical buildings: a school and an office. In both buildings, the construction stage was the most expensive, but the occupancy stage consumed the most energy. This is because during the construction stage, labour and materials make up the bulk of the consumption in terms of cost, both of which have a relatively low embodied energy per pound spent. In the occupancy stage, direct energy consumption plays a more significant role, allowing a greater quantity of energy to be consumed per pound spent.

Varying the structural methods had a very small impact on the cost of the construction stage of the school, and a larger effect on the energy consumption. Figure 30 below illustrates the ratio of cost to embodied energy for a wider range of structural methods within the school, the office and a hospital[12]. The trends indicate that, in general, cheaper structural methods are also associated with lower embodied energy. Interestingly, all structural methods for the school appear to have a higher embodied energy per m² than for the office, although it is significantly cheaper overall. This serves to further emphasise our findings that proportionality between embodied energy and cost exists only within defined boundaries, and cannot be applied to a general case.

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[11] The embodied energy of a material, as explored in chapter 6, may itself be a function of the labour and direct energy consumption involved in manufacture. This implies that the lifecycle energy consumption of a building could ultimately be divided into only labour and direct energy consumption.

[12] The hospital was the third building featured in the original Concrete Centre study, although we chose not to include it in our extended research.

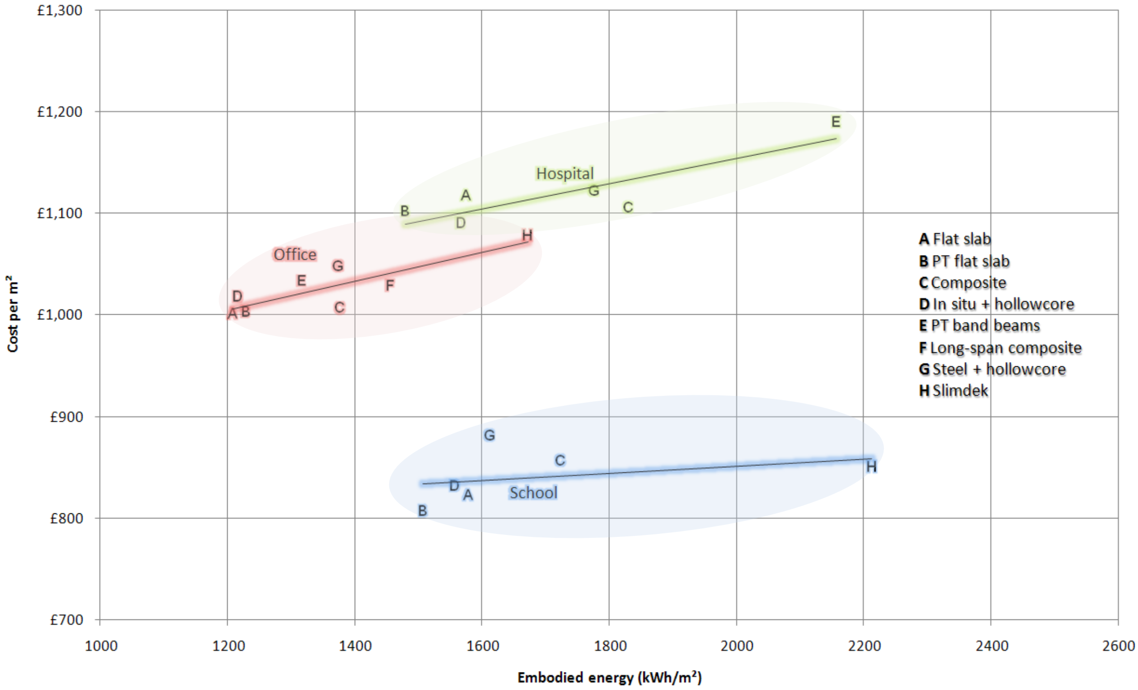

Figure 30: Cost vs embodied energy for a range of structural methods in a school, office and hospital

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