Net energy analysis of a solar combi system with Seasonal Thermal Energy Store


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Abstract: EU targets require nearly zero energy buildings by 2020. However few reviews exist of how this has been achieved in practise in individual residential buildings. This paper presents a carbon analysis of a real installation based on the recorded performance of a low-energy house in combination with a solar DHW and space heating system which incorporates a seasonal thermal energy store. Key findings for the project are presented including the recorded DHW and space heating demand, the performance of the solar system including the Seasonal Thermal Energy Store (STES) and the results of an embedded carbon and operational carbon analysis of the heating system. The life cycle energy consumption and life cycle carbon analysis in addition to net energy ratios, are calculated for five heating system scenarios.
Net Energy analysis of a Solar Combi System with Seasonal Thermal Energy Store

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Abstract

EU targets require nearly zero energy buildings (NZEB) by 2020. However few monitored examples exist of how NZEB has been achieved in practice in individual residential buildings. This paper provides an example of how a low-energy building (built in 2006), has achieved nearly zero energy heating through the addition of a solar domestic hot water and space heating system (“combi system”) with a Seasonal Thermal Energy Store (STES). The paper also presents a cumulative life cycle energy and cumulative life cycle carbon analysis for the installation based on the recorded DHW and space heating demand in addition to energy payback periods and net energy ratios. In addition, the carbon and energy analysis is carried out for four other heating system scenarios including hybrid solar thermal/PV systems in order to obtain the optimal system from a carbon efficiency perspective.

Keywords:

1. Introduction

The European Union "20-20-20" commitment set three key objectives for 2020:
- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

Given that 40% of energy is consumed in buildings, EU Member States have committed to implementing nearly-zero energy buildings by 2020 through the adoption of the recast Energy Performance of Buildings Directive [1]. Article 9 of the Directive states:

"Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”.

A nearly zero-energy building is defined in Article 2 of the EPBD recast as

"a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”.

In considering how best to achieve Net Zero Energy Buildings in practice, a number of studies have considered how existing low-energy standards such as the Passivhaus standard [2] could be used as the basis for achieving NZEB for example Musall & Voss [3] and Hermelink et al [4], including when used in conjunction with renewables such as solar energy e.g. Mohamed et al [5].
A number of studies have carried out Life Cycle Assessments (LCA) of low energy houses such as those constructed to the Passivhaus standard [6]. Other studies eg Leckner & Zmeureamu [7] have performed the LCA of Net Zero Energy Houses when used in conjunction with Solar Combisystems. Further studies such as Saman [8] and Ayman et al [9] have looked at different methodologies for achieving NZEB with Ayman et al specifically considering use of the Passive House with Solar Heating. Coa [10] considers the challenges of the implementation of a hybrid renewable energy system to meet the reducing carbon intensive energy demands. However despite much working being done on the approach to achieving NZEB, given that building regulations in European countries to date have not required NZEB, few monitored examples exist of how existing buildings have achieved NZEB. This paper provides an example of how a low-energy building (built to the Passivhaus standard in 2006), has achieved nearly zero energy heating through the addition of a solar domestic hot water and space heating system (“combi system”) with a Seasonal Thermal Energy Store (STES). The paper also considers a carbon analysis of a number of potential heating systems in order to obtain the optimal system from a carbon efficiency perspective. In order to do so a number of approaches are used including the cumulative energy and cumulative carbon consumption and the Net Energy Ratio.

1.2 The Passive House
The Passive House building standard specifies a space heating demand of less than 15 kWh m\(^{-2}\) a\(^{-1}\) [2] and is a voluntary low-energy standard which has seen widespread adoption, with over 50,000 examples having been built over the past 20 years [11]. The study of buildings constructed to the Passive House building standard allows us to gain an insight into how the nearly zero-energy buildings which are now mandated will perform in the future.

1.3 Application of solar seasonal thermal energy storage
A number of methods have been employed to address the remaining Passivhaus space heating demand and domestic hot water demand through the use of renewable sources on or close to the site. The approach which is used is typically tailored to the specifics of the site in question, often through the application of solar energy.

![Figure 1. Yearly Global Radiation Incident on Optimally Inclined Plane in European Countries [12]](image)

The usefulness of solar gain for heating buildings is a function of the ratio of incidental insolation to heat loss [13]. Figure 1 above shows that the average global solar radiation (represented by the continuous black line) experienced in Ireland is similar to that experienced in Germany, the country
with the fourth largest penetration of solar thermal systems in Europe [14]. In Temperate Maritime Climates (TMC) the long heating season coupled with the low peak space heating demand in winter means that the solar resource in Temperate Maritime Climates provides a good match with the space heating demand for energy efficient buildings [15]. By sizing solar thermal installations to meet the space and domestic hot water demands in spring and autumn, a significant portion of the annual heating demand can be met with solar. By integrating this system with a Seasonal Thermal Energy Store (STES), a portion of the surplus heat from the summer can be stored for winter use, thereby further increasing the solar fraction. Dincer, I. & Rosen, [16] recognised the advantages of saving low-cost heat using a Seasonal Thermal Energy Store. Applying the principle of storing low-cost surplus thermal energy from a domestic hot water and space heating installation, it has been demonstrated that it is possible to supply over 70% of the heating needs of a Passive House through the application of STES in a TMC [17]. The most common seasonal thermal energy stores are Aquifer Thermal Energy Stores (ATES) and Borehole Thermal Energy Stores (BTES). However both of these require suitable ground conditions that do not always exist [16], leading to the requirement for a tank based STES solution. The size of STES is also important to consider, as efficiency and economic viability improve with scale [18]. This suits countries where community-based heating systems are common such as the Netherlands, which currently has the largest number of STES installations in Europe [19]. However, in countries where the largest proportion of houses built are individual dwellings (such as in Ireland with 62.3%, 60.8% and 57.0% for 2011, 2012, 2013 respectively [20]), community-based systems are not appropriate requiring consideration of STES for individual dwellings. Individual dwellings also often afford the advantage of providing sufficient land for the installation of a seasonal thermal energy store.

Thus, this study considers the application of aqueous STES for the single dwelling.

2.0 Case study performance

The dwelling under consideration is a 215m² detached Passive House constructed in 2006. A solar installation comprising 10.6 m² evacuated tube solar array 300l Domestic Hot Water (DHW) tank, 23m³ aqueous Seasonal Thermal Energy Store (STES) and combined underfloor and Heat Recovery and Ventilation (HRV) space heating system was installed and has been monitored since June 2009. The installation has been described previously [17] along with the maximum theoretical solar fraction [21] and a high level carbon analysis of the installation [22]. The DHW demand over the period considered was 705kWh (with solar contribution of 629kWh), reflecting the use of the dwelling as an office. Of the total space heating demand of 1592 kWh between June 2010 and May 2011, only 450 kWh was borne by the electric heating system. The Solar Fraction (SF) over the heating season was 72%, with 739 kWh (46%) of the total space heating demand being met by direct space heating, and the remaining 406 kWh (26%) by means of inter seasonally stored heat [22].

3.0: Life cycle energy & carbon analysis

3.1 The context of the carbon analysis

A review study by Sartori & Hestnes [23] that examined 60 case study buildings, both conventional and low-energy, found that as operational energy was reduced the relative importance of the embodied energy was increased. Conventional buildings had an embodied energy of between 2-38% of total life cycle energy whilst the embodied energy of low energy buildings was between 9-46%. Of particular interest in this review is a zero-energy solar house, as discussed further by Ramesh et al., [24], which has such a high embodied energy from the use of photovoltaic panels that it exceeds the total life cycle energy of some low-energy buildings. As such when operational energy levels are
reduced to very low levels and employ significant amounts of renewable technologies a focus is
required on the embodied energy and carbon of the systems employed in order to ensure there is a
net benefit in terms of life cycle energy and carbon. This study does not analyse the embodied energy
of the dwelling (in this case a Passive House), but rather focuses on the heating system required in
order to produce the relatively small heating energy needed. Thus, the paper is examining the carbon
efficiency of the renewable heating element exclusively using the life cycle assessment (LCA)
framework as standardised in ISO 14040-ISO14044 series.

3.2 Assumptions and approach

A number of assumptions were made in regard to the expected service life, maintenance
requirements and performance of installed systems for the purpose of performing the carbon
analysis.

Solar thermal is a mature technology, the various components carry long warranties and it is
anticipated that with minimal intervention, systems will continue to operate for a service lives of 15
to 40 years [25]. Typical warranties for solar collectors are 10 years with some manufacturers
offering 20 year warranties [26], with warranties of up to five years typical for pumps, while tanks
have lifetime warranties.

In this analysis, scheduled maintenance of the system is assumed to be every six years, and it is
assumed that the solar thermal system will continue to operate for 20 years without further capital
investment. Unless otherwise stated, the analysis has assumed that the viability of all equipment
(with the exception of the STES) at the end of the 20 year period is zero. However, while this is a
reasonable assumption in the case of the DHW and space heating systems, the STES has been
assumed to have the same service life as the building i.e. 80 years.

It is assumed that a replacement of the solar collector, DHW and direct space heating and seasonal
energy storage heat exchanger coils will be required at year 20. It is assumed that the seasonal energy
storage tank and DHW tank will not require any extra maintenance at 20 years.

There are environmental impacts and energy consumed for the extraction, production and assembly
of the materials used in the heating system. The ISO 14040 series life cycle assessment framework,
can be used to quantify these environmental impacts.

Two of the most common indicators calculated are embodied energy (MJ) and embodied carbon
dioxide equivalent (kgCO2e). Embodied energy includes all the energy consumed in the different
stages of a products life such as extraction, production and transport. Embodied carbon accounts for
the amount of greenhouse gas emissions that have been produced during the different stages of
manufacture and use over a product’s life.

At the time of writing the Sustainable Energy Authority of Ireland was developing a methodology for
the measurement of embodied energy and carbon for applications in life cycle assessment of
buildings. This methodology is based around the ISO 14040 and ISO 14044; which detail the life
cycle assessment framework and the PAS:2050 for the calculation of greenhouse gas emissions. As
this database was still in compilation for the Republic of Ireland, other sources were used to
approximate the embodied energy and carbon in this study. See Table 1.

The EcoInvent database was used to approximate the embodied energy and carbon associated with
the different possible configurations of equipment that could fulfil the space and water heating
requirements of the building.

The life cycle impact assessment method used within Simapro was the International Panel on
Climate Change (IPCC) Global Warming Potential 2007 100a method and Cumulative Energy
Demand (CED) method which calculated the embodied carbon (kgCO2e) and embodied energy (MJ)
respectively. The CED method provides a result that corresponds to the total amount of primary
energy used over a products life cycle to deliver 1MJ of heating. Primary energy sources consist of
conventional sources such as fossil fuels, nuclear, hydropower and renewable energy sources
including solar, geothermal, biomass etc.[27]. Embodied carbon is not limited to carbon dioxide
emissions only but includes other greenhouse gases such as methane (CH₄) and nitrous oxides (NOₓ).
<table>
<thead>
<tr>
<th>Material / Process</th>
<th>Quantity</th>
<th>Unit</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propylene glycol, liquid, at plant /RER</td>
<td>19</td>
<td>kg</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Stainless steel hot rolled coil, annealed &amp; pickled, elec. Arc furnace routr</td>
<td>153.03</td>
<td>kg</td>
<td>ELCD 1,2,3,4,5</td>
</tr>
<tr>
<td>Tube insulation, elastomere, at plant/DE</td>
<td>1.12</td>
<td>kg</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Copper sheet, technology mix, consumption mix, at plant, 0.6mm thickness EU-15</td>
<td>20.68</td>
<td>kg</td>
<td>ELCD 4,5</td>
</tr>
<tr>
<td>Inverter, 500W, at plant/RER/I</td>
<td>1</td>
<td>number</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Photovoltaic panel, multi-Si, at plant/RER</td>
<td>5</td>
<td>m²</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Polystyrene foam slab, at plant/ RER</td>
<td>584.71</td>
<td>kg</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Cellulose fibre, inclusive blowing in, at plant?CH</td>
<td>467.136kg</td>
<td>kg</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Concrete, normal at plant/CH</td>
<td>5.9</td>
<td>m³</td>
<td>EcoInvent 4,5</td>
</tr>
<tr>
<td>Foam glass, at plant/RER</td>
<td>15.57</td>
<td>kg</td>
<td>EcoInvent 1, 2, 3,4,5</td>
</tr>
<tr>
<td>Heat, at tube collector, one family-house, for combined system / CH</td>
<td>80</td>
<td>MJ</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Pump 40W, at plant/CH/I</td>
<td>1</td>
<td>number</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Evacuated tube collector, at plant/GB/I</td>
<td>10.6</td>
<td>m³</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Expansion vessel 25L at plant/CH/I</td>
<td>1</td>
<td>number</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Auxiliary heating, electric, 5 kW, at plant/CH/I</td>
<td>1</td>
<td>number</td>
<td>EcoInvent 2,3,4,5</td>
</tr>
<tr>
<td>Heat pump RER/I</td>
<td>0.00001</td>
<td>number</td>
<td>EcoInvent 1,2,3,4,5</td>
</tr>
<tr>
<td>Electricity, PV, at 3kWp slanted-roof, ribbon-Si, panel, mounted /CH</td>
<td>574</td>
<td>kWh</td>
<td>EcoInvent 5</td>
</tr>
</tbody>
</table>

Table 1. Embodied Energy and Carbon metrics

These gases are multiplied by Global Warming Potential (GWP) factors, as defined by the IPCC, allowing them to be expressed in the terms of carbon dioxide equivalent. The IPCC have developed three time horizons of 20, 100 and 500 years with 100 year horizon most common.

3.3 Operational energy & carbon analysis

During the period under consideration, the total solar space heating contribution was 1142 kWh. During the same period, solar contributed 629kWh of the DHW load, giving a total solar contribution of 1771kWh. Operation of the solar pump consumed 35.1kWh and operation of the underfloor/HRV
HX pump consumed 43.8 kWh over the heating period, giving a total of 78.9 kWh. Subtracting the 78.9 kWh from the 1771 kWh electricity saved, gives a balance of 1692 kWh. Thus there is a carbon emissions saving of 878 kg of CO$_2$ pa using the figure of 481 g per kWh [28]. Had the total DHW and space heating load of 2298 kWh been met by electricity, the emissions would have been 1192 kg. Thus a carbon emissions reduction of 75.3% was achieved for the actual installation over the period of monitoring.

In order to understand if the current configuration of the system is the optimal system from a life cycle and operational carbon emissions perspective, five scenarios are considered. They range from considering a wholly electric heating system (Case 1) which represents the smallest investment in both capital cost and embodied energy (but the highest operational energy consumption), through to one which is wholly solar (Case 5), representing the highest cost and embodied energy, but the lowest operational energy consumption. See Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Energy source</th>
<th>DHW (kWh)</th>
<th>Space Htg (kWh)</th>
<th>Total (kWh)</th>
<th>Total Solar &amp; Electric (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar Thermal</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2297</td>
</tr>
<tr>
<td></td>
<td>Electric (grid)</td>
<td>705</td>
<td>1592</td>
<td>2297</td>
<td>2297</td>
</tr>
<tr>
<td>2</td>
<td>Solar Thermal</td>
<td>682</td>
<td>0</td>
<td>682</td>
<td>1650</td>
</tr>
<tr>
<td></td>
<td>Electric (grid)</td>
<td>58</td>
<td>1592</td>
<td>1650</td>
<td>2332</td>
</tr>
<tr>
<td>3</td>
<td>Solar Thermal</td>
<td>629</td>
<td>739</td>
<td>1368</td>
<td>2332</td>
</tr>
<tr>
<td></td>
<td>Electric (grid)</td>
<td>111</td>
<td>853</td>
<td>964</td>
<td>2332</td>
</tr>
<tr>
<td>4</td>
<td>Solar Thermal</td>
<td>629</td>
<td>1142</td>
<td>1771</td>
<td>2376</td>
</tr>
<tr>
<td></td>
<td>Electric (grid)</td>
<td>111</td>
<td>494</td>
<td>605</td>
<td>2376</td>
</tr>
<tr>
<td>5</td>
<td>Solar Thermal</td>
<td>629</td>
<td>1142</td>
<td>1771</td>
<td>2376</td>
</tr>
<tr>
<td></td>
<td>Solar Electric</td>
<td>111</td>
<td>494</td>
<td>605</td>
<td>2376</td>
</tr>
</tbody>
</table>

Table 2. Solar, Electric and Total Energy consumption for DHW and Space Heating

**Case 1: Electric domestic hot water and space heating**

The base case of electric heating for Domestic Hot Water and space heating is considered in Case 1. As can be seen from Table 2, the total domestic water and space heating demand is met using the electricity network, giving a total electrical network consumption of 2297 kWh.

**Case 2: Solar domestic hot water in addition to electric DHW and space heating**

In this scenario, a typical 3.6 m$^2$ of evacuated tube solar collectors is used (via a heat exchanger coil) to heat the domestic hot water. Backup DHW heating is provided by the existing 3 kW immersion heater. Space heating continues to be provided by electricity. Given the relatively low DHW consumption of 705 kWh, in order to make meaningful comparisons, the PHPP was used to calculate the solar DHW production for an evacuated tube array of 3.6 m$^2$ coupled with a 300 L tank, and the average monthly DHW demand was used to estimate the annual solar fraction and therefore the solar heat in kWh.
Case 3: solar DHW and space heating in addition to electric DHW and space heating

In order to provide for space heating in addition to the domestic hot water system, the solar collector is increased to 10.6 m² of evacuated tubes and a water to air heat exchanger is added to the existing heat recovery and ventilation system. Thus, in this scenario, the relatively high embodied energy of the seasonal thermal energy store is avoided, while the benefit of the (relatively small) STES contribution to the space heating demand is forgone.

Case 4: addition of the STES to the solar system

This case represents the figures from the actual installation monitored and provides the base data from which the other scenarios are derived. The facility to store excess summer heat for use during the winter is provided by the addition of an aqueous STES to the existing domestic hot water and space heating solar system. As can be seen from table 2, more operational energy is consumed in this case due to the extra electricity required to operate the pump which transfers the seasonally stored heat from the STES to the house. The transfer of 450 kWh of heat from the seasonal store requires 44 kWh of electricity to operate the pump.

Case 5: addition of a PV solar array

While monitoring has shown that the solar thermal systems considered in case 4 can provide 72% of the space heating needs, the shortfall in the zero carbon heating objective could potentially be met with the addition of a photovoltaic solar array. In this scenario it is assumed that the DHW and Space Heating electrical needs of 605kWh can be met with a PV array of 4.95m². This assumes that electricity net metering is available. Table 2 demonstrates that no grid electricity is used, with solar energy providing all of the electricity required to meet the DHW and space heating needs.

The embodied, operational and maintenance energy and carbon of the different possible configurations of domestic hot water and space heating requirements for cases 1-5 are shown in Table.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial embodied energy (MJ)</td>
<td>1153.67</td>
<td>3079.94</td>
<td>6580</td>
<td>27926</td>
<td>32944</td>
</tr>
<tr>
<td>Annual operational energy (MJ)</td>
<td>8269</td>
<td>5940</td>
<td>3470</td>
<td>2178</td>
<td>0</td>
</tr>
<tr>
<td>Expected maintenance energy (MJ)</td>
<td>0</td>
<td>22117</td>
<td>69331</td>
<td>69331</td>
<td>123758</td>
</tr>
<tr>
<td><strong>Carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial embodied carbon (kgCO2e)</td>
<td>475</td>
<td>913</td>
<td>1550</td>
<td>5850</td>
<td>6680</td>
</tr>
<tr>
<td>Annual Operational carbon (kgCO2e)</td>
<td>1192</td>
<td>856</td>
<td>500</td>
<td>314</td>
<td>0</td>
</tr>
<tr>
<td>Expected maintenance carbon</td>
<td>0.00</td>
<td>1231.34</td>
<td>3839.71</td>
<td>3839.71</td>
<td>6239.71</td>
</tr>
</tbody>
</table>

Table 3. Embodied, operational and maintenance energy and carbon for case 1-5
Figures 2 and 3 show the cumulative life cycle energy and carbon for each of the five cases. Embodied energy and carbon are represented by the initial year zero. Maintenance requirements such as replacing the solar fluid at six year intervals and replacing evacuated tubes and solar panels at twenty year intervals have been included. Case 1 whilst having the lowest embodied energy and carbon and maintenance, has the highest life cycle impact as operational demand is met by a non-renewable electrical supply source. Case 5 whilst having the largest initial investment in terms of carbon and energy has the lowest associated life cycle impact.
To evaluate the performance of each of the five case studies the energy savings, energy payback and the net energy ratio of each of the five cases were calculated. The energy savings are calculated by considering the primary energy factor of the power source and the efficiency of the system.

\[
\text{Energy Savings} = \text{Solar Output} \times \text{Primary Energy Factor}_{\text{Aux heating}} - \text{Electricity Used by Pump} \times \text{Efficiency}_{\text{Aux heating}}
\]

\[
\text{Energy Payback} = \frac{\text{Embodied energy}}{\text{Annual energy savings}}
\]

\[
\text{NER} = \frac{\text{Annual energy savings} \times \text{service life}}{\text{Embodied energy}} = \frac{\text{Service life}}{\text{Energy payback}}
\]

<table>
<thead>
<tr>
<th>Case</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy savings {MJ}</td>
<td>0</td>
<td>8239.5</td>
<td>16574.5333</td>
<td>21412.45</td>
</tr>
<tr>
<td>Energy payback (Years)</td>
<td>N/A</td>
<td>4.03</td>
<td>5.61</td>
<td>7.93</td>
</tr>
<tr>
<td>NER</td>
<td>0</td>
<td>5.0</td>
<td>3.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Figure 3** Life cycle carbon production including embodied, operational and maintenance.
4.0 Discussion and Conclusions

Figures 2 and 3 demonstrate that the most attractive option from the perspective of cumulative life cycle carbon emissions and life cycle energy consumption over any time period in excess of 33 years is that represented by case 5 i.e. that which makes the maximum use of both solar thermal and photovoltaic solar energy.

Both figures also clearly demonstrate that the largest investment of both energy and carbon is that represented by case 5 due to the highest embodied energy.

Considering the cumulative life cycle energy, case 2 is a more attractive option than case 1 from year four, with case 3 being more attractive than case 1 or 2 for any period exceeding six years. Due to the high embodied energy of case 4 as it is currently configured, the analysis shows) despite becoming more attractive than case three in year 59), case 5 has already become the most attractive proposition from year 34.

When one considers the analysis from the perspective of cumulative life cycle carbon (figure 5), both case 2 and case 3 become more attractive than case 1 in year two. Case 4 is never the most attractive option, with case 5 becoming the most attractive option for any time periods considered in excess of 12 years.

Table 4 shows that, despite having the lowest energy savings, case 2 represents the most attractive proposition from the energy payback and net energy ratio perspectives given the relatively small energy investment and high energy savings possible due to the high solar fraction for the DHW.

Consideration of case three demonstrates that the energy savings can be doubled for an additional "investment" of 1.57 years in terms of energy payback, with the consequential reduction in the net energy ratio from 5.0 to 3.6. The net energy ratios of case 4 and five are very similar at 2.5 and 2.4 respectively, representing the larger energy investment under consideration.

Overall, the analysis demonstrates that in achieving the energy savings outlined in table 4, care needs to be taken in choosing the correct metrics such that the appropriate objective is achieved. This analysis has shown, that for the Passive House monitored, consideration of the Net Energy Ratio leads to the addition of a modest solar thermal array for domestic hot water heating being the most attractive proposition for reducing the already small energy demand. Considering the objective of achieving lowest cumulative energy, the installation of a combined solar thermal energy system and seasonal thermal energy store with supplementary photovoltaic array is not attractive until year 34.

However, such a system is attractive for any periods exceeding 12 years if the objective is to achieve the lowest cumulative life cycle carbon emissions.

Another key finding is that while the solution incorporating the STES in combination with PV is the most attractive proposition from a life cycle carbon emissions perspective, the specific STES installation considered has a high embodied energy, which impacts significantly in the analysis.

Previous analysis has shown that the STES under consideration has significantly reduced the energy consumption and is financially viable [17]. In the planning of such systems in the future, consideration also needs to be given to the optimisation of STES installations from an embodied energy and carbon perspective, ideally at the design stage.

Finally, it should be noted that previous analysis has demonstrated that the significant increase in energy savings (in the order of 50%) could be achieved through relatively modest changes in the solar installation. Even without optimising the STES from the embodied energy perspective, such changes would have a significant impact on the analysis by making case 4 and five significantly more attractive. Further work needs to be done in analysing STES installations from a carbon perspective in order to obtain a more holistic perspective on the attractiveness of STES installations from a life cycle carbon perspective.

5.0 Acknowledgements

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6.0 References


[8] Saman


