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A New Model for Designing Cost Effective Zero Carbon Homes: Minimizing Commercial Viability Issues and Improving the Economics for Both the Developer and Purchaser

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Abstract: There is a limited penetration of housing which offsets all operational carbon emissions within UK housing developer portfolios. This paper develops a balanced approach to zero carbon housing design from both architectural and national house builder perspectives. The paper discusses the techniques which can be used to reduce build costs, simplify designs and simplify renewable energy systems, resulting in more cost effective homes. The paper develops a technical and economic linked model to optimise a zero carbon design and then develops a home using this technique. It acknowledges that extra costs are inevitable but minimises them and details a lifecycle costing approach to provide economic justification. The paper then focuses on how the building designed can function more efficiently and economically than a Part L 2013 Building Regulation compliant building. Improved functionality is demonstrated both with and without the use of feed in tariffs. A key finding from this research is that zero carbon homes can benefit the consumer without impacting the developer. The results also demonstrate that homes could be better marketed on economic rather than environmental or technical attributes.

Keywords: building design optimisation; cost effectiveness of housing design; renewable energy strategy

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1. Introduction

Creating commercially viable new homes that offset all their operational carbon emissions, termed zero carbon homes, has proven more difficult than first envisaged by policy makers [1–4]. Goodchild and Walsall trace many of the problems surrounding these zero carbon homes back to the lack of defined plans for delivering the zero carbon targets [1]. They state that the government and the green building council wanted architects, designers and builders to create new thinking that broke away from incremental changes but did not define how this was to happen. They also note that the government envisaged radical changes in technology and design would occur based on targets alone. As such targets were ambitious but achieving them was ill defined. The ill-defined space in both the definition of zero carbon and in the prescription of how to achieve targets created a widely accepted problem regarding how to mainstream zero carbon homes [1,2,5]. The main consequence of this had been to lock many zero carbon designs into the green niches they carved out for themselves with little prospect of breaking through to the commercial builder market [1,2,5]. In the UK the commercial house building market represents the largest market segment of residential build volume, approximately 75% of the total annual market share [2]. In order to increase the deployment of zero carbon homes, developing a commercialised approach to zero carbon architecture is critical. To do so an understanding of commercial barriers inhibiting the uptake of zero carbon homes is required to design a home appropriate for this market.

This paper conducts an analysis of issues facing commercial residential development to provide a baseline for designing a zero carbon home. It develops a set of criteria to augment best practice design methods to create more commercially acceptable single family homes. The focus of this paper is to provide an economic rationale for full decarbonisation and to create economically viable designs. This paper does not focus on market values of properties. Market values vary greatly depending on location of the building in the UK. Instead the focus is on cost neutrality. Cost neutrality is defined as the point where the home does not financially impact the developer or the potential buyer.

This paper is not a comparison of different passive house, nearly zero and zero carbon design standards, this research is well defined in the literature [3–5]. Instead the focus of this paper is to determine if it is possible to create a more commercially viable design using existing policy instruments to reduce the costs of decarbonisation using market ready technologies. The aim is to understand how to improve implementation rates within the current market and technological environment.

The research in this paper falls into the "ecological modernisation" school of thought and emphasises the need to create "compatibility through design" to ensure that environmental improvement occurs without major changes in lifestyles [6,7]. As such, this paper does not review the potential to decarbonise through behaviour change or for excessive or frugal use of lighting and heating by occupants. Instead behaviour is considered to follow "Business as usual" whilst delivery of the energy for this scenario is adapted to be zero carbon. The designs in this paper focus on single family dwellings and excludes multiple person buildings such as apartments.

2. Background

2.1. Augmenting Best Practice to Reduce Commercial Barriers

When designing sustainable buildings it is the responsibility of the architect and the engineer to design a building that optimises the electrical, heating and cooling loads [8]. This includes the selection of equipment that is used to satisfy the buildings energy demands. Three tiers to sustainable design are suggested [8]:

(1) The basic design form and fabric. It is the architect's role to specify materials to use and use them to reduce loads.
(2) The design of passive gains. It is the architects role to reduce energy loads by maximising passive design and utilise free energy gains
(3) The specification of mechanical and electrical equipment to meet loads. It is the role of the architect and engineer to design the mechanical and electrical system to satisfy energy loads.

Similar principles are set out in the Zero (fossil) Energy Development (ZED) standards [9]. The ZED standards state that architects should take the lead on developing houses that are super-insulated, airtight, have properly oriented windows, use correct U-value assumptions, utilise passive gains and solar gains, have highly efficient appliances and low energy lighting. Both authors focus on developing buildings which function better by using less energy, less resources and producing less carbon [8,9]. They develop their philosophies into thorough guidelines detailing the different approaches an architect and engineer could take towards achieving sustainable design goals, however, neither of these literatures adequately take into account the role of meeting commercial stakeholder objectives.

This research proposes a methodology which incorporates the main commercial barriers into the design choices architects and engineers make. It is argued that by including these issues early on in the design process it will be possible to bridge the gap between the commercial residential developers, architects and engineers to create more commercially viable buildings.

It is acknowledged here that a methodology which includes stakeholder objectives will narrow down design choices, but it is also argued that what is left will be a guiding methodology for commercially viable buildings.

2.2. Identifying Barriers to Commercialisation

Code level 6 energy standards within the "Code for Sustainable Homes" outlines the benchmark for zero carbon design [10]. Research has shown that the cost of meeting this standard can be up to £26,000 extra expenditure relative to a home built to 2010 Part L building regulation standards [10]. The "Costs of building to the Code for Sustainable Homes" final report considered this to be 25% extra over capital costs [10]. When observed across a one hundred home development this would add up to £2,600,000 to the build costs and when viewed against a national house builder annual build volume of 1000 units per year this equates to £26,000,000 of additional cost. As such it is critical to either remove these costs or generate additional profit for developers to cover them. This is key as the "House Building Federation" considers the cost of cutting carbon onsite to be too expensive to justify. The Government, in the 2015 productivity paper, corroborated this and removed the 2016 on site energy efficiency standards from policy [11–13]. As such there is no longer a regulatory drive to achieve zero carbon standards.

A major concern for zero carbon design is the current lack of established open market sales values for zero carbon homes. Combined with this is a lack of evidenced price premiums for homes with zero carbon features. The basis for the issue affecting sales uplift is that energy efficiency and low carbon living are just two factors within the wide a range of purchase decisions for home buying [14–16]. As such these factors are considered to be insufficient by surveyors to command a premium price. When viewed in conjunction with other factors such as proximity to local schools, transport links, or bedroom sizes the impact is further reduced. Developers are therefore more likely to direct resources to criteria known to drive sales values. As such there is neither a regulatory or perceived market advantage to drive the implementation of zero carbon homes.

It is also cited that commercial risk is a barrier to commercialising housing which uses new technology [4,15,16]. The increased risk is based on an industry perspective that higher construction cost zero carbon homes are harder to sell and less profitable [4,15,16]. This inhibits the amount of commercial builders interested in adopting zero carbon designs as well as limiting the availability of project finance. As such it is harder to fund an innovative housing development when compared to building what the market expects, thus exacerbating the issue. Given the recent changes to energy policy, industry leaders consider that investment in low carbon development may diminish further in the future along with investor confidence [17].

Issues relating to marketability and consumer demand are also cited in the literature [18–20]. Many zero carbon designs in the past have relied on technologies that require home owners to change their behaviour *i.e.*, the use of biomass heating systems which require owner-occupiers to change how they purchase fuel and use heating systems [18,19]. The market for homes that impose consumer change is more limited if it is based on consumer willingness to accept lifestyle change [20]. This is based on empirical research results on the public's complacency about their actions and climate change, their de-motivated stance based on the perception that UK actions have minimal impact compared to other larger nations and their current understanding of the issues requiring low carbon practices [20].

Policy has been cited on numerous occasions as pertinent to shifting the market towards more sustainable design by mandating change. Unfortunately the effect that policy has had in the UK to date has been mixed. In 2015 Government analysts from the HM treasury considered that productivity in the housing sector was more important than mandating onsite energy efficiency [13,21]. Industry analysts have been using this argument for a long time to oppose zero carbon regulation, considering that such standards impact construction volume targets by restricting output. They consider the cost impacts of decarbonising the housing stock to have a direct impact on what can be built [2,15,19].

UK house builders thus argue they cannot meet affordable housing targets, housing volume targets and low carbon targets together [15,19].

Developers in the past have preferred to opt for the lowest design benchmark and this has been reflected in recent changes to the UK building regulations. The regulatory zero carbon definition now only takes into account emissions arising from the as built building services loads (provision of lighting, heating, pumps and fans) [22,23]. This definition excludes the predicted in use loads such as cookers, televisions and computers [22,23]. The effect that this has had on commercial residential development has been to make achieving zero carbon status easier and more cost effective but has significantly reduced the impact that the domestic sector will have on 2050 CO_2 reduction targets. As such a zero carbon home under regulatory parameters will in fact emit around a tonne of CO_2 per annum despite being termed zero carbon [22]. In 2015 the UK government moved to support this position further by removing the 2016 onsite energy efficiency targets from policy [23]. The next target date for nearly zero homes does not arise until 2019.

The second policy instrument developed to address cost based barriers to low carbon technologies focused on improving their investment potential through feed in tariffs and grants (FITs). The grants were designed to reduce the implementation costs of renewables whilst the tariffs were designed to provide a guaranteed return on renewable investments. Whilst grants had limited effect, feed in tariffs were seen as a way to create a more attractive and longer term investment proposition [24,25]. In the 2013 reports on the "Costs of Building to the Code for Sustainable Homes' and the "Code for Sustainable Homes and the Housing Standards Review" reducing costs of renewables are credited with reducing the cost of building to code level 6 energy standards [10,11]. This reduction has mainly been driven by FITs policy [26]. Unfortunately the impact of policies relating to zero carbon housing have been somewhat restricted by the implementation process. This was especially notable in the industry reaction to the FITs changes whereby the initial tariff rates were reduced without industry consultation [27]. This policy change was widely considered to have been poorly handled and caused many developers and investors to avoid including tariffs when creating long term business plans [27]. Further to this the government launched a consultation to further reduce FITs rates by 87% for solar in 2015 [28]. Due to such inconsistency in the policy instruments it is important to look beyond support policies, using them as transitional tools and not permanent economic drivers.

2.3. Adapting Design Criteria to Address Commercial Barriers

In order to address these commercial barriers to zero carbon homes within the design process four zero carbon design criteria, to be used in addition to Lechner [8] and Dunster *et al.* [9] methodologies, have been developed. The four criteria are:

(1) Cost reduction. The methodology for assessing cost reduction used in this research is based on offsetting the additional the extra over capital costs of creating a zero carbon home when compared against a benchmark cost of a 2013 Part L building regulations home. This is based on the extra over capital cost when building to a higher energy standard than Part L 2013.

(2) Reduction and simplification of the technologies. The number of additional technologies required to create the zero carbon home should be minimised to reduce both costs and the requirement for user practice change. Technologies that are easy to use when compared to traditional heating and electrical systems and have a documented history of reliability should be prioritised. The aim should be to reduce risk as well as complexity by focusing on market ready technologies and building fabrics that are considered standard for lending criteria.

(3) Any additional costs that cannot be offset via simplification or material substitution must be economically justified against running cost reductions or incomes generated. A microgeneration led approach is proposed for this purpose to develop zero carbon homes that could function on a single unit basis. This objective is to generate maximum investment returns for owner-occupiers. This paper models both subsidy backed and open market power purchase agreement options to demonstrate what happens with and without FITs. The aim is to build in resilience to potential

subsidy cuts proposed within the 2015 FITs consultation and use the FITs as a transitional tool only.

(4) Maximise decarbonisation above proposed zero carbon regulatory definitions. Zero carbon homes should offset the entire annual energy load of the building via grid connected microgeneration technologies to make maximum impact in decarbonising the sector by including emissions unaccounted for in the building regulations.

3. Methods

3.1. Optimising a Zero Carbon Home

To establish if these design criteria could be used to create a more commercially viable zero carbon home, a baseline design was developed using a detached 4 bedroom property. The house type was a compact 3 storey home with a gross internal floor area of 142 m^2 designed to fit into a site masterplan of 50 homes per hectare. The planning portal states that densities of 50 to 100 homes in city centres and 50 to 65 dwellings along transport corridors should be aimed for when designing eco towns [29]. It is anticipated that at this density all homes could be oriented for maximum solar gain and renewable energy generation.

A detached property was selected as this typology is most effected by heat loss through the building fabric. This makes it harder to achieve zero carbon status then semi-detached or terraced house typologies. The building was oriented to maximise the south facing roof space for renewable energy technologies. The baseline design layout was selected from a site masterplan for an eco-village that had failed to be built on commercial grounds after planning permission was granted.

The first stage in the methodology was to conduct a technical and cost analysis of the best available zero carbon microgeneration technologies. The largest cause of carbon emissions from a home in the UK result from space heating to replace heat lost through the building fabric, heat lost though ventilation, supplying hot water and household electrical demands. Key technologies designed to reduce these loads and supply the residual energy demand via zero carbon energy generation were investigated. Key technological solutions were then combined to create a number of different holistic building fabric, space, hot water and electrical generation systems. The designs were then modelled to establish energy losses, energy usage, energy use reduction and energy production outputs. Costs were obtained from manufacturers and distributors based on a 100 home development. These costs were verified by an independent quantity surveyor based on the drawings submitted. The cost based analysis incorporated both implementation and running costs to observe the effect that cost savings from reduced consumption and income generated.

The initial modelling was conducted using parametric analysis in an equation based model. Parametric analysis was chosen as, whilst not strictly an optimisation method, it can be used to optimise a building if systematically and methodically approached [30]. Given the combined technical and cost optimisation that this study required, parametric analysis was the best option to use. Parametric analysis allowed the use of spread sheet software to design a model that linked both these elements together so that the effects of changing one parameter could be observed across both the technical and economic outputs.

Within the parametric analysis some of the parameters were fixed and some variable. The fixed parameters were for space heating demands using an 18 °C set point, hot water demand based on 5 person occupancy and 50 L of hot water/person/day, and predicted appliance load electrical consumption including lighting energy use. Other parametric factors were variable and included wall and window u-value, space heating consumption, ventilation rate energy loss with heat recovery, heat recovery efficiency, heating and hot water system efficiency, passive solar gains and internal gains, energy generation by different renewable energy systems, renewable energy system sizing, implementation costs, build costs and running costs. Changes in each of these parameters and the resulting effects on other parameters were then observed to allow for optimisation. U-values were calculated using Build Desk U version 3.4 and Thermal bridging calculations were conducted using THERM [31]. Equations for thermal loads, heat loss through the fabric, heat loss through ventilation and heat loss through infiltration were taken from Frazer [32]. The effect of thermal mass, solar gains and internal gains were taken from SAP [33,34].

Heat loss was calculated by the equation:

$$H = H_t + H_v + H_i \tag{1}$$

where

- H = overall heat loss (W)
- H_t = heat loss due to transmission through building envelope (W)
- H_v = heat loss caused by ventilation (W)
- H_i = heat loss caused by infiltration (W)

The heat loss through the building envelope was calculated by the equation;

$$H_t = A \cdot U \cdot (t_i - t_o) \tag{2}$$

where

- H_t = transmission heat loss (W)
- A = area of exposed surface (m^2)
- U = overall heat transmission coefficient (W/m^2K)
- t_i = inside air temperature (°C)
- t_o= outside air temperature (°C)

Heat loss due to ventilation was calculated using the following formula;

$$H_v = c_p \cdot \rho \cdot q_v \cdot (t_i - t_o) \tag{3}$$

where

- H_v = ventilation heat loss (W)
- c_p = specific heat capacity of air ($J/kg \cdot K$)
- ρ = density of air (kg/m^3)
- q_v = air volume flow (m^3/s)
- t_i = inside air temperature (°C)
- t_o = outside air temperature (°C)

Mechanical Ventilation with Heat Recovery (MVHR) reduces ventilation heat loss as this was calculated using the using the following:

$$H_v = (1 - \beta/100) \cdot c_p \cdot \rho \cdot q_v \cdot (t_i - t_o) \tag{4}$$

where β = heat recovery efficiency (%).

The Thermal Mass Parameter (TMP) for a dwelling is required for heating and cooling calculations. Firstly the heat capacity was calculated for the materials. The heat capacity, or kappa value per unit area (k in kJ/m^2K), for the thermal mass elements was calculated as follows:

$$k = 10^{-6} \sum (dj \cdot rj \cdot cj) \tag{5}$$

where

- dj is the thickness of layer (mm)
- rj is density of layer (kg/m^3)
- cj is specific heat capacity of layer ($J/kg \cdot K$)

The calculation was used for all layers in the element, starting at the inside surface and stopped at whichever of the following conditions was encountered first:

- The total thickness of the layers exceeds 100 mm
- The midpoint of the construction is reached
- An insulation layer is reached (defined as thermal conductivity $\leqslant$ 0.08 W/mK);

Secondly the above calculations are used in the following formula:

$$(\text{Area} \times \text{Heat Capacity})/\text{Total Floor Area (TFA)} \tag{6}$$

The total TMP includes, walls, ground floor and inter floor materials.The benefit of thermal mass is taken into account in the utilisation factors.

Internal gains arise from lights, appliances, cooking and metabolic gains from the occupants. Useful heat gains and metabolic gains were used in the heating calculations based on their utilisation factors [33,34]. SAP standards were used for internal gains and solar gains [33,34]. Solar heat gains that arise through glazed elements with a glazing area greater than 60% were included in the calculations [33,34]. Solar gains were calculated separately for glazing on different elevation orientations. The equation for calculating solar gains used was:

$$\text{Solar Gain} = 0.9 \cdot A \cdot S \cdot G \cdot FF \cdot Z \tag{7}$$

where

- 0.9 is the typical average ratio of transmittance at normal incidence
- A is the area the opening (m^2)
- S is the solar flux (sum of direct and diffuse solar radiation) on a surface in W/m^2
- G is the total solar transmittance factor for the glazed element at normal incidence (from manufacturer)
- FF is the frame factor for windows and doors (fraction of opening that is glazed)
- Z is the solar access factor due to over shading. This is assumed to be less than 20% due to new build passive solar design and thus an access factor of 1 is used here

S was calculated for the heating season using the formula below for converting horizontal irradiance to vertical:

$$F_x(m) = R_{htov}(\theta) S_h \tag{8}$$

where

$$R_{htov}(\theta) = A + B\cos(\theta) + C\cos(2\theta) \tag{9}$$

$$A = 0.702 - 0.0119\,(\varphi - \delta) + 0.000204\,(\varphi - \delta)^2 \tag{10}$$

$$B = -0.107 + 0.0081\,(\varphi - \delta) - 0.000218\,(\varphi - \delta)^2 \tag{11}$$

$$C = 0.117 - 0.0098\,(\varphi - \delta) + 0.000143\,(\varphi - \delta)^2 \tag{12}$$

where

- F_x (m) is the vertical solar flux for an element in month m with orientation q (W/m^2)
- (m) is month
- $R_{htov}(\theta)$ is the factor for converting from horizontal to vertical solar flux
- θ is the orientation of the opening measured eastwards from North (e.g., East = 90) (°)
- φ is the latitude of the site (°) = 53.4° N for heating calculations
- δ is the solar declination for month m (°)
- S_h is the horizontal solar flux (W/m^2)

Appliance and electrical loads were established using data from The University of Surrey "Efficient household Appliance Survey" [35] and manufacturer's data to calculate loads and run times.

Hot water energy consumption was calculated in kWh per person per annum using the following formula:

$$Q = \text{density}(\text{rho})\cdot \text{Specific Heat Capacity (cp)} \times \text{Usage (L/day)} \times \text{Frequency (days)} \times \text{Temperature rise (dTw)} \times 0.001/3600 \tag{13}$$

Hot water systems also suffer losses due to distribution. Distribution losses of 15% were also added to this figure.

To estimate solar electrical generation and average daily temperatures over the 24 h period the "Joint Research Centre of the European Commission's" Photovoltaic Geographic Information System (PVGIS) software was used [36]. PVGIS data is inputted from ground station measurements taken using pyranometer readings and factors beam, diffuse and reflected irradiation into the measurement. The data used in PVGIS is taken over a 10 year data spread [37]. The PVGIS tool was chosen for both its usability and accuracy. The mean bias error (MBE) was only 0.3% and the root mean square error (RMSE) only 3.7% for the entire dataset within the model [37]. As such the over-estimation by the model is considered to be as low as 3.2%. London Gatwick was chosen as the weather station.

3.2. Cost Impact Modelling

Each technically viable energy system was analysed to observe both the implementation and running cost impacts. Further design iterations were then conducted to identify additional areas for value engineering by reducing components, substituting materials or improving efficiency *versus* increasing energy production. By establishing what was technologically possible and then varying the design based on the findings, economic parameters such as implementation costs, build costs, running costs and cash flows were also optimised. Options modelled included different building fabric compositions, varying combinations of PV, air and ground source heat pumps, passive and mechanical heat recovery ventilation systems and thermal stores.

The economic element of the model included a full cost based analysis based on a net benefits-deficits approach to implementation and running costs. The net benefit was calculated using the following formula:

$$NB = T_i + T_a - T_o \tag{14}$$

where

- NB = Net benefit/deficit
- T_i = Total Cash Inflows
- T_a= Total Avoided Cost
- T_o = Total Cash Outflows

Cash inflows were determined by capitalising the FITs income, avoided costs were calculated by capitalising energy load reductions and renewable energy consumption, and cash out flows by incorporating residual energy costs for electricity demands at 2014 market rates [38]. The technical model was used to calculate and compare the energy losses of the zero carbon design with those of a home built to 2013 Part L building regulations. Potential energy savings for the zero carbon design were calculated and then translated into a monetary benefit which could be attributed to elements such as the extra insulation, heat recovery technology and improved air tightness levels. The economic model was projected forward over the 20 year FITs period. The forward projections enabled the viability of the model to be established in the longer term. Fuel price escalation and inflation were also included in the model at 5% and 3% Compound Annual Growth Rates (CAGR) respectively. Fuel price escalation is predictive and subject to significant uncertainty but the mean average of Ofgem's "Project Discovery" and DUKES was used [39,40].

The latest available published data from OFGEM was used for the FITs tariff rate for installation dates up to the end of December 2014 [41]. Generation rates were used based on the predicted PV system outputs and export tariffs were based on the 50% of the energy being exported [40]. The net benefit model was also run using FITs estimates for installation dates in 2015. From 2015 onwards price degression rates for install costs were applied which matched degression rates set-out within the FITs scheme. The model was then run without the FITs scheme using only open market power purchase agreement prices for energy exported back to the grid. The rate used was based on FITs export rate at 50% deemed export [41].

The economic model developed assumed that the extra capital costs for zero carbon design would be passed to the consumer via a higher purchase price. As the initial capital outlay is significant for the combined microgeneration platform, extended mortgage payments were assumed to be the finance method. As such the extra over mortgage costs were incorporated into the calculations for deriving an economic benefit. A mortgage rate of 5% was used over a typical 25 year mortgage period.

The reduced energy demand for both regulated and unregulated energy loads were capitalised and an allowance made for the bought in energy requirement during times of insufficient PV production. A cost saving for the PV produced electricity was also accounted for in the same way. The energy generated was then capitalised using the appropriate FITs rate in the initial case and without the FITs rate in subsequent cases. The totals were then summed and the extra over mortgage costs for the additional insulation and energy system components deducted to give the net benefits-deficit figure for each year.

3.3. Verification

Given the combined technical and economic (implementation and life cycle cost) outputs required to optimise the design, linking these two aspects was critical to optimisation. It was determined that this was not possible using a dynamic computer model in the first instance due to the separation of these two elements. Instead the final design was validated using a dynamic modelling tool. TRNSYS was chosen for this verification. TRNSYS is a transient systems simulation program developed by the University of Wisconsin [42]. It is widely used for energy in building simulation. TRNSYS enabled different usage and occupancy patterns to be modelled as well as more dynamic passive and thermal gain modelling to be incorporated such as internal radiative gains and wall gains. TRNSYS models thermal behaviour of a building divided into different zones and models thermal demands hourly for each thermal zone [42]. Thus whilst TRNSYS models are less flexible to rapid changes and in observing technical and economic optimisation they offer more detailed and accurate outputs. The orientation of the building, temperature set points, ventilation strategy, occupancy, thermal emitters and heating system were kept the same, however, the TRNSYS model was divided into 15 individual thermal zones with different occupancy patterns and usages. The thermal energy requirement determined by the TRNSYS model was within 3% of the equation based model. The equation based model yielded a slightly higher energy consumption and this was used in the economic modelling so as not to understate the energy demand.

Usability was then assessed on whether or not technologies required significant user practice change compared to energy systems using traditional energy generating technologies. This was determined subjectively by examining the control systems and levels of automation compared against traditional gas boiler controls. The usability of the systems was then combined with the technological and economic analysis to identify the most cost effective, technically viable and user friendly design achievable.

4. Results

4.1. Construction System Strategy

An oversized timber semi-balloon frame construction method was used for the finalised design. A balloon frame uses light weight and thinner framing members than traditional wooden construction and the studs in the wall carry an equal distribution of the vertical and compressive loads of the building [43]. Rigidity is provided by the outer OSB sheeting. Upper floors are carried by horizontal joists on top of the studs [43]. The timber frame was oversized because the sizing of the studs allowed for a relatively more heavy weight frame to standard balloon frame buildings to be created. This meant the building could take increased insulation thickness and loads. Load bearing was important for incorporating thermal mass. The semi-balloon frame also allows for the breather membrane and airtightness layer to be dressed in a continuous layer up the wall face making airtightness detailing to a higher level easier [43]. The specification and material break down of the timber frame is detailed in Table 1 and Figures 1 and 2.

Table 1. Wall and roof build-up.

Layer	Wall Build-Up
1	15 mm cement board
2	200 mm × 75 mm C16 vertical studs at 600 mm centres full filled with 200 mm mineral wool
3	15 mm OSB3
4	50 mm × 100 mm horizontal battens at 450 mm centres full filled with 100 mm mineral wool
5	Breather membrane and 25 mm × 38 mm battens at 400 mm centres
6	15 mm cement board
Layer	**Roof/Ceiling Build-Up**
1	18 mm OSB3 deck
2	200 mm × 75 mm C16 joists full filled with 200 mm mineral wool
3	200 mm × 75 mm C16 joists full filled with 200 mm mineral wool
4	Breather membrane and 25 mm × 38 mm at 400 mm centres
5	18 mm OSB3 deck

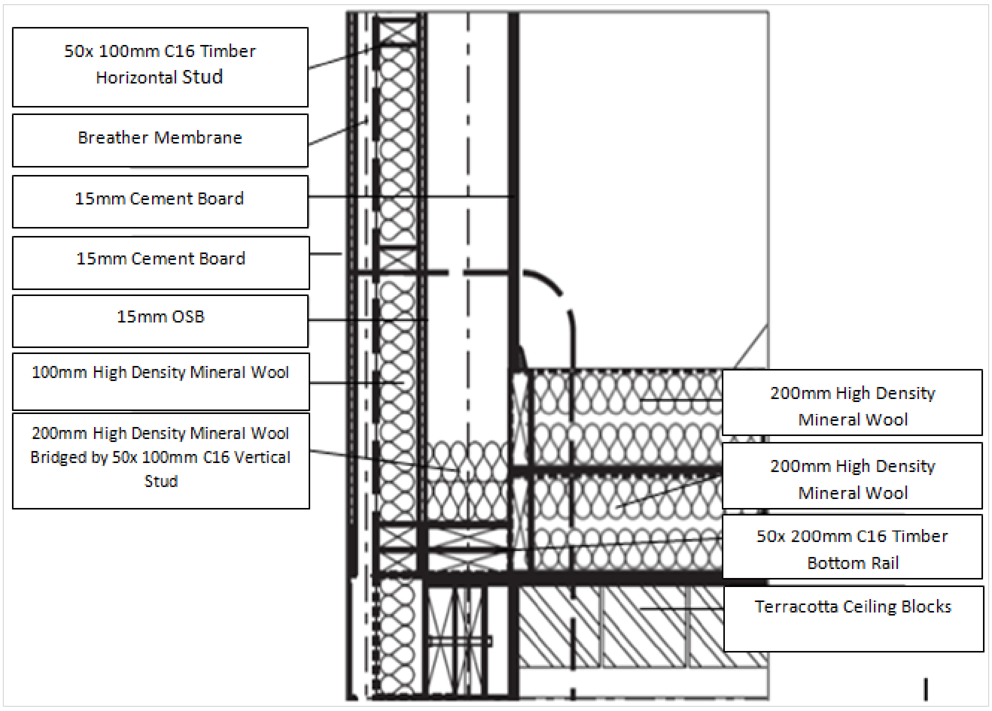

Figure 1. Wall and roof build-up under integrated PV panels.

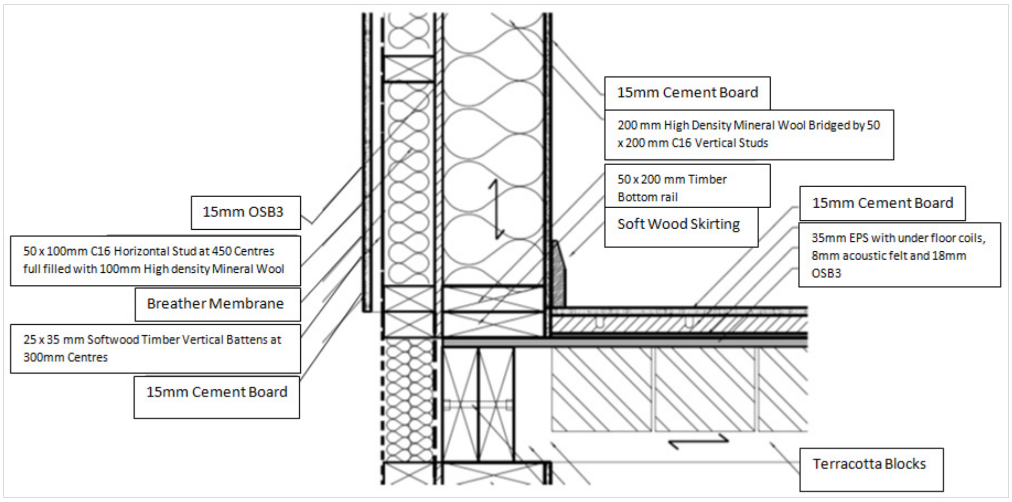

Figure 2. Wall and floor build-up under north roof.

4.2. Fabric Energy Performance Strategy

A mineral wool roll with a Lambda value of 0.037 W/m^{2}K was chosen due to its cost effectiveness and inert nature. Mineral wool is odourless and non-hygroscopic. It is also rot proof and does not encourage the growth of fungi, mould or bacteria. Mineral wool is also CFC free, HCFC free has a low ozone depletion and low environment impact potential. Mineral wool offered the best trade off in terms of price and performance of all the natural insulation materials used to arrive at the same U-value. Fossil fuel derived materials were discounted from the study due to high embodied carbon, ODP's, CFC's or VOC's. A combined 300 mm of mineral wool insulation was used in the framing system with 200 mm in between the studs and 100 mm in between the horizontal studs. The combined 300 mm of insulation enabled low wall U-values to be created which reduced heat loss and conserved energy. Splitting the insulation also helped in breaking the thermal bridges.

The ground floor slab was insulated using a high density Polystyrene (EPS) Passive Slab foundation system. This foundation design was based on using a concrete ring beam sited on a 300 mm permanent form insulation raft of Polystyrene (EPS). This method was chosen as it eliminated cold bridging at the wall-floor junction detail. Eliminating this cold bridge is critical to reducing heat loss as the higher levels of insulation in the walls causes the effect of the wall-floor cold thermal bridge to increase in importance as it becomes a major source of heat loss. By using this method to eliminate the cold thermal bridge at the wall-floor junction a U-value of 0.1 W/m^{2}K was achieved. Details can be seen in Figure 3.

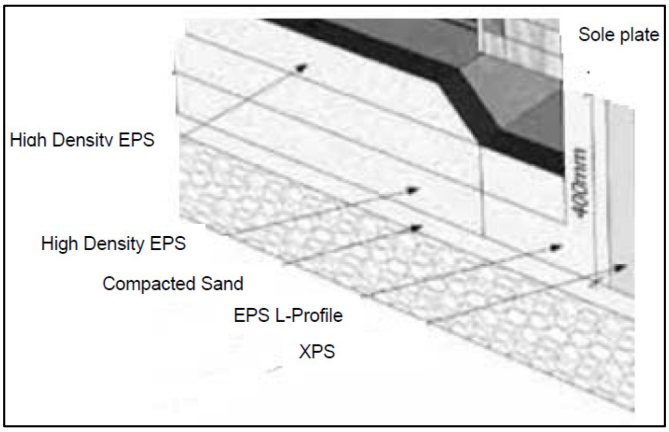

Figure 3. Section through foundation detail.

A wall U-value of 0.14 W/m^{2}K was achieved for the walls and 0.1 W/m^{2}K for the floor and ceiling. Build desk calculations also confirmed the build ups to avoid critical humidity points and neither mould growth nor interstitial condensation were risks. The design detailing of the envelope ensured that the insulation formed a continuous unbroken layer around the roof, walls and floor of the building fabric to reduce thermal bridging losses. Thermal bridging values were calculated using THERM and verified by the BRE.

Air tightness is also a critical factor in reducing heat loss. Airtightness is provided by the materials and continuity of the airtightness line. At 15 mm the OSB3 is considered to be air tight if correctly taped and sealed. All critical junctions were detailed to ensure the continuity of the air tightness line along with the correct taping and sealing of penetrations. The design airtightness goal for this building was to achieve 1.5 air changes per hour at 50 Pascals based on the taped and sealed OSB3.

Thermal mass is also important to the energy strategy. Timber framed buildings are more lightweight than other buildings and it is more difficult to maximise the thermal mass parameter (TMP). An overall thermal mass parameter of 239 kJ/m^{2}K for the building was achieved. Good practice thermally massive designs should exceed 200 kJ/m^{2}K.

Window choice was also critical. Windows have higher U-values than walls so to minimise heat loss high performance windows are required. Double glazed windows were chosen as they did not add a significant cost premium unlike triple glazing. Double glazing is also standard in Part L 2013 building regulation builds so care was taken to source high performing double glazing.

Window frames are also a weak point thermally as significant thermal bridges can be created here. As such the windows sourced were thermally broken timber framed windows to reduce thermal bridging. Given the other energy saving measures the optimised design used windows with a U-value of 1.2 W/m^{2}k, G-value of 0.51, a frame factor of 0.65 and light transmission of 0.72.

4.3. Residual Energy Loads

After the loads have been reduced the remaining thermal and electrical loads need to be met. Table 2 below shows the hot water requirements for the building. This is based on 50 L of hot water per person per day. A 300 L insulated hot water tank was selected for the thermal store. The hot water required was then adjusted for distribution losses. Heat loss from the tank was based on manufacturers' data.

Table 2. Annual hot water usage allocated per person (based on 50 L).

Contribution to Annual Load	kWh
Annual heat energy/person/annum (Q)	779
15% distribution losses	117
Total	**896**
Heat loss kWh/day	0.9
Annual heat loss from cylinder	329
Annual heat loss from cylinder/person	55
Total hot water energy requirement/ person/ annum	**951**

To calculate the monthly and annual heating electrical loads and adjust seasonal efficiencies of heating technologies, monthly loads and weather profiles were created. The monthly load profiles took into account the usable internal gains and solar gains. Profiles were modelled using a 24 h average of temperature (°C). The peak loads, heating loads and heating technology efficiencies were combined with the hot water requirements. This created the full annual regulated energy profile for the optimised design.

4.4. Unregulated Energy Load Data

In addition to regulated energy loads for lighting, heating and hot water the design philosophy also required the building to take into account other energy loads. These are detailed in Table 3.

Table 3. Electrical appliance loads

Load	Annual (kWh)	Use Frequency
Lighting	3.45	5 Hours Daily
Fridge freezer	474.5	Daily
Dish washer	383.25	8 per Week
Washing machine	328.5	8 per Week
Dryer	219.0	7 per Week
USB powered items (3 number)	5.5	5 Hours Daily
LCD TV (2 number)	365.0	5 Hours Daily
Satellite receiver (2 number)	109.5	5 Hours Daily
Laptop computer (2 number)	36.5	6 Hours Daily
Central heating pump	397.5	5300 Operating Hours Annually
MVHR (22w combined fan power)	192.7	24 Hours Daily
Induction cooking and A rated oven	600.0	1.3 kW Daily
Microwave, Kettle and Miscellaneous	290.0	Annual
Total	3405	Annual

Table 4 below summarises the energy usage and balances annually for the optimised design.

Table 4. Housing data and energy balances.

Demand	Usage (kWh)
Total annual electrical consumption	5136
Ventilation heat loss (MVHR @ 90%)	345
Total space heating requirement from plant	1304
Total hot water demand (including losses)	4755
Annual hot water and space heating consumption	6058

4.5. Renewable Energy Platforms

Once load reduction techniques were defined and thermal performance established the remaining thermal and electrical loads needed to be met by renewable energy systems. Fourteen building energy systems were designed and these were rationalised down to four technically and economically viable systems. These four renewable energy platforms are outlined in Table 5 and discussed in detail in Section 5.3.

Table 5. Energy systems.

Energy System	Technology Platform
System 1	Solar PV + MVHR + Ground Source Heat Pump
System 2	Solar PV + MVHR + Air Source Heat Pump + Solar Thermal
System 3	Solar PV + Integrated MVHR + ASHP + Solar Thermal
System 4	Solar PV + MVHR + Exhaust Air Source Heat Pump
Notes	
Building Envelope U Values (W/m^2/k)	Walls: 0.14, Ground Floor: 0.1, Roof: 0.1, Windows: 1.2 (whole window), Door: 0.9
Airtightness	1.5 Air Changes per Hour (ACH) at 50 Pa
Heating	Set Point 18 °C, Heating Emitters: Under Floor Heating Coils
Whole House Ventilation Rate	0.6 ACH
Solar Thermal	2 number 16 tube collectors (2.1 m length evacuated tube). 3.472 m^2 gross area, 1.522 m^2 absorption area
Photovoltaics	250 w Mono-crystalline 15.3% efficiency
Air Source Heat Pump	3.5 COP (Annual mean) (Adjusted monthly based on Average Monthly Temperature Profile)
Ground Source heat Pump	4 COP
MVHR and Integrated	90% Efficiency Using ASHRAE Ventilation Rate Standards

5. Discussion

5.1. Construction System Strategy

The wall construction systems designed were costed based on m^2 rates using the wall build-up developed. The timber frame construction method offered marginally better out turn construction costs (£127/m^2) for a fully erected external wall build-up than traditional masonry construction (£129/m^2) or an alternative eco-block construction (£135/m^2) (when built to the same thermal efficiency). The out turn construction costs for masonry construction were based on a quantity surveyor supplied rate and the eco block construction price was supplied by the manufacturer.

The timber frame construction method also created a number of technical and secondary benefits. Firstly the construction system was easier to adapt to different thicknesses of insulation between the studs, internally and externally. This meant optimising the energy reduction and energy generation strategies were easier. As such the options for optimising energy usage, implementation cost, and life cycle costs were greater and more flexible.

Secondly the over sizing of the frame increased the capacity of the building to take thermal mass which enabled more internal gains to be utilised. This reduced energy inputs and life cycle costs. A number of different options for the thermal mass were considered but integrating into the ground floor ceiling best enabled the TMP and cost to be reconciled. The beam and block thermal mass flooring system used was specifically designed for lightweight frame systems and thus functioned well with the timber frame methodology. An additional rationale for integrating the thermal mass into the ceiling was to reduce other costs. This was achieved by substituting traditional ceiling build-ups and finishes by using a product that was already finished.

The timber framed solution was predominantly comprised of dry construction methods that did not require wet trades on site, reducing the number of contractors and simplifying the build process. When combined with partial offsite construction and prefabrication of wall panels on site build times could be reduced, as well as facilitation of "Just in time deliveries". This reduces predicted construction programme length and costs. Total costs are presented in Table 6.

A key secondary benefit was that it did not constitute a "Modern Method of Construction" (MMC). MMC's are disliked by many warranty provides as they do not have a documented history to show that they will last longer than sixty years. As such mortgaging them under standard terms is more difficult. As the frame type did not use MMC it meant that the house would not require special considerations for lending purposes, reducing developer risk. This has important implications for its appeal to national house builders as not only is there a cost reduction but the construction method would qualify for lending and LABC warranty under standard terms. This also reduces developer and market risk.

5.2. Insulation Strategy

The walls of the building were insulated to a U-value of 0.14 W/m^2K. The ground floor slab and roof were insulated to a U-value of 0.1 W/m^2K. This was due to the disproportionate cost of reducing the U-value further than 0.14 W/m^2K for the walls. A secondary impact was the thickness of the walls. On a constrained site this would mean lower density housing and/or reduced gross internal space. This would impact the end property value and the gross development value by reducing the number of properties on the site and/or size of the properties.

A U-value of 0.14 W/m^2K still allowed cost effective energy system design as the impact on the thermal load did not significantly increase the plant size. For example, a reduction to 0.12 W/m^2K required and additional 100 mm of insulation but only reduced the thermal energy input by 200 kWhr per annum. This additional thermal load did not require a larger heating plant to satisfy it as the peak load only changed from 4.025 kW to 4.107 kW with the reduction in insulation. The increase in the wall thickness was 200 mm on the North-South and 200 mm on the East-West walls when combined. This had both a cost implication in terms of additional insulation and building footprint/site density implication.

The depth and position of the ceiling rafters required for structural loads meant that it was easier to incorporate additional insulation into the ceiling plain to achieve 0.1 W/m^{2}K more cost effectively than it was in the walls. As ceilings do not affect the gross internal floor area or the plot size on a site masterplan this would not affect density or building size.

The ground floor slab method was easier to insulate to a lower U-value. A U-value of 0.1 W/m^{2}K was achieved due to the concrete ring beam being sited on the 300 mm permanent form insulation raft. An added benefit of this foundation method was it eliminated the need for external footings. It also reduced the amount of concrete required. This meant that the concrete only needs to be poured once, thus reducing concrete costs and installation over traditional strip foundations. The cost of the foundation ranged from £5,800 to £15,000 depending on ground condition. The mid-range option of £10,700 was used in this paper.

5.3. Energy Systems

The trade-offs in energy system design were decided based on implementation cost, life cycle costs, usability and simplicity. Four systems were designed to meet the energy load of the modelled building, however, three were subsequently found not to effectively balance the cost-usability trade-off. Primary renewable energy generation was solar based for both thermal and electricity. PV was chosen as the default option for electrical generation based on documented run times, ease of use, low maintenance and relatively dominant market position when compared to other technologies such as micro wind. Solar thermal was also considered in some options to reduce electrical load. The aim was to reduce technical risk and market risk by designing out significant user practice changes.

System 1 was simplistic and easy to use, however, it also had the highest capital and installation costs and was thus too capital intensive to be cost effective. The higher COP of the heat pump helped reduce both life cycle costs and the PV costs, however, the cost of the installed ground source system was too prohibitive. The total extra over system cost, installed including coils and cylinder, was estimated at £25,775.

System 2 substituted the ground source heat pumps for air sourced heat pumps to reduce cost. It also added solar thermal panels. This reduced electrical demand for hot water heating and compensated for the lower COP. Whilst these substitutions significantly reduced capital costs over option 1, it increased system complexity by adding an additional technology. This meant additional storage tanks and control systems as well as ongoing maintenance procedures would be required. As such the system did not minimise user requirements due to complexity. The total extra over costs for system 2 were £14,513.

System 3 aimed to reduce costs further by using an integrated mechanical ventilation heat recovery (MVHR) and air-source heat pump unit. It also included solar thermal panels to meet hot water demands within the electrical production limit. As such system 3 did not reduce costs over system 2 and did not, in the end, minimise user requirements by combining the air source heat pump and MVHR. This was due to the addition of solar thermal controls.

The combined MVHR and heat pump unit also had a negative impact on heating loads as the combined system over ventilated the building to meet winter heating and hot water loads. This increased the ventilation rate from 0.6 ACH to 1.3 ACH. This was due to two issues. Firstly the air supply to the heat pump took priority which meant that when a thermal demand existed the MVHR was bypassed. This in effect cooled the building by bringing cold air in without recovering the heat from the extract air (which went to the heat pump). As such the unit had to provide more heat for longer by using electricity. Secondly there was an inability to regulate the air flow whilst the heat pump was in operation causing the ventilation rate to increase under certain conditions. As such more energy was required to maintain the steady state heating requirement of the building than if a non-integrated unit was used. The total extra over costs for system 3 were £14,825.

System 4 offered the best balance of costs and usability. The removal of solar thermal, increased electrical demand for heating and hot water but simplified the storage and control systems. It also reduced a layer of installation and capital costs. The separation of the MVHR from the air source heat pump remedied the over ventilation and MVHR bypass issues experienced when modelling option 3.

The removal of the solar thermal collectors also simplified the system, however, this required more electrical energy to provide hot water which increased energy demands from electrical sources. By removing the solar thermal the size of the PV array could be increased by utilising the roof space vacated by the solar thermal collectors. This allowed the additional electrical energy consumption of the heat pump to be offset by the increased PV output. This also brought into question the cost benefit of energy saving *versus* technology choice and income. The PV offered better cost benefits than the solar thermal and thus although it increased electrical energy demand it reduced life cycle costs. The total extra over costs of this system was £13,484.

5.4. Further Cost Reductions

As a consequence of this research it was identified that roof mounted PV and standard Building Integrated PV (BIPV) were not the most economical way to incorporate PV panels into a new build home. This was due to the need to install a roofing build-up and then include PV panelling as an additional cost on top. Roof integrated BIPV technologies were investigated to see if the potential existed for further costs reductions. The main issue with existing market ready solutions was that the BIPV was used primarily to create a flush fitting roofing plain to improve aesthetics and this attracted a price premium. Many components of tradition roofing solutions were still required such as the rafter, vapour permeable layer, decking, sarking, counter batten and tiling batten. This did not reduce extra over costs.

According to calculations based on SPONS 2012 costs for a roof occupying the approximate area to meet energy loads would equate to £4,500–£5,500 depending on roof type. Design iterations showed that if the roofing substrate from the rafter level upwards was replaced by PV it offered significant opportunity for improved cost effectiveness as long as the cost of the PV panel did not significantly increase. As such methods for reducing costs further were developed. The main changes required to integrate the PV panel into the roof involved engineering modifications to enable the conversion of a PV panel into a complete roofing substrate. The edge extrusions of the panels were reengineered to utilise an overlapping flashing cap to create a weather proof seal to the PV tiling system. EPDM seals and gaskets were used in the panel joints to increase the resistance to weather conditions, especially wind driven rain. A condensate drainage channel was also developed to allow the panels to be securely fastened to the rafters to protect against wind uplift. Finally eaves, ridge and verge flashings were developed to complete the roof. The finished design was tested and certified by the Building Research Establishment to meet with the appropriate BS and EN standards for roofing products and released to the market.

According to calculations based on SPONS 2012, a roof occupying the same area equates to around £83 per m^2 [44]. The cost of the integrated PV roofing system equated to £170 per m^2. The net extra over cost to justify was only £87 per m^2. For comparison, a roof mounted system would be approximately £283 per m^2. The cost benefit of the integrated PV roof system was thus only £83 m^2 *versus* £287 m^2. The net benefit from using the roof integrated system was £204 m^2. As such the total extra over cost for system 4 was reduced to £10,244.

5.5. Total Building Cost

To price the full building specification all elements were priced using current rates from manufacturers, SPONS, and quantity surveyor prices [44]. This included the cost of interior finishing. Table 6 below details the quantity surveyor verified costs (based on the drawings and material specification submitted) of the complete building fit out. Total construction cost was only £1184 m^2.

Table 6. Costs of the complete building.

Work Packages	Line Items
Raft foundation system + dwarf wall details	£13,000
Frameworks	£30,443
Incoming services	£5,000
Wall system	£12,724
Glulam beam and terracotta block floor	£5,000
Cost for the supply & 1st fix of staircases (Excluding spindles, aprons and other 2nd/3rd fix items)	£2,534
300 mm MW + 100 mm MW+ VCL to solar loft floor	£872
EPDM tanking under PV roof (required for LABC)	£2,200
Ventilation hatches to solar loft (18 mm ply, hinges, chain and catch/clasp):	£300
North facing roof complete	£3,097
PV Roof: Materials only	£8,250
PV roof: Fixing only	£600
Velux roof lights	£1,200
Flashing to solar loft wall / roof junction:	£200
Window and doors, installed excluding internal reveals and external cills	£8,250
External Cills supply only cost (install cost inc in windows)	£272
MVHR + ASHP inc. Under floor system installed	£7,754
inverter, sundries, consumer units, electrical labour,G59, MCS handover packs	£2,481
External trims and finishes	£2,000
Soffits and barge boards	£2,214
Rainwater goods	£564
Soil stack (110 mm PVC)	£150
Sub-total	£109,106
Sub-total shell and core services inc developer costs	£117,835
Finishes-to completion (QS Pricing)	£50,283
Total on plot Turnkey costs (Excluding Site infrastructure, planning, Section 106)	£168,117
M^2 on plot Turnkey costs (Excluding site infrastructure, planning, Section 106)	£1,184

5.6. Lifetime Cost Benefits

Whilst the extra over costs were reduced they were not eliminated. It was therefore important to justify the residual cost uplift through life cycle cost savings. Figures 4–6 show the results of the life cycle cost modelling. These figures detail the economic outputs based on the energy consumption and production.

Figure 4 shows the monthly cash flows and avoided costs. The chart demonstrates that the additional monthly mortgage payment is always lower than the income generated from the FITs without having to take into account the avoided costs. This underpins the short term viability of the model. The chart also demonstrates that inflation and fuel price escalation significantly increase the effect of the avoided costs over time. This underlines the importance of abating energy costs in the long term and underpins the long term viability of the model. As such the technologies that reduce energy consumption are as important as the income generated through the FITs backed PV system.

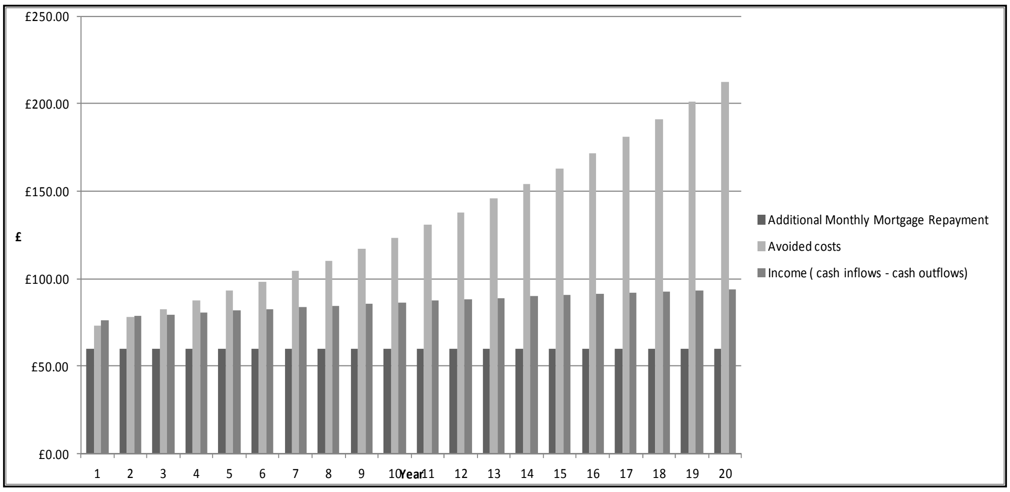

Figure 4. Monthly cash flows and avoided costs.

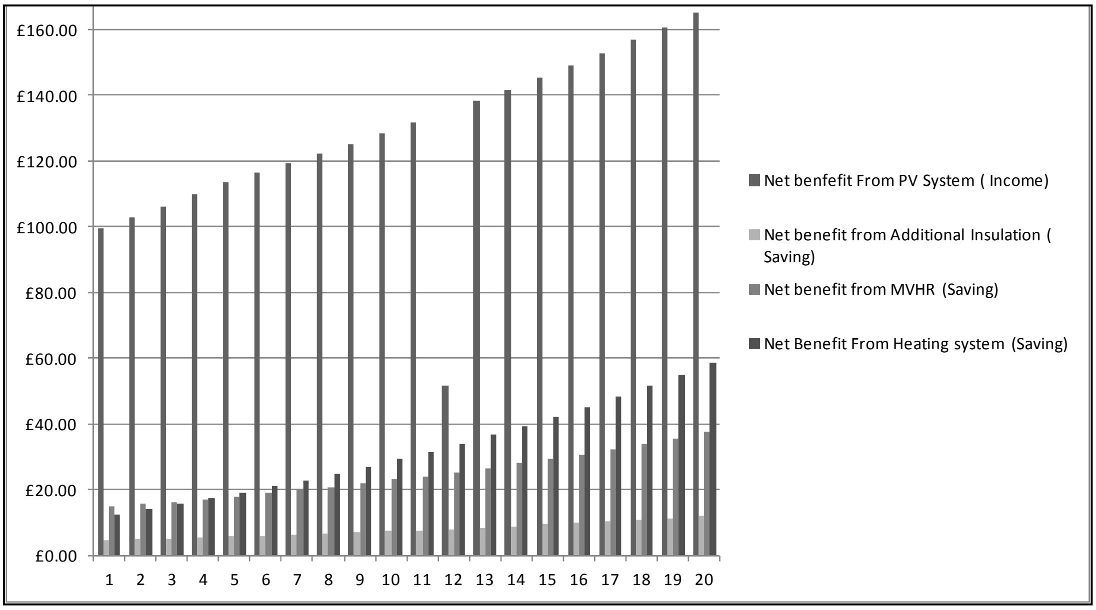

Figure 5. Contribution to net monthly benefit from income/cost savings.

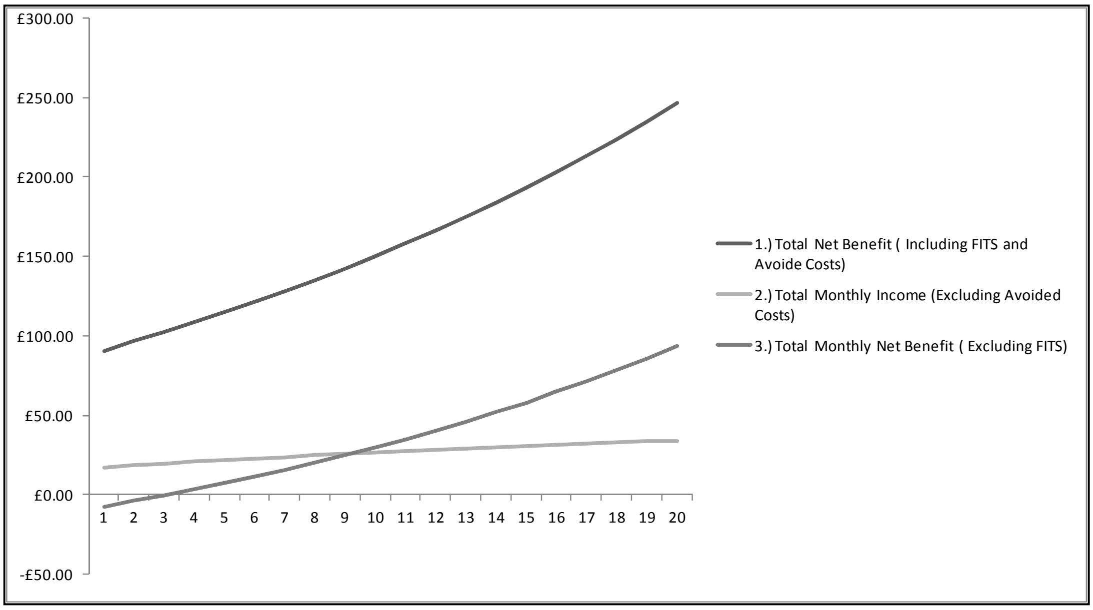

Figure 6. Short, mid and long term viability under different income scenarios.

A secondary outcome demonstrated by Figure 4 is that the running costs are effectively substituted by the increased mortgage cost. This provides an additional benefit to the owner-occupier as these costs pay down the debt on the building instead of in a 2013 Part L compliant building where outgoings are used to pay an energy provider. This creates a residual investment benefit for the mortgage holder. It is important to note that this benefit is only possible when using the FITs, however, recent policy changes have indicated that longevity of FITs at the currently proposed levels are not guaranteed to remain.

When the net benefit contributions are further analysed the role each technology has in creating the net benefit can be better understood. Figure 5 shows the contribution each technology has in the net benefit calculation in terms of income or avoided cost. In year twelve it is assumed the inverter for the PV system is replaced and this accounts for the dip in monthly income in that year.

Figures 4 and 5 show FITs backed PV income to be the most significant contribution to the net benefit equation. This could lead to criticisms of the model as it appears to heavily rely on subsidy support, bringing the long term viability into question. As subsidies are not considered a long term solution it is important for the model demonstrate that it can create a net benefit without the FITs.

Figure 6 shows a comparison of the net benefit model under three scenarios. Scenarios represented by lines one and two demonstrate the short-term viability by including the FITs payments. Line one includes the avoided costs and line two excludes them. Critically a net benefit exists without the avoided costs, eliminating any financial impact on the consumer. Line three demonstrates the long term viability by removing the FITs generation tariff income from the calculation.

These findings demonstrate positive net benefits can be achieved in both the short and long term. Firstly, the positive net benefits achieved with the FITs mechanism gives short term viability. This is demonstrated by the positive year one to year twenty cash flows. Line two demonstrates that this is possible using cash inflows alone by excluding the avoided cost component. This means that the optimised zero carbon home is more economical to live in than a 2013 Part L building regulations home from year one, even with an increased mortgage payment. This effectively eliminates energy bills over the course of the year by using the FITs to offset the residual energy bills with enough surplus to offset the annual additional mortgage costs. Line three shows that when the FITs generation tariff is omitted the model still returns a positive net benefit from year three onwards. Whilst there is a slight deficit in year one to three of the investment the seventeen years in positive cash flow far out weigh this. This emphasises the combined effects of fine tuning the energy system for life cycle cost reduction and reduced implementation costs. The outcome is a design that improves on the life cycle costs of a 2013 Part L design without requiring support tariffs. This adds resiliency to the methodology by moving zero carbon design towards commercial viability without the need for economic support. It is important to note that whilst the FITs is not required to create a home that is more economical to live in compared to a 2013 Part L complaint home it is does not offset the additional mortgage cost with an income. This is because the FITs income offsets the mortgage payment in scenarios one and two (lines one and two) but avoided costs provide the majority of net benefit in scenario three (line three). As such the FITs based model is more attractive to the consumer through its income provision. The more attractive cost benefits derived from the FITs model should be used to stimulate uptake in the early adoption stages and phased out with volume. The FITs is thus proposed as a way to stimulate the diffusion of innovation into national builder portfolios by enabling the developer to pass the additional costs of zero carbon construction on to the consumer without negatively impacting either party. This has important implications for policy makers in the UK who need to consider the impact that reducing the FITs again, by as much as 87%, could have on the uptake of zero carbon homes.

6. Conclusions

This research identified a number of important areas which may help support the roll out of zero carbon homes. The majority of issues currently faced by national house builders revolve around returns, costs, risks and markets. To improve returns, cost reduction took priority as well as finding additional ways to create price justification. Due to the fact extra over costs still exist the need to justify these costs for both the developer and the purchaser becomes critical. Encouragingly the modelling demonstrated that tariff incomes could offset the additional costs involved when mortgage financed. This effectively makes the zero carbon energy production and efficiency package cost neutral to the owner occupier even with the developer passing these costs forward. This opens up the potential for developers and lenders to explore ways to incorporate these into mortgage criteria. It also opens up the potential for developers and surveyors to revisit how best to incorporate the financial benefits of zero carbon design into valuation criteria. As the UK housing market is dominated by houses constructed by commercial residential developers this is core research finding.

Communicating the energy and life cycle cost benefits effectively takes on more importance as the potential to create competitive advantage based on life cycle costing exists. This could help reduce commercial barriers based on consumer demand. Unfortunately when purchasing and lending criteria are factored into the situation the potential to leverage this benefit may well be eroded, however, this paper aimed to establish if cost neutrality was possible and the potential to incorporate the findings into valuation and purchasing criteria is beyond the paper's scope.

The fact that the model works without FITs is important to acknowledge because it demonstrates the model is resilient to policy changes. Such changes have impacted developer and investor confidence in the past so demonstrating financial viability without tariff backed policy should reduce risk for investors. It also reduces the models reliance on policy drivers. Given the current policy trajectory for both zero carbon housing policy and FITs rates, this attribute could become critical within a relatively short period of time.

The results also show that cost effective zero carbon design could offer more profitable developments then following the regulatory routes. The economic model only works when income and energy generating technologies are maximised for decarbonisation which means a zero carbon home built to regulatory definitions would not be as cost effective as the optimised design developed here. If this can be reflected in purchase price it poses the question of whether doing the minimum possible to comply with building regulations is the best route for developers take.

The use of traditional timber frame construction over MMC also provided a risk benefit. As the timber frame design complied with LABC warranty criteria the building fabric specification reduced risk for the developer by limiting the number of innovations required to create the design. This was also true of the energy generating systems which used the minimal number of technologies required and only used technologies with a documented history of performance *i.e.*, PV panels, air source heat pumps and MVHR. An additional benefit of this is reduced impact on user practice change. The control systems of the optimised design can be automated and the residual user inputs are similar to conventional heating systems. The finalised design is also fully electric which reduces the need for the developer to bring a gas supply to the home which could also offer further cost savings. From an investment perspective in a rational economic context, greater demand could exist for the optimised zero carbon home than the equivalent building regulation design given the positive net benefits. To substantiate this further research into the social and contextual factors affecting the decision making process is needed.

What the research presented here shows is that by iterating commercial barriers early on in the design brief, a focused design process can be employed to create homes that are more economical to live in than 2013 Part L building regulation compliant homes, without impacting developer profit. Further research in this field will be required to establish the extent that the new cost principles resulting from this design method can be fit into current commercial build models. However, the technical and economic outputs demonstrates that, with new thinking, the potential for commercially viable and subsidy free zero carbon homes exist.

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