Energy use in occupation of low energy homes: A case study GreenGauge Design Lingwood.

A report prepared for Flagship Housing group

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September 2009

Acknowledgements:

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Funded by Carbon Connections and Broadland District Council

Chapter 1 Introduction

In the village of Lingwood, in Norfolk an exceptional housing development of 15 low energy homes demonstrates an innovative approach to rural, affordable, housing provision.

The development was designed and constructed by a consortium of partners, brought together by Flagship Housing Group Ltd, who developed the affordable housing model, called GreenGauge Homes, which brings together the latest in innovative construction methods and low carbon technologies. GreenGauge Homes is one of Flagship Housing Groups' major long term projects.

The development comprises seven 3 bedroom homes and eight 2 bedroom homes with eleven for affordable rent and four for shared ownership. These homes which were constructed on an exception site have been built to address the long-term sustainability of the community. People local to Lingwood or with a local connection to the village are eligible for this much needed housing scheme.

GreenGauge Homes design principles combine low energy, Modern Methods of Construction (MMC[1]) with the use of sustainable materials and a commitment to using renewable energy sources where practical. The approach makes novel, pioneering use of sustainable materials and alternative energy resources whilst remaining affordable and buildable on a larger scale. The development has achieved an Ecohomes rating of 'Excellent'.

The 15 GreenGauge homes constructed in Lingwood, which is a large village 12 miles from Norwich in Norfolk, are all built with good levels of insulation and have distinctive untreated larch cladding. With the exception of one pair of homes, the development uses differing combinations of low and zero carbon technologies and design approaches. These include ground source heat pumps, solar thermal, solar photovoltaics and passive solar techniques. The passive solar combines thermal mass, unusual in an otherwise all timber construction, with mechanical ventilation and heat recover.

With funding support from Carbon Connections[2], researchers at the University of East Anglia, undertook a carbon footprint of the development that included monitoring and evaluating the houses energy performance.

This report presents and discusses the results of the energy and carbon performance of these innovative low energy affordable homes during their first year of occupation.

Outline of the report:

This report is sister to a report which presents the findings of a study of the carbon emissions (embodied carbon) associated with the construction of the same development. This

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[1] MMC refers to offsite manufacture of building components. Varies in scale from individual components, to pods and entire homes.

[2] Carbon Connections is an investment body, set up by the Higher Education Funding Council for England (HEFCE) to seek out, encourage and invest in carbon-saving innovation either through technological advance or behavioural change.

report includes the results of the embodied carbon for construction and the technologies of each house type.

The following report is arranged in 5 chapters. The following chapter provides detail on the methodology used. Chapter 3 presents the results from each house type in isolation and considers energy, carbon and cost of use from a year's monitoring cycle. Qualitative results from the occupants and the impacts of their behaviour are also given. Chapter 4 compares the different approaches taken and discusses the implications of the results. The concluding chapter summarises these findings and makes recommendations for future homes.

Chapter 2 Methodology

GreenGauge Homes design principles

GreenGauge homes are characterised by the following design principles:

- Highly insulated: super insulated roof and additional site installed insulation to offsite manufactured walls and floors.
- Good ventilation: Well sealed homes need to be ventilated. Ventilation is through passively designed ventilation. Passi-vents were incorporated into the window frames to provide ventilation.
- Sustainable materials: Offsite manufactured timber frame, combing the benefits of low impact sustainable material and resource efficiency in production. Timber weather boarding. All timber FSC certified. Avoidance of UpVc, using timber framed windows. Minimal use of high embodied energy materials such as masonry and concrete.
- Passive solar design: Design elements to maximise 'free' energy from the sun, using sunspaces and thermal mass to collect heat during the day to radiate out at night. Heat recovery to circulate the warm air into the living space.
- Renewable energy technologies: With ever tighter carbon standards for housing the use of renewable energy technologies is becoming more likely. The technologies used include solar hot water, photovoltaic's, and ground source heat pumps[3].
- Water efficiency: Low water use toilets, baths and taps. Rainwater collection for grey water use (toilets and washing machines).
- Affordable: A GreenGauge home is affordable to both build and to live in. A GreenGauge home has to be replicable and will not rely on additional grant funding to achieve its objectives. Cost efficiency at all stages in the delivery of GreenGauge homes is fundamental to its long term success.

The GreenGauge Lingwood development

The development, completed in January 2008, comprises seven 3 bedroom homes and eight 2 bedroom homes with eleven for affordable rent and four for shared ownership. These homes have been built to address the long-term sustainability of the community. People local to Lingwood or with a local connection to the village were eligible to rent or buy these much needed homes.

All of the homes are constructed using the same materials and offsite constructed timber frames. All the homes are orientated with the front south facing to maximise solar potential. The fifteen homes are arranged in four blocks of terraced homes. Each block having a different renewable energy technology (Figure 2.1). The homes are either 2 bedroomed with an internal floor area of 71m^2 or 3 bedroomed with an internal floor area of 83m^2.

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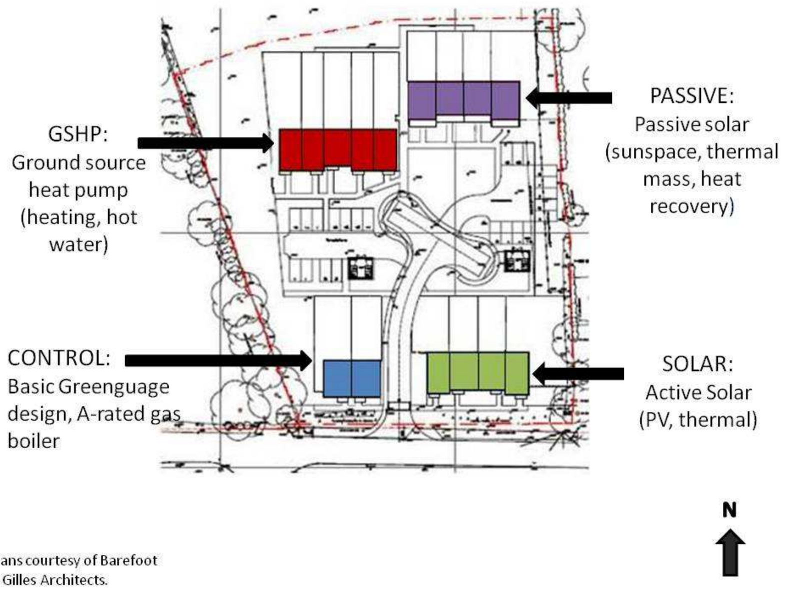
[3] Heat pumps use electricity to condense heat, typically grid electricity is used and are therefore not strictly a renewable energy technology.



Plans courtesy of Barefoot & Gilles Architects.

Figure 2.1: GreenGauge Lingwood Site Plan

The construction details:

The GreenGauge Lingwood development utilised an innovative engineered structural panel timber frame construction, with a concrete block and beam ground floor. The timber frame panel system specified was supplied with factory installed insulation. An additional layer of insulation was installed during construction to enhance the thermal performance of the construction. Larch clad exterior weatherboarding was used externally.

Careful attention was paid during design and construction to air tightness. The design was specified to be relatively air tight and passive ventilation was incorporated by small vents in a number of the window frames.

The openings were timber framed double glazed units.

The construction was fast, relatively dry with minimal concrete used. High initial energy demand due to the effects of drying out was not anticipated during the first year of occupation.

All fixed lighting was dedicated low energy lighting. All appliances, including cooking, were the occupants own, purchased new upon occupation or bought with them from their previous homes. Both electricity and gas were used for cooking.

Table 2.1: Energy modelling parameters and results

u-value (Wm^2k):	
wall	0.18
floor	0.16
roof	0.14
windows	1.80
doors	2.40
air permeability (m^3hm^2@50Pa)	7
heat loss parameter (Wm^2K)	1.33
DER ($kgCO_2m^2year$)	22.30
TER ($kgCO_2m^2year$)	23.73
space + water heat demand ($kWhm^2year$)	50

Initial space heating energy modelling using SAP 2005 9.81 compared the CONTROL house against a notional house of the same construction and dimensions that met minimum regulation standards, TER (Table 2.1). Modelling of the CONTROL house demonstrated a 7% saving in annual space heating energy demand and CO_2 when compared with the notional house.

CONTROL homes

Two of the homes are designed to be controls in that, although they are built to GreenGuage specifications, they do not contain any renewable technologies. Therefore they can be used as baseline for the remaining homes to be compared against. These 3 bedroomed properties are referred to as CONTROL throughout the remainder of this report. Heating and hot water is provided via a conventional A-rated condensing combi- gas boiler (91.1% SEDBUK efficiency rated[4]).

SOLAR homes

Four homes have active solar technologies, solar hot water and photovoltaics (PV), plus an equivalent boiler system to the CONTROL homes. These homes are referred to as SOLAR throughout the remainder of this report. Two area 3 bedrooms with a 1.5kWp PV and 4m^2 solar thermal collector, while the other two are 2 bedroom with a 1.6kWp PV and 2m^2 solar thermal collector.

Ground Source heat pump homes (GSHP)

Five of the homes, which are all electric, have their heating and hot water demand met by ground sourced heat pumps. These homes, one of which is 3 bedroom and four are 2 bedroom, are referred to as GSHP throughout the remainder of this report

Mechanical ventilation homes (MVHR)

The remaining four homes utilise passive solar design principles. These homes have a different, and distinctive, south facing elevation to the other properties, with a double height south facing sunspace to the front of the property. These homes are referred to as PASSIVE throughout the remainder of this report. In addition to the same boiler system as CONTROL these homes are also ventilated with a mechanical ventilation and heat recovery unit (MVHR) which provides filtered, pre warmed fresh air to the property. Two are 3 bedroom and two are 2 bedroom.

Internal living space in all fifteen properties is arranged with the main entrance, kitchen, WC and bathrooms to the front of the properties (south). The main living areas are all located to the rear of the properties (north facing). Apart from the additional heating space at the front of the MVHR homes, the layout of all the 3 bedroom homes was identical, as was the 2 bedroom homes.

The monitoring and evaluation study:

The monitoring and evaluation study included the following aspects:

- The energy used during occupation and the resulting carbon emissions
- The energy produced by the different renewable energy technologies
- The contribution of the renewable energy produced to total annual energy budget and the resulting carbon savings
- The effects of occupant lifestyle and behaviour on annual carbon emissions
- An assessment of the occupant views of the technologies and how they used them.

An innovative smart metering system was going to gather data on energy consumption, appliance use, renewable energy production and direct use of renewable energy in the home. Unfortunately, technical issues with the smart metering technology were unable to be resolved in the short project timeframe. The programme of data collection was reduced and an alternative monitoring programme was put in place. The results presented in this report are derived from manual meter readings and the results of modelling energy use and energy generation from the various technologies employed.

The study included contributions from the occupants. Surveys, semi-structured

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[4] SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) provides a basis for fair comparison of the energy performance of different boilers. A database of ratings for most boilers available in the UK is published at www.sedbuk.com

interviews and informal conversions were used to gather valuable qualitative data pertaining to lifestyle, patterns of occupation and energy use as well as attitudes to energy and the environment. This provided a back ground story to the energy use data collected. The occupants contributed feedback on their experience with the homes and the different technologies and commented on the information provided.

Data

The data presented is anonamised to protect the privacy of the occupants.

- Energy data is presented as averaged raw data for each house type or normalised for weather, area and occupancy to enable fair comparison and differences using an energy indices where appropriate. A Normalised Performance Indicator (NPI) was used to calculate an energy index for comparison. The NPI is widely used and accepted method for assessing and comparing the energy performances of buildings[5]. This approach was used to enable comparison between the different house types and against national benchmarks. The calculation methodology is given in Appendix One.
- Energy data is presented in units of kWh at end use.
- Published government carbon emissions factors current to the time of analysis were used in any calculations of carbon emissions (see Appendix Two for emissions factors used)[6].
- Embodied carbon for the renewable technologies was derived from published literature[7]. A sister report to this one details the embodied carbon in the construction[8].
- Energy costs were based on published average regional pence per kWh prices (see Appendix 2 for cost factors used). Some switching activity occurred. The use of a regional average, rather than actual, gave results that were both realistic and comparable. The average energy annual household expenditure in 2008 for the region was £909[9].

Monitoring:

Energy data was collected from periodic meter readings. Early delays in installing the smart metering, and later complete withdrawal, resulted in a sparse amount of data from the initial six months of monitoring. During the final six months monthly meter readings were taken.

Five of the homes were not occupied during the first six months of the monitoring period. Where a home was not occupied during the full year back casting of data based on recorded consumption was undertaken to give a year’s estimated consumption.

The lack of high resolution use data was partly resolved by supporting the metered energy consumption data with quantitative and qualitative data. This supplementary data was gathered by audits of appliances and questionnaires and interviews with occupants. Occupational patterns, appliance use patterns and behavioural influences could then be

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[5] Beggs, C (2002): *Energy: Management, supply and conservation*. Great Britain, Butterworth-Heineman.

[6] Department of Environment, Food and Rural Affairs: 2008 Guidelines to Defra's GHG Conversion Factors Update April 2008

[7] Ecoinvent Centre, 2008. ecoinvent data v2.0. Final reports ecoinvent 2000 No. 1-15, CD-ROM; Dübendorf, Switzerland: Swiss Center for Life Cycle Inventories.

[8] Monahan J and Powell JC 2009: Embodied primary energy and carbon in offsite timber framed housing: A case study GreenGauge Design Lingwood. UEA.

[9] Department for Business, Enterprise and regulatory reform Energy Statistics Prices Table 2.2.3 Average annual domestic electricity bills in 2008 for selected towns and cities in the UK and average unit costs

inferred and incorporated into models of energy use.

East Anglia experienced a cool, relatively wet, summer and cold winter in 2008 - 2009. It was anticipated that total space heating demand would be high during 2008. Analysis of the degree day data indicated an increase of 8% for the period march 2008 to February 2009 over the 20 year average at 15.5^{o}C base temperature.

Chapter 3 Results

CONTROL: Low energy and efficient - the basic design model

The CONTROL homes represent the base case GreenGauge design model, as constructed on the Lingwood site, against which the other homes, enhanced with low carbon and renewable technologies, could be compared. One of the two 2 bedroom CONTROL homes was occupied for a full 12 months of the monitoring period, the other being occupied for just under half this period.

Heating and hot water was provided from a high efficiency condensing gas fired combination boiler, achieving a seasonal energy efficiency of 91.3%. The heating system was controlled by an advanced seven day programmer and thermostat. Radiators were fitted to all rooms except the kitchens. All radiators were fitted with thermostatic valves. A warm air electric powered kick space heater was provided in the kitchen.

Results:

Table 3.1 presents the raw data by m^2 of floor area. The data is uncorrected for weather and occupancy for the two CONTROL properties.

So how do these basic GreenGauge homes perform?

The most recently published local energy consumption figures for the UK suggest that these homes used 3% more electricity and 59% less gas than the average home in the UK[10].

Table 3.1: Control house average energy consumption per m^2

	kWh/m^2	**kgCO_2/m^2**	**£/m^2**
Gas	88	18	2.63
electricity	54	29	5.97
total	141	47	8.60

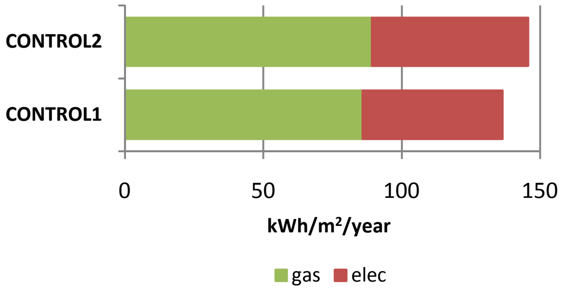

Figure 3.1: CONTROL annual energy consumption

The two homes showed a slight difference in annual consumption (6% difference in total annual energy) (Figure 3.1). It is not possible to say whether this is an artefact of the back casting due to the partial occupancy or it is attributable to occupational and lifestyle differences. Both households had similar patterns of occupation, same number of

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[10] Department of Energy and Climate Change Regional and local authority energy consumption statistics

occupants of similar ages and lifestyle. The difference could be explained for the most part by differences in electrical consumption, the households using different cooking fuels and appliances.

Gas for space and water heating was the largest energy consumer by end use (62% of total kWh used). Electricity for appliances, lighting and cooking formed the remainder.

Although gas usage formed the majority of the total energy consumed by kWh, it is electricity consumption associated with lights and appliances that are responsible for the largest proportion of emissions of CO_2 (63%) (Figure 3.2). Per kWh electricity at point of use is more carbon intensive than gas.

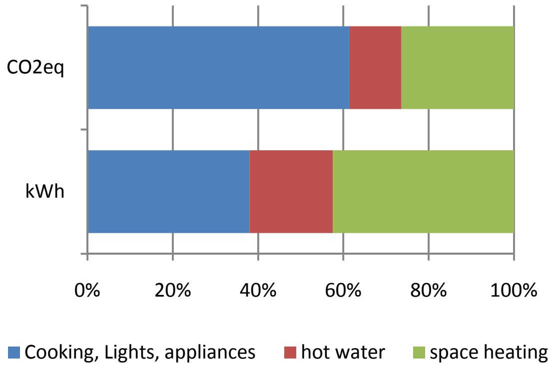

Figure 3.2 CONTROL house energy and carbon emissions by end use

Normalised performance indicator:

The NPI for the CONTROL homes was 94 $kWh/m^2/year$.

Running costs:

The average estimated fuel expenditure for the control home was £714 (exclusive of standing charges). £495 for electric and £218 for gas.

Carbon Emissions:

The annual carbon emissions from the use of grid electricity and gas were estimated to be 47 kg CO_2/m^2. The majority attributed to grid electricity (61%).

Embodied carbon:

In addition to the carbon emissions produced by the consumption of energy there are additional carbon emissions produced during the manufacturing, installation and maintenance of the heating, hot water and other generating technologies used (referred to as embodied carbon). Each of the different house types used a combination of different technologies to deliver energy. The embodied energy from each of these technologies is required to enable a comparison between each approach used over a period of time.

The embodied carbon associated with the manufacture and installation of the conventional heating system was estimated to be $0.6tCO_2$.

Occupant feedback:

Only one of the households gave feedback.

When asked about the information pack and how useful it was they responded that they had “flicked” through the pack.

They had consulted the relevant heating system information when it was needed, including the boiler controls. The information provided was the manufacturers’ instruction booklet which contained a lot of technical information that was difficult to understand and more relevant to installation and maintenance.

They had altered the boiler programming to suit them. They already knew how the programming worked because it was similar to their previous boiler. They had also adjusted the radiator valves to lower heating in some areas.

When asked about how comfortable they found their new homes:

> "It's lovely...we sit there thinking how lovely it is compared to our last house. We don't need the heating on all the time now."

They did report overheating during hot spells. This was dealt with by opening windows and doors.

> "Overall I'm really pleased with the heating side of things."

Overall the tenants reported that they were extremely happy in their new home especially as their energy costs had reduced dramatically compared with their previous home.

When asked about draughts or uncomfortable areas they reported draughts coming through the passi-vents when it's windy. Inspection of the vents showed them to be closed during visits. Indoor air quality was indirectly mentioned. The family suffered from asthma and other respiratory problems, which have improved enormously since their move.

SOLAR: Active solar (Solar thermal and photovoltaics):

The SOLAR home consisted of a block of four homes, two 2 bedroom (71m^2) and two 3 bedroom (83m^2) terraced homes. Their design, construction and facilities were the same as the GreenGauge basic model (CONTROL). The SOLAR homes were characterised by the addition of a roof mounted array of active solar technologies. These included grid connected photovoltaic (PV) array to generate electricity and a solar thermal system for providing hot water.

The SOLAR homes had a grand total of 6.2kWp PV, covering a total area of 51m^2, and 13m^2 flat plate solar thermal collectors installed on the south facing roof space. Each home had its own separate PV and solar thermal system. Two of the homes had 1.6kWp PV and 2m^2 solar thermal collectors. The other two had 1.5kWp PV and 4m^2 solar thermal collectors.

The solar contribution:

Evaluation of the contribution that the solar systems made to the overall energy use of the SOLAR homes was hampered by the lack of smart meter monitoring. The PV system was metered and readings were taken when access was possible over the monitoring period. The proportion of electricity used directly and exported to grid was estimated. It was not possible to measure the solar hot water contribution to the households total hot water consumption, this has also been estimated.

Photovoltaics:

The PV system consists of a total of 38 polycrystalline modules installed on a south facing roof at an angle of approximately 45^o and covering 51m^2 of roof area, giving a total install capacity of 6.2kWp. The modules were split between the four homes giving each their own separate grid connected systems. Two of the homes had ten and two had nine PV modules (1.6kWp and 1.5kWp respectively) [11]. An inverter was installed in a visible position inside each home with an LCD display metering the electricity generated in kWh.

A sunny Beam wireless monitor was supplied to each of the solar homes. Unfortunately these went missing prior to the occupants moving in. Readings of gross production were taken from the inverter during the monitoring period. The system efficiency, solar contribution to total household electricity consumption and directly used solar electricity are estimated in this analysis[12]. Qualitative

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[11] The PV system installed provides electrical power during daylight hours to supplement the mains power being drawn from the national grid. The solar modules on the roof convert radiant energy from the sun into a direct electrical current (DC). The modules are connected in series to form a string (Solar Array). The string is then connected to the properties own inverter. The inverter converts the DC supply from the solar array into alternating current (AC) at 50Hz. This is the same frequency as the national grid supplied to homes. The output from the inverter must be synchronized with the main grid supply and the supplied inverter carries out this function. In addition the inverter has a built in LED indicator panel which meters the energy being generated.

[12] The solar fraction is the amount of energy provided by the solar technology divided by the total energy

data on patterns of occupation and appliance use was collected during the monitoring period and this was used to model the proportions of PV generated power directly consumed and that exported to grid.

In total the whole 6.2 kWp installed produced an estimated 6224kWh of DC power during the monitoring period. The inversion from DC to AC is not 100% and some losses do occur. The accepted range of system efficiencies is between 80 – 98%, with an average of 90%. A comprehensive study of 170 1-5kWp grid connected PV systems in Germany found that system losses fell within a range of 10 – 16%[13]. Taking the technical literature for the installed equipment into consideration the Lingwood system losses were estimated to be 10%.

The annual yield of 903kWh/kWp for 2008 falls within the expected range based on published studies and the location (Table 3.2). The annual yield will vary with each year depending on climate factors. The conversion efficiency (amount of available sunlight converted to DC current) of the modules will also reduce over time. The causes for degradation in continuous operation can be many, but typically include photon degradation, severe discoloration, de-lamination, cracking of cover glass, splitting of back-sheets, wiring degradation and junction box failure[14].

Table 3.2: Lingwood PV vital statistics

array area	51m^2
total generated	6224 kWh
system losses	622kWh
annual yield 2008	903kWh/kWp

Some of this zero carbon electricity will have been consumed directly in the home; the remainder will have been exported to the grid. Currently in the UK there is no direct benefit in reduced meter readings from exporting to the grid (known as net metering or feed in tariffs). Financial benefit is derived by a negotiated fixed payment received periodically[15].

There are very few studies available to estimate the proportions of available solar electricity that are utilised directly in the home. The studies that are available indicate a very wide range of between 20 – 73%[16,17]. The direct use of solar will be dependent upon occupation patterns and behaviour. For

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required. It is dependent upon the systems overall efficiency, the interaction of the solar system with other technologies (e.g. boilers), overall energy demand and patterns of energy usage.

[13] Decker, B and Jahn U 1997: Performance of 170grid connected PV plants in northern Germany, Analysis of yields and optimization potentials. *Solar Energy* V59 (4-6) pp. 127-133.

[14] Dunlop ED and Halton D2006: The Performance of Crystalline Silicon Photovoltaic Solar Modules after 22 Years of Continuous Outdoor Exposure. Prog. Photovolt: Res. Appl. 2006; 14:53–64

[15] Currently the UK does not have net metering or feed in tariffs for renewable energy installations such as PV or wind. Net metering can be thought of as the meter rolling backwards when generated electricity is fed into the grid. Currently, when there is an export of PV production to grid the meter remains stationary. A fixed payment is sent to the householder or the housing association rather than payment for the actual energy produced and exported.

[16] T. Erge, , V. U. Hoffmann and K. Kiefer 2001: The German experience with grid-connected PV-systems Solar Energy 70(6) pp 479-487

[17] A number of individual enthusiasts have published their own data as web blogs or discussed in web forums. The percentages cited range from 50% to 60% during the initial early stages of monitoring and rise to in excess of 70% after altering behaviour to accommodate solar generation.

example a household that is out all day and tends to use appliances (such as washing machines, dishwashers and electric cookers) during the evening will be using a very small fraction of the solar electricity directly. Conversely a household that is at home for a large proportion of the day or times activities such as washing machines, electric ovens and so on to coincide with power production will use a much higher proportion directly.

In the absence of net metering or other smart metering it was not possible to separate the PV production into that directly consumed in the home and that exported to the local grid. The contribution of the solar PV generated electricity to total household load was modelled. It was assumed that electricity consumption was constant during the year. Therefore metered electrical consumption during December and January, where daily solar production is at its lowest, would be representative of average daily electricity consumption.

It was assumed that the increased use of electricity for lighting and other activities during the longer winter evenings would be offset by the small amount of solar produced during the same period. This daily average was extrapolated to give an estimated total annual electricity demand. Cross referencing with appliance audit, occupancy patterns and qualitative data on lifestyle indicated that the modelled consumption were within acceptable limits.

Only data from three of the homes was available for this analysis. Overall 54% of the total PV produced power was used directly. Table 3.3 presents the results for three cases. It is estimated that the proportion of solar directly used by the occupants ranged from 29 - 93%.

The PV system contribution to the total annual household electricity consumption was estimated to range from 22 – 41%.

Those households with low electricity consumption and high daytime occupancy gained the most direct benefit from the PV systems as demonstrated by SOLAR1. SOLAR2 was estimated to make the most use of the PV generated power. This household had a relatively high annual electricity consumption which lowered the overall annual contribution when compared with SOLAR 1. SOLAR 3 derived the least benefit from the PV system in the absence of net metering. Although this household had relatively low annual electricity consumption the household also had a low daytime occupancy, with much of the household out at work, school, college or socialising during the peak PV production times so much of the PV production went direct to export. The use of timers on appliances such as washing machines and cookers would boost the proportion used directly for such households in the absence of net metering.

Table 3.3: Modelled PV results

	kWh				%	
	PV installed kWp	Annual metered	Solar directly used (estimated)	Total Estimated Annual consumption (Grid and solar)	Solar contribution to total annual electricity (estimate)	solar generation used direct (estimate)
SOLAR1	1.5	1681	1187	2868	41	89
SOLAR2	1.5	4236	1239	5475	23	93
SOLAR3	1.6	1532	434	1966	22	29

Solar Hot Water:

The solar hot water system supplemented the main hot water heating provided by an efficient gas condensing boiler. Two homes had a single $2m^2$ solar collector module and two homes had a double $4m^2$ solar collector module.

The contribution that solar hot water can make to a households overall hot water heating demand varies significantly depending upon a) how they use their system with their boiler and b) how much hot water the household uses. Recent studies have found the solar proportion ranges from 26 – 70% with an average of 50-55%[18,19,20].

Households that work with their solar hot water systems and use their boilers in partnership with the system have a much higher solar proportion and maximise the benefits of the available hot water. Households that do not alter their boiler timings or patterns of hot water demand will have a low solar proportion. The most successful results from solar hot water systems rely on properly timed and controlled input from the subsidiary heating system.

There was no direct monitoring of the hot water systems and contribution of the boiler and solar hot water systems. The hot water demand was estimated for each of the households. Data was collected on bathing habits (time and frequency) and washing up (time and frequency) and metered water consumption.

The solar fraction was then estimated based on household patterns of hot water use (i.e. when bathing and showering occurred in the day and whether the household altered boiler settings with regards to hot water).

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[18] DTI 2001: Side by side testing of eight solar water heating systems ETSU S/P3/00275/REP/2 DTI/Pub URN 01/1292.

[19] Energy Savings Trust 2001: GIR88 Solar Hot Water systems in New Housing (2001 Edition) http://www.energysavingtrust.org.uk/uploads/documents/housingbuildings/GIR88%20-%20Solar%20Hot%20Water.pdf

[20] BRE 2009: Viridian Solar – Clearline Solar Thermal Test Report – Average Household Simulation Prepared for: Viridian Solar 30 January 2009 Client report number 251175 http://www.viridiansolar.co.uk/Assets/Files/BRE_Report_Viridian_Solar_Average_House_Simulation.pdf

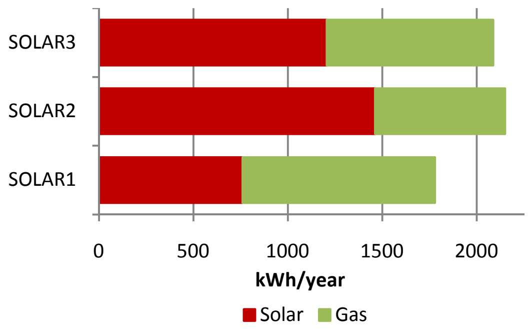

Figure 3.3 Estimated solar contribution to hot water demand

The results show that the solar hot water system contributed between 45 - 70% of annual hot water demand (Figure 3.3.)

Despite having the largest hot water demand of the three solar homes analysed, SOLAR2 derived the most benefit. SOLAR 2 timed bathing activities, in particular during summer months, to mid day and again in the evening. This household switched off their boiler during the summer months, only using a boost from the gas fired boiler when it was required.

SOLAR1 derived the least benefit overall. This household had the lowest hot water demand but did not alter patterns of behaviour, hot water drawn off principally in the evening and first thing in the morning. There was no interaction with the boiler controls leaving the boiler on timer throughout the year.

Summary:

The overall contribution of the solar systems to the estimated total annual energy consumption ranges between 15 - 22%.

For the displaced grid electricity and gas this represents an annual carbon saving of 0.5 – 0.8tCO_2 a year, and a cost saving of £80 – £157 year[21].

Results:

The SOLAR homes on average had a higher level of occupancy in comparison to the other house types in the study. With the exception of SOLAR3 these homes had longer hours of occupation and more occupants per m^2 than the other house types.

Table 3.4 presents the raw data by m^2 of floor area. The data is uncorrected for weather and occupancy.

Table 3.4: SOLAR homes average annual energy consumption per m^2 per year

	kWh/ m^2	kgCO_2 /m^2	£/m^2
gas	71	15	4.28
electricity /grid	38	21	2.14
solar thermal	20		
electricity.PV	12		
total	**142**	**35**	**6.42**
total PV produced	18		

The average total energy demand for the four solar homes was estimated to be 142kWh/m^2/year (Table 3.4) includes grid and estimated generated power), although, as discussed earlier, there was significant variation between the homes. Of this 66% was for space heating and hot water demand provided by both mains gas and solar hot water.

The four homes showed a wide variation in total annual energy consumption (Figure 3.4). There was found to be a 27% difference between the lowest energy demand and highest energy demand.

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[21] The estimated carbon and cost savings are for the electricity and gas displaced by the directly used energy generated by the PV and solar hot water energy.

Theoretically the PV contribution could be higher, however the emissions factor for grid electricity accounts for renewable energy generation within the total UK electricity production. Without net metering the householder will not derive the full cost benefit of the PV system.

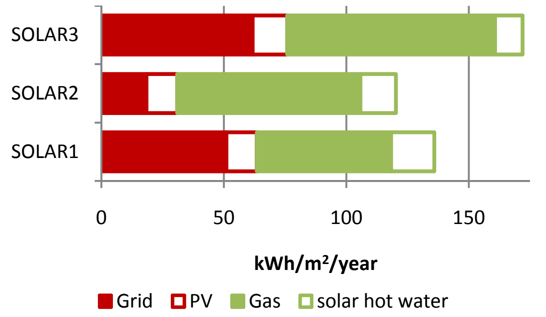

Figure 3.4: SOLAR total energy by source

The aggregate average total carbon emissions were found to be 35kgCO_2/m^2/year. Cooking lights and appliances were found to be responsible on average for 58% of the total emissions (Figure 3.5). Hot water was found to produce an average of 9% of the total emissions.

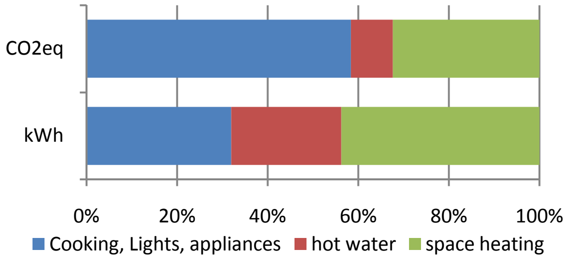

Figure 3.5: SOLAR average energy and carbon by end use

Normalised performance indicator:

The standardised NPI for SOLAR was 93 kWhm^{2}year. This was calculated including the modelled contribution from the solar systems to total energy consumption. It compares well with the result for the CONTROL suggesting the modelling approach used was adequate.

A calculation of NPI based on metered consumption, excluding the solar contribution, gave the result of 73 kWh/m^2/year. This was used in a comparison analysis of the four GreenGague approaches used (see chapter 4).

Running costs:

The estimated average fuel expenditure was £495 (exclusive of standing charges), of which £165 on gas and £330 on grid electricity.

In the absence of available information it was assumed that no income was derived from the PV generated electricity exported to the grid.

Carbon Emissions:

The annual carbon emissions from the use of grid electricity and gas were estimated to be 35 kgCO_2/m^2. The majority attributed to grid electricity (60%).

The active solar systems were estimated to contribute between 21 - 27% of total annual energy demand. This represents an annual carbon saving of between 0.4 – 0.9 tCO_2 a year.

Embodied carbon:

The embodied carbon in the renewable energy systems and boiler were estimated to be 3.95 tCO_2. This is comprised of:

- Solar hot water system 0.8 tCO_2
- Photovoltaic 2.6 tCO_2
- Gas boiler 0.6 tCO_2.

Occupant Feedback

The SOLAR households reported a lack of understandable information on how to use the solar systems to maximise benefit. Three of the households reported that they had read the Information packs provided but did not find the information that they were looking for. The occupants also reported the housing association were unable to give advice or support as they too did not have sufficient experience.

Three of the SOLAR households reported that they had altered their boiler system in some way, either resetting timing and thermostats to suit or altering hot water to boost rather than on timer. Most had also altered the thermostatic radiator valves to avoid overheating, mostly in the upstairs areas.

All the SOLAR households reported that their main living area was difficult to heat during cold weather. Most attributed it to the relatively small radiator in the space.

Some of the SOLAR households had switched energy suppliers within a very short period of moving in. The tenants were unaware of the PV payback negotiated with the original supplier and were not asked to negotiate terms for the PV by the new supplier. It is unclear whether they receive any financial benefit at all from exported PV generation or whether the housing association gains this benefit.

Until net metering is available the timing of appliance use to coincide with daylight and PV power production is fundamental to achieving the greatest benefit for households. Households should be encouraged to recharge phones etc during daylight hours. Plug timers are relatively cheap and easily available and should be encouraged on appliances such as washing machines, dishwashers and so on.

The interaction of the boiler system and the solar hot water system is fundamental to achieving the best results. Programming the boiler to heat water just before use enables the solar collector to provide a larger share of the heating required, i.e. programming the boiler to heat the tank during the evening and using the boost when necessary, rather than timing the boiler to heat the tank first thing in the morning and again in the evening. Only two of the households actively altered the boiler to work with the solar (i.e. removing timer and using boost when required. The household with the least contribution from the solar thermal reported that a friend set the boiler up on timer when she moved in and it has remained with way since.

PASSIVE: Sunspace and mechanical ventilation and heat recovery

Four of the Lingwood homes were constructed with a passive solar design strategy. These homes were predominantly constructed in the same manner as the control homes, with the same dimensions, internal layout and heating system. However in addition, these homes had a single skin brick facing to the front elevation plus a south facing double height sunspace giving the homes a distinctive appearance. The sunspace was coupled with a mechanical ventilation and heat recovery system (MVHR). Two of the homes were 2 bedroom and two were 3 bedroom.

The aim of the sunspace is to trap heat during the day (as in a greenhouse). The wall between the house and sunspace is a dark coloured brick single skin wall against an insulated timber frame. The brick acts as thermal mass, absorbing heat from solar gain during the day time and releasing this heat back into the space during the night. The mass is also thought to act to attenuate temperature extremes, reducing the highs and lows in temperature within the sunspace.

The mechanical ventilation and heat recovery system extracts the warm air from the sunspace and uses it to preheat incoming, cooler air and reducing the heating that the boiler has to do.

This analysis considers the annual energy demand and resulting carbon emissions for these homes. The first part considers the MVHR system and the sunspace contribution to the overall energy demand. The following part presents the headline results for the four PASSIVE homes.

In the absence of detailed monitoring the results presented are based on metered and modelled energy consumption. Two of the PASSIVE homes were occupied for the full monitoring period and two were occupied later in the project.

The Mechanical Ventilation and Heat recovery system:

The system used was a balanced whole house extract with heat recovery. The MVHR unit is housed in the loft with insulated ducts leading to the inflow and extraction vents (Figure 3.6). The vents are found in the ceilings of the sunspace, kitchen, bathrooms, living room and bedrooms.

The vents in the sunspace, kitchen and bathrooms are extract vents. Warm stale air is taken from these rooms up into the heat recovery unit in the loft where it is used to warm cold fresh air brought in from outside the house. In theory the pre-warmed air reduces the work the boiler has to do and reduces the boilers annual heating energy demand.

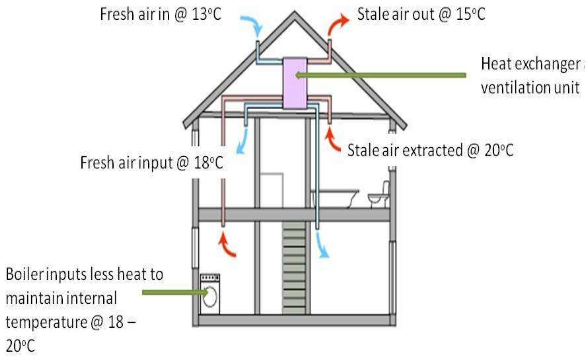

Figure 3.6: Diagram of MVHR system

The warmed fresh air is then passed into the house through the vents in the living room and the bedrooms. The heat exchange unit controls the amount of air flowing through the system. The occupier has control over the air flow coming into the home by an air flow controller (positioned by the bathroom door). There are three factory set speed settings:

1. Night (100m^3/h)
2. Day (150m^3/h)
3. Boost (225m^3/h)

The unit has a filter which requires regular maintenance to ensure efficient running of the unit.

The system had a specific fan power of 1W.l.s and a heat exchange efficiency of 89%.

The MVHR systems are not passive systems and require power to run fans and associated equipment (called parasitic energy demand). In theory a well designed MVHR system in a relatively air tight building will offset this parasitic energy demand through the energy savings derived from heat recovery. The air tightness of the building is critical to the effectiveness of the MVHR.

A simple model was run (using SAP9.81, the manufacturers' product data and the design parameters of an 83m^2 GreenGauge home) to compare the energy demand for heating of natural ventilation against mechanical ventilation at different air permeability rates (q50)[22]. The results indicate that there is no real carbon benefit until q50 falls below 6m^3/m^2/hr@50Pa (Figure 3.7).

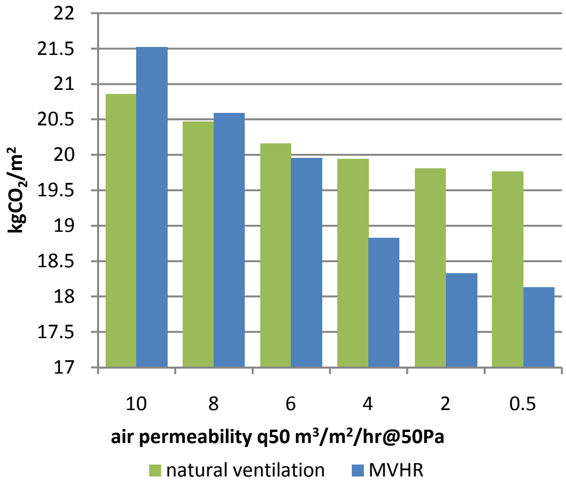

Figure 3.7: carbon emissions natural ventilation compared against MVHR for different air permeability rates

The homes were pressure tested prior to occupation and achieved an air permeability, q50 of 6.25 m^3/m^2@50Pa. This is just on the cusp of being of net carbon benefit compared with natural ventilation, assuming the occupants utilise the equipment as anticipated during the design stage.

In the absence of monitored energy data, SAP 9.81 and the published manufacturers data

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[22] Air permeability, known as Q50, has units of cubic metres per hour per square meter of envelope area (m^{3}hrm^2.) It is the volume of air that passes through the enclosing fabric in one hour at Pascall 50. It is used as an indicator of the rate of natural ventilation through a building, the lower the number the more air tight a building is said to be.

was used to model the theoretical parasitic energy demand and energy savings from the recovered heat at the tested air permeability rate of 6.25 m^3/m^2@50Pa . It was assumed that parasitic energy demand was met by grid electricity and the energy saved was displacing gas[23]. Whilst there was a net heating energy saving of 295kWh a year, there was a net carbon increase of 28 $kgCO_2$ a year (Table 3.5). This is due to electricity having greater carbon emissions per unit than gas.

Table 3.5: MVHR estimated energy and carbon balance

	kWh/yr	$kgCO_2$/yr
parasitic energy used (electric)	226	127
energy saved (gas)	522	99
net difference	295	-28

In reality the energy consumed is likely to have been much higher. Households were observed using the ventilation system in warmer periods as air conditioning, altering the ventilation setting to maximum to provide cooling draughts. At the same time cross ventilation had been made by opening up the front door on to the sunspace and opening up the back patio doors. The resulting spike in monitored energy consumption raised the total annual consumption. The researcher broke protocol and explained the implications on likely energy costs of this behaviour to the occupants. The occupants modified their behaviour and are not known to have repeated it.

The Sunspace:

A passive solar design strategy uses solar gain and the natural flow of heat in the building's design and construction to collect, store and distribute solar energy. In the PASSIVE design the addition of a double height sunspace and a single skin brick wall facing into the sunspace was used.

The addition of the sunspace and brick wall as a design strategy has the following benefits:

- it acts as a buffer between the outside and the occupied space, reducing heat loss.
- it acts as a heat collector, preheating air which can then be moved into the building via a ventilation system (in this case mechanical with heat recovery)
- to act as thermal mass (i.e. thermal storage, absorbing and releasing heat over time) increasing the preheating provided to the MVHR.
- it also provides additional living space, particularly during spring and autumn, and creates an attractive elevation.

The sunspace had a glazed area of 15m^2. The design minimum thermal mass area was calculated to be 45m^2. The mass, as applied in this development, was a single skin brick wall, 102mm deep and an area of 28m^2. The walls at each end and the walls containing glass were timber framed. Additional mass was available in the floor but this had been isolated by a carpeted floor covering.

The sunspace, in this application, was principally designed to provide reduced heat loss, solar heating and thermal mass buffering against seasonal extremes of temperature. To achieve this the rule of thumb ratio of glazing area to mass area should be a minimum of 3:1[24]. The area available as constructed was substantially lower than the design optimum (1.8:1).

To optimise thermal mass, if this ratio cannot be met, the material used to absorb and store available solar radiation needs to have a

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[23] It was assumed that the boiler was SEDBUK 91% and the total amount of gas saved was adjusted for this.

[24] Brown GZ, DeKay M: sun, wind and Light Architectural Design Strategies. 2001

relatively good ability to absorb heat (specific heat capacity, SPH). The optimum thickness of the material being used as mass has also been found to be no greater than 150mm. The use of a single skin brick wall composed of a dark colour brick with a relatively high SPH in these GreenGauge homes provided an optimum solution. The sunspace wall was estimated to have a useful thermal mass of 1.08 kWh for every degree increase in temperature[25].

How much of this useful thermal mass is utilised in practise will depend on a number of parameters, not least of which is how the occupants utilise the sunspace and the MVHR system. The sunspace glazed wall contains operable windows at eaves height, manually operated by a switch, excess venting or, conversely, no venting will alter the overall temperature and available useful thermal mass. Some households had elected to permanently vent their sunspace, reducing the overall solar gain and the benefit to heating.

Temperature data were collected from four locations in one predominantly unoccupied PASSIVE home over a short period (July to November 2008). The MVHR and boiler systems were disabled until later in the period when the occupants moved in. The internal doors were open to allow free movement of air within the property. The sunspace ventilation windows were closed during the period until post occupation. There were no other incidental gains other that from the climate. The data is presented in Figure 3.8.

The data indicates that in the absence of heating and other internal gains the internal temperature was on average 26% higher than the external temperature (equating to a difference of 4^{o}C). The diurnal fluctuations of temperature internally were also smoother. It is not possible to attribute this effect to the sunspace alone. Other factors, such as insulation, will also be acting to the same effect.

As a design strategy the sunspace's greatest contribution was as a climate buffer zone. As a heat sink in partnership with the ventilation strategy it is unlikely to have contributed a great deal. The area of mass is too small in relationship to the overall area of glazing to enable the available thermal mass to work to its optimum potential.

Summary:

The contribution of the MVHR system in this application is likely to be a net energy user, even with the additional sunspace and thermal mass. For this reason it is recommended that mechanical ventilation systems are avoided until air tightness is such that healthy ventilation cannot be provided by passive means alone.

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[25] Determined by multiplying volumetric heat capacity of material by total accessible volume of material. In this case 2.85m^3 of brick (SHC 1360 kj.m^3.k) :
1360 X 2.85m^3 = 3880 kj
To convert to kWh:
3880/3600 = 1.08kWh

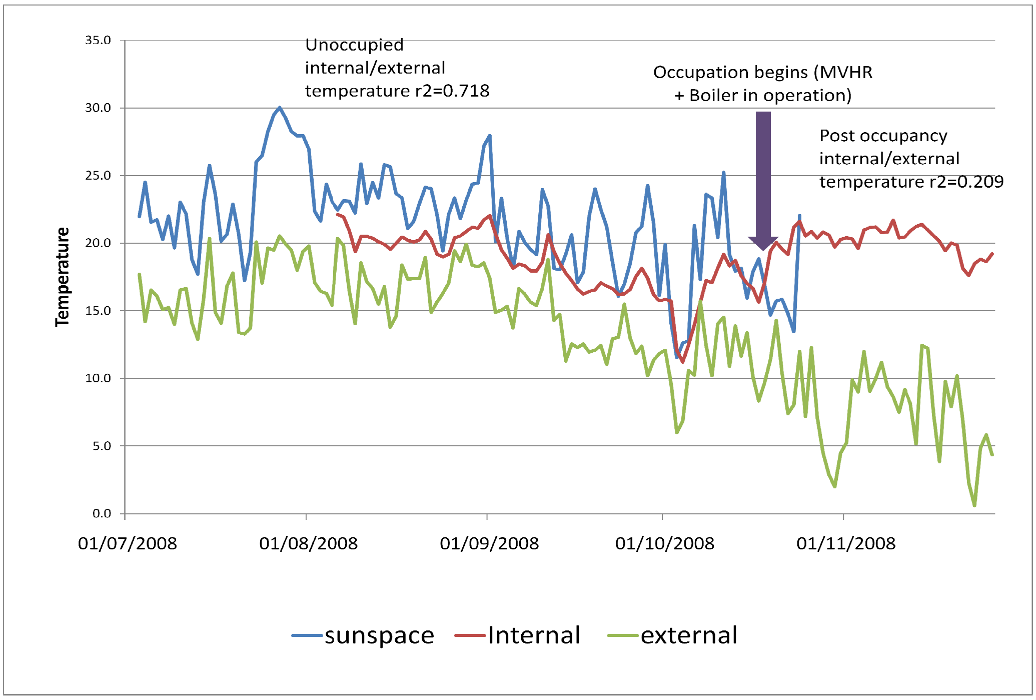

Figure 3.8: Temperatures recorded in four locations of an unoccupied PASSIVE home (August - November 2008)

The thermal mass within the sunspace was not in the right proportions to enable a significant contribution to the heat recovery strategy. This will particularly be the case during the main heating season when the available stored heat is likely be to be in equilibrium with the sunspace air temperature at an earlier period in the day. The sunspaces primary contribution is likely to be as a climate buffer and, during sunnier spells, a source of direct heat during the daytime if the doors and windows from the sunspace in to the homes are open to allow free flow of air from the sunspace directly into the homes.

Results:

The four PASSIVE homes showed a wide variation in annual metered energy consumption (Figure 3.9). The total energy consumption ranged from 104 - 150 kWh/m^2/year. These four homes had the most varied occupation patterns, behaviour and lifestyles of all the house types.

Gas consumption ranged from 69 – 102 kWh/m^2/year. Of this between 56 – 71 % was estimated to be used for space heating. Based on the modelled heating contribution of the MVHR system it was estimated that the MVHR system saved between 8 – 14% of the annual heating gas demand. The remainder was attributed to hot water and a small proportion to cooking.

Table 3.6: PASSIVE average energy consumption per m^2

	kWh/ m^2	kgCO$_2$/ m^2	£/m^2
gas	91	17	2.74
electric	40	22	4.46
total	131	39	7.20

Electricity consumption ranged from 33 – 49 kWh/m^2/year. It is estimated that electricity demand to power the MVHR system ranged 6-9% of total electricity demand for these homes. However, during the project the use of the MVHR systems became erratic, some households elected to turn them off, others chose to operate the systems occasionally and others did not alter their systems throughout the entire period.

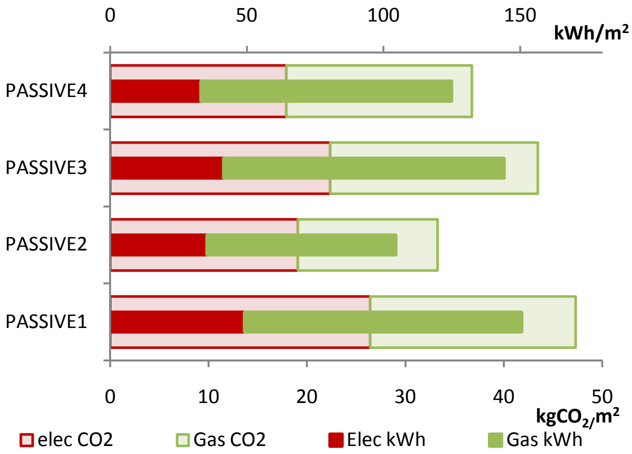

Figure 3.9 PASSIVE energy and carbon

Normalised Performance Indicator:

The standardised NPI for PASSIVE was 88 kWh/m^2/year.

Running costs:

The estimated average fuel expenditure was £555 (exclusive of standing charges), £211 gas and £343 grid electricity.

Carbon Emissions:

The annual carbon emissions from the use of grid electricity and gas were estimated to be 39 kgCO$_2$/m^2. The majority attributed to grid electricity (55%).

It was not possible with the small quantity of data to assess the contribution to any degree of accuracy the passive sunspace made to the overall heating energy budget of these four homes. Further monitoring work is required to establish this.

The MVHR systems were estimated to contribute a net saving of 295 kWh a year. This was estimated to be a net carbon cost of 28 kgCO$_2$ a year.

Embodied Carbon:

The embodied carbon in the MVHR system and boiler were estimated to be 0.7 tCO$_2$. This is comprised of:

- MVHR system 0.1tCO$_2$
- Gas boiler 0.6 tCO$_2$.

The sunspace resulted in an additional construction burden. The additional embodied energy in the sunspace itself is 10.9 tCO$_2$. The construction related embodied carbon is considered in a separate sister report[26].

Occupant feedback:

Of all the four house types monitored the PASSIVE homes could be argued to require the most driving from the occupant. The interaction of the sunspace, ventilation and heat recovery system was not automated and required the occupant to balance the three elements to get the best performance. For most households this was not the norm.

The tenants pack did not contain any usable information on how to run these homes to their most efficient potential. The householders interviewed were reticent about the MVHR systems, complaining of draughts and cold air. The researcher intervened and provided an instruction sheet and information.

The households interviewed reported uncomfortable draughts in areas where the ceiling vents were positioned. Positioning of furniture appeared to avoid placing seating

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[26] Monahan J and Powell JC 2009: Embodied primary energy and carbon in offsite timber framed housing: A case study GreenGauge Design Lingwood. UEA.

directly underneath or within the vicinity of the down vents in the main living areas of the three homes accessed during the monitoring period was observed.

The sunspaces were largely used as additional floor space. The sunspaces were monitored and the following activities were recorded:

- Cloakroom (coats, shoes etc)
- Drying space
- Home gym
- Home office
- Utility room (installing washing, drying equipment)
- Smoking room
- Children's play area
- Indoor garden

One PASSIVE home installed a water supply to service washing equipment in the sunspace (vacant space in kitchen used to install dishwasher). This household had drilled through the wall in two locations to provide water to the sunspace and to an outside tap. This effectively removed the careful workmanship during the construction phase to preserve the air tightness of the finished home. This household also used the space as a home office and smoking room, keeping the ventilation windows open for long periods of time. This household also reported disabling the MVHR system. It is unlikely that the sunspace and heat recovery system will contribute any energy benefit.

PASSIVE4 has adopted the sunspace as a pre-heat. The ventilation windows were mostly observed closed, the door to the house was usually open when occupied and the occupants altered the MVHR to suit the prevailing internal environment, typically it was reported to be turned low or off. A net heat benefit was derived from circulating warm air directly from sunspace into the home. This household had a relatively low consumption (both for electricity and gas) despite being occupied all day.

PASSIVE 3 had an artificially high electricity consumption. During a hot spell the ventilation setting was put on high effectively using the system as air conditioning. At the same time a through draught of warm air had also been created by opening the door between the sunspace and home and opening the rear patio doors. Advice was given that this was probably not the most efficient way of cooling the home and the household quickly adapted. The subsequent electricity consumption reduced considerably after this advice had been given.

A key question that was asked by all but one of the households: Who is responsible for the maintenance of the ventilation filters? The filters require inspection and cleaning on a regular basis. The responsibility for this was not clear. In social housing situations the housing association needs to be aware of its responsibility to maintain these systems regularly.

Of all the four design types on this GreenGauge development the PASSIVE homes would benefit from a design rethink in future application. All the households benefited from the perceived benefits of additional, open and sheltered living space. However it is doubtful that the MVHR has contributed any net benefit in terms of energy saving or carbon emissions abatement. Until the GreenGauge home becomes significantly more air tight it is recommended that careful attention to passive ventilation strategies is given during the design phase in homes that adopt a passive solar strategy. With further monitoring it could be that the boiler is actually doing more work to counteract the MVHR.

GSHP: All electric homes with ground sourced heat pumps

The block of five terraced GSHP homes were designed to test an alternative heating system in situations where no mains gas was present. These five homes were constructed to the same specifications and with the same internal design as the CONTROL and SOLAR homes. The GSHP homes were all electric and were without connection to mains gas. Heating and hot water were provided by a ground sourced heat pump. An under floor heating system provided heating to the ground floor with efficient low flow radiators providing heat to the first floor.

Four homes were 2 bedroom and one 3 bedroom. Four of the GSHP homes were occupied for the whole monitoring period. One was a shared ownership home and was occupied for a six months of the monitoring period.

Ground Source Heat Pumps:

Ground Source Heat Pumps take heat from the ground and convert it into energy, which can be used to heat buildings and water. The technology used is the same as that used in a fridge. In the same way as a fridge extracts heat from inside itself and pumps it into the kitchen so a ground source heat pump extracts heat from the earth and pumps it into a building. GSHPs main application is for space heating but are also able to provide hot water, as in the Lingwood development.

Heat pumps are very efficient if electricity is the most convenient option for home heating. For each unit of electricity used to power the pump approximately 2 – 4 units of useful heat are produced (Figure 3.10). This is referred to as the coefficient of performance (CoP)[27]. The product manufactures data states the CoP for the units installed in Lingwood to be 3.8.

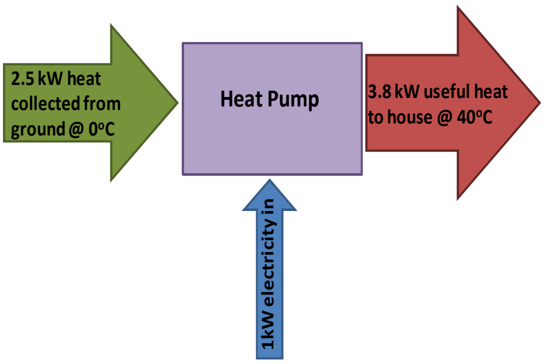

Figure 3.10 Principles of a heat pump

A Ground Source Heat Pump system comprises three basic elements - a ground loop, the heat pump, and a heat distribution system (Figure 3.11). The ground loop is a pipe buried underground in either a horizontal trench or a vertical borehole and acts as a heat exchanger (collecting heat from the surrounding area[28]). The heat pump itself takes the heat provided by the collector and compresses it to condense to a higher temperature for use in a heat distribution system. The heat distribution system is typically an under floor heating loop. Although heat pumps are best suited to lower temperature distribution systems radiators can be used but the overall efficiency of the system will be reduced.

A total of 50 ground source heat exchangers to 16m depth were installed to serve the five homes, each system was anticipated to supply 3.75kW. The ground source heat exchangers were installed by vertically pushing into the ground using hydraulic rigs with the installations cross-connected to produce a closed-loop installation. This approach

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[27] The Coefficient of performance is measured as the heating output (kW) divided by the total power consumed by the system including fans, pumps and controls (also in kW)

[28] Heat exchangers in heat pump systems can be in contact with air, water or ground

minimised on construction time, ground works, disturbance, waste and materials required.

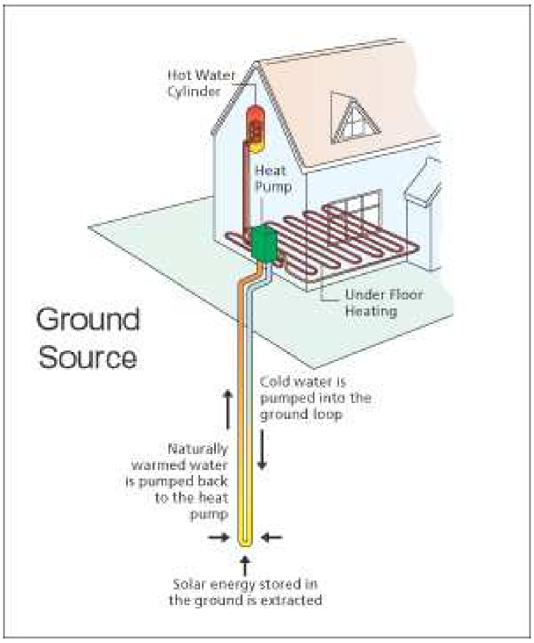

Figure 3.11 schematic of a ground source heat pump (source: Heat Pump Association)

The occupants had no access to the control settings of the heat pumps. The heat delivery was controlled by a dial 'thermostat' positioned in the hallway and a summer/winter switch setting to operated the heating seasonally. The thermostatic controller had no indicative numbers to correspond to a set temperature.

The heat pumps are housed externally in insulated purpose built housing with the controls and hot water tanks housed inside in the under stairs space and a purpose built cupboard in the upstairs bathroom respectively (Figure 3.12– Figure 3.15). It was estimated that the total floor area required for the heat pump components was 3.5m^2. This was estimated to be 4% of the total internal floor area.

Results:

Unfortunately there was not enough data of suitable quality to assess with confidence the coefficient of performance, CoP, of the ground sourced heat pumps. The results presented here are best guess estimates based on metered electricity consumption, modelling and data supplied by the occupants.

There was limited data available for the home that was partially unoccupied, it was removed from the analysis.

The attribution of energy to end use was estimated from modelling of occupancy patterns, appliance data and qualitative data. The base load (all energy consumption other than space heating) was calculated based on the energy consumption during the months of June to September. During this time period the homes had the summer 'hot water only' setting in their heat pump systems. It was assumed that metered energy consumption would be representative of all energy demand other than space heating. This is likely to be an underestimate due to the following parameters: mains water will be at a higher initial temperature; cooking is likely to be less and lighting demand is likely to be lower during these months.

The total average energy consumption was 77/kWh/m^2/year (Table 3.7 and Figure 3.16). Unsurprisingly there was a wide range in the annual metered energy consumption, the highest consumer using 38% more than the lowest consumer. However, with the exception of GSHP1 all other energy uses showed a remarkable similarity (range 30 – 33 kWh/m^2/year).

Figure 3.12 Heat pump external housing and contents

Figure 3.13 Heat pump external housing and contents

Figure 3.14 Ground floor under stairs controls

Figure 3.15 Upstairs hot water

The results shown in Figure 3.16 indicate that for the majority of these homes space heating forms just over 55% of the annual energy budget (GSHP1, 2 and 4).

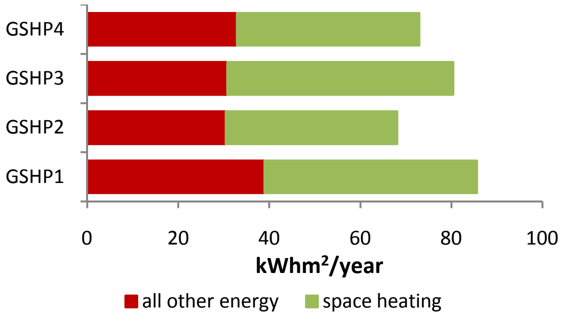

Figure 3.16 GSHP energy use kWh/m^2/year

For GSHP3 the proportion was slightly higher at 62%. There is no indication that this household preferred a higher internal temperature or had a significantly different pattern of occupation. This household did have a heavy carpet throughout the heated ground floor area. The isolation of the under floor heating by any insulating materials (i.e. carpet and underlay) acts to reduce the flow of heat into the space. The heat pump has to work harder to maintain a set air temperature and, consequently uses more energy to do the same work reducing its overall efficiency and the associated CoP.

The CoP was modelled to give an estimate. The results are given in Table 3.8. The CoPs suggest that all the systems are working to provide a performance greater than 1 (i.e. 1 unit of electricity in gives 1 unit of heat out). However none of them indicate a CoP approaching the 3.8 claimed by the manufacturers.

Table 3.7: GSHP house average energy consumption per m^2

	kWh/m^2	kgCO$_2$/m^2	£/m^2
electricity	77	41	9

The estimated CoPs are not robust enough to draw any further interpretation or conclusions. Future monitoring work is required to provide a sufficient quality of data to be able to make any robust claims for these particular systems.

Table 3.8: Energy data and CoP for GSHP homes

	all other energy/ kWhm^{2}year	space heating/ kWhm^{2}year	CoP
GSHP1	39	47	2.07
GSHP2	30	38	2.43
GSHP3	31	50	1.75
GSHP4	33	40	2.22

Normalised Performance Indicator:

The NPI for the GSHP homes was 51 kWh/m^2/year.

Annual Running costs:

The running costs were calculated based on regional average unit prices[29]. The average estimated fuel expenditure was £644 (exclusive of standing charges).

Carbon dioxide emissions:

The annual carbon emissions were estimated to be 42.6 kg CO_2/m^2.

Embodied carbon:

The embodied carbon in the GSHP system was estimated to be $4tCO_2$

Of this:

- 64% was attributed to the closed loop heat exchanger
- 19% was attributed to the hot water tank and expansion vessels
- 18% was attributed to the under floor heating system.

Occupant feedback:

There were a number of issues reported by the tenants. All the households reported there was only a minimum of information provided on the system (a laminated A4 instruction sheet provided by the installation company). The installation company visited one household upon request to explain the system. This household became the focal point for information for the other four households. The housing association representatives had no formal or informal training on the system and were unable to help the occupants.

The occupants fitted out the floor covering to their own specifications. The majority followed the advice given and used coverings that were suitable for under floor heating, such as laminated wood or uninsulated short pile carpet. One household elected not to follow this and installed a thick pile carpet with an insulated backing. This household had the highest energy consumption for the GSHP homes.

Getting the system operating to meet the occupants comfort was a matter of trial and error in the first few months. The 'thermostat' was a dial with no numbers or indicators of temperature or high /low settings.

A number of the households reported early problems with overheating or under heating, particularly during the transitional seasons of spring and autumn where external temperatures can be more variable than winter or summer. The GSHP systems are not as responsive as conventional boiler heating systems that the occupants were accustomed to. A number of the households reported becoming more weather aware, reporting that they paid attention to the weather forecast, and adjusted their systems accordingly as a pre-emptive strategy.

The all of GSHP households did not use the radiators upstairs and relied exclusively on the under floor heating during the monitoring period.

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[29] Department for climate change energy statistics Quarterly energy prices tables 2.2.3. and 2.3.3 http://www.berr.gov.uk/whatwedo/energy/statistics/index.html

Chapter 4 Discussion: Comparing the technologies and approaches

This chapter compares the merits of the four different GreenGauge house types constructed at Lingwood. The monitoring results presented are based on one single years measured energy consumption (metered gas and electricity)[30]. The following discussion considers the grid electricity and mains gas consumed and compares the resulting emissions of CO_2 and energy costs associated with that consumption.

The sample groups were too low to use statistical analysis to support the findings suggested by the results. Consequently the results shown and discussion points made are not conclusive. Future research with a larger, more diverse sample group is required.

The results presented are based on two homes with conventional technologies (CONTROL); four homes with solar hot water, SHW and photovoltaic, PV (SOLAR); four homes with mechanical ventilation and heat recovery and a solar sunspace (PASSIVE); four homes with ground source heat pumps (GSHP).

Comparison of GreenGauge Homes

Compared to the average UK domestic customer the GreenGauge CONTROL homes space heating gas demand was 59% lower (Figure 4.1)[31]. This is an unsurprising result given the high level of insulation and careful attention to reducing unwanted ventilation during design and construction. The average SAP rating for homes in the UK is 50 which is indicative of poorly insulated stock[32]. The CONTROL homes achieved a SAP rating of 86 when modelled using SAP 9.81.

The electricity consumption of GreenGauge homes was 4% lower than the UK average.

Energy consumption is highly variable and is greatly influenced by lifestyle and behaviour. With such a small sample group drawing any firm conclusions is not possible.

However, it does indicate that whilst heating related energy consumption in the UK is reducing through the provision of better buildings the converse is true of electrical consumption for all other end uses. Even with the contribution of 100% dedicated low energy lighting and PV there does not appear to be the radical savings in electrical consumption needed. The data collected from the Lingwood GreenGauge project indicates that, in the absence of drastic changes to a) the generation of electricity and b) the efficiency of technologies, efficiency and environmental targets will not be met without robust demand reduction activities.

The difference in total energy consumption equates to a 35% saving in CO_2 from gas and electricity when compared with the UK average.

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[30] The analysis uses energy units of kWh delivered (grid electricity and mains gas) and not primary energy.

[31] Department of Energy and Climate Change: Regional and local authority electricity and gas consumption figures 2007.

[32] Department of Communities and Local Government: The English House condition Survey Headline Report 2007. HMSO, London January 2009

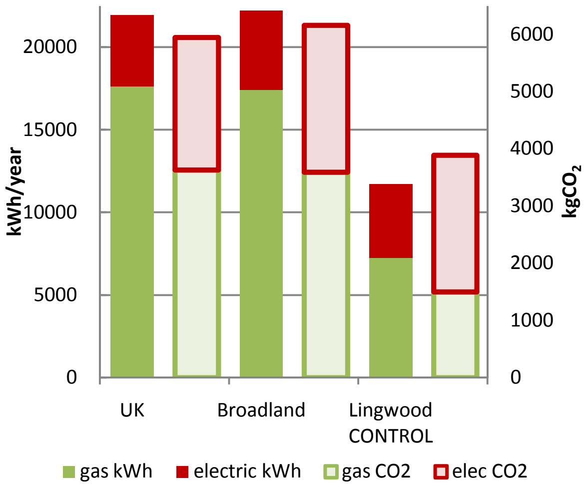

Figure 4.1: Average domestic consumption of gas and electricity

Annual energy compared:

The sample groups are too small to undertake any statistical analysis. The following results are indicative only and should not be used to draw any wider conclusions.

For the purposes of this analysis the metered energy consumption from gas and electricity is apportioned to either space heating or all other end uses (hot water, lighting, cooking and appliances).

Figure 4.2 presents the normalised energy performance index, NPI, for annual metered energy demand for gas and electricity from 14 of the Lingwood GreenGauge homes[33]. The results indicate the property types are showing some evidence of clustering within the wide variations shown. The GSHP homes are showing the lowest total annual energy consumption (NPI), followed by the SOLAR homes. The PASSIVE homes and the CONTROL homes are showing similar results within the wide variation found.

Annual carbon emissions compared:

The results for emissions of carbon dioxide, CO_2, from metered energy consumption by end use are presented in Figure 4.3. Note that, other than dividing by total floor area, the raw energy data is not normalised for this analysis.

Within this limited sample, with the exception of GSHP, there does not appear to be an overall pattern of emissions associated with each particular house type.

With the exception of SOLAR4, the majority of emissions for all house types are associated with end uses other than heating, accounting for 50 – 70 % of total emissions (hollow portion of bar in Figure 4.3). These emissions also had a larger range than that associated with heating (13 – 33 and 10 – 27 $kgCO_2\ m^2\ yr$ respectively). In terms of overall emissions it

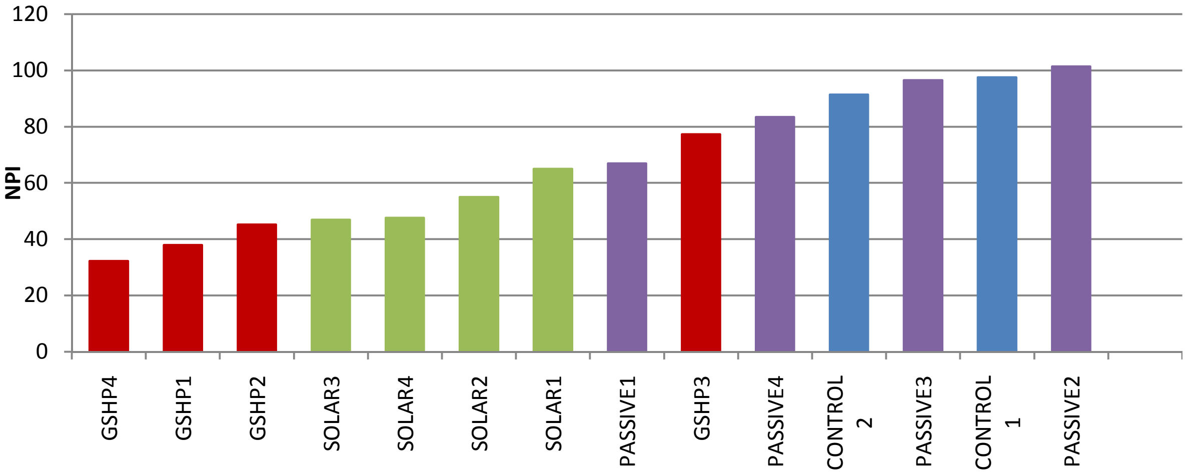

Figure 4.2: Normalised annual energy (NPI) end use.

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[33] See appendix for description of normalisation and NPI.

is those associated with end uses other than space heating that determine overall total emissions of CO_2.

For space heating the largest emitters were GSHP homes. The emissions of CO_2 from GSHP homes for heating are approximately 89% greater than those from the CONTROL homes. The GSHP homes are all electric. Grid electricity has a relatively high emissions factor when compared with cleaner fuels such as gas.

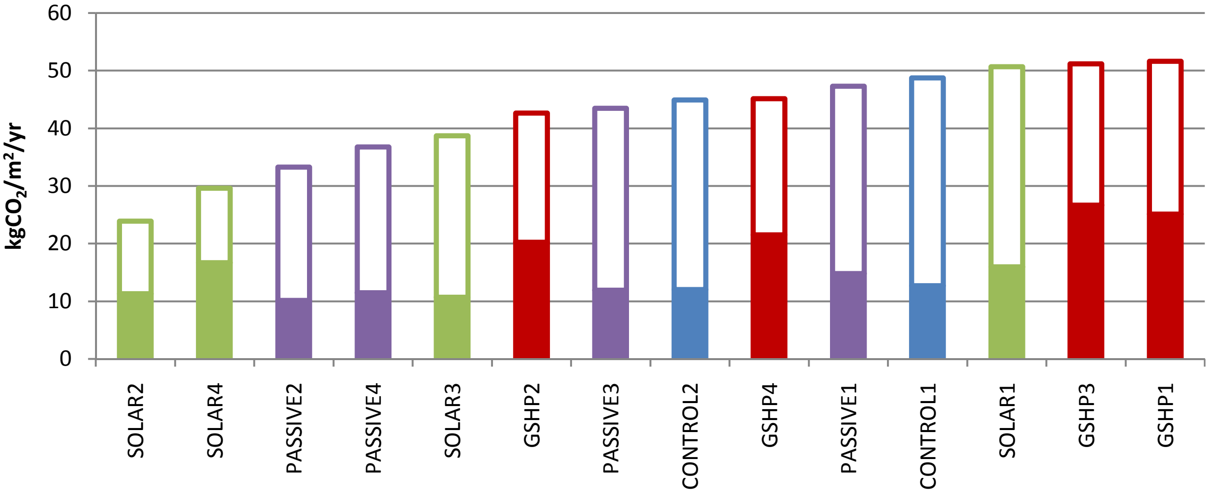

Figure 4.3: Carbon emissions for annual metered energy consumption per m^2 of floor area by space heating (solid) and all other end uses (hollow).

Summary results:

Figure 4.4, Figure 4.5 and Figure 4.6 below summarise the results for each house type. The results shown were calculated by aggregating the energy consumption data and floor area.

The aggregate NPI indicates that the three alternative GreenGauge house types used less energy overall than the CONTROL. The results indicate that GSHP had the lowest energy demand overall (Figure 4.4).

When considering both the environmental and cost performance (Figure 4.5 and Figure 4.6 respectively), the story is different. The three alternatives show lower overall emissions and annual running costs than the CONTROL. Of the three alternatives, the GSHP homes are the most costly to run both in terms of CO_2 and annual bills.

These summarised results indicate that the SOLAR homes gave the optimum performance in considering all three evaluation criteria.

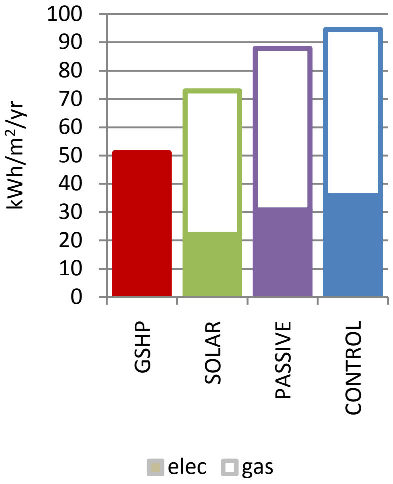

Figure 4.4:
Annual energy consumption (Normalised) per m^2

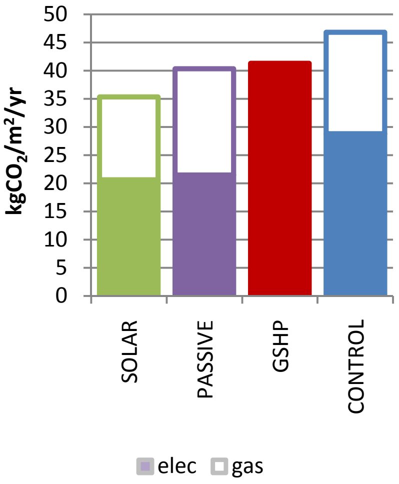

Figure 4.5:
Annual carbon emissions from energy consumption per m^2

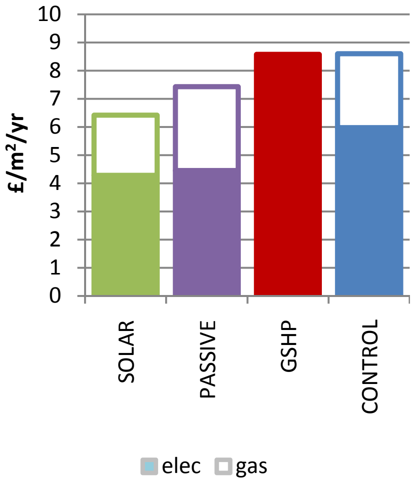

Figure 4.6:
Annual energy costs per m^2

Embodied carbon and energy payback:

Energy and CO_2 emissions in use cannot be considered in isolation. The initial construction and each of the different technologies used will have significant energy and CO_2 emissions associated with their production and supply (known as embodied energy or carbon). This section considered the embodied energy and carbon in conjunction with the energy and emissions associated with the use of these homes. The embodied carbon data is summarised from a separate report.

The annual measured energy demand and associated emissions of CO_2 were combined with the initial energy and CO_2 emissions embodied in the production of each different house type. The energy and CO_2 emissions were modelled for a 20 year period. During this time it was assumed that no significant replacement or maintenance of either the homes or the energy providing technologies would be required. It was also assumed that there would be no significant de-carbonisation of UK electricity supply. The results are shown in Figure 4.7 and Figure 4.8. Despite differences in the initial embodied carbon and annual emissions of each house type, by the end of the twenty year period there is a convergence with all the house types with the exception of the SOLAR homes.

The PASSIVE home has the highest initial embodied carbon of all the four house types (Figure 4.7). This is due to the substantial additional embodied carbon associated with the construction of the sunspace. The additional embodied costs are offset, to a very small degree, by a net annual carbon saving. Although this saving does not recoup the initial additional carbon costs until the end of the first 20 year period, compared with CONTROL.

The SOLAR homes show that the additional embodied carbon costs of the PV and solar thermal systems are recouped in a much shorter time period. In carbon terms the SOLAR homes out perform all the other house types considered. SOLAR homes recoup the additional carbon investment during year three, compared with CONTROL.

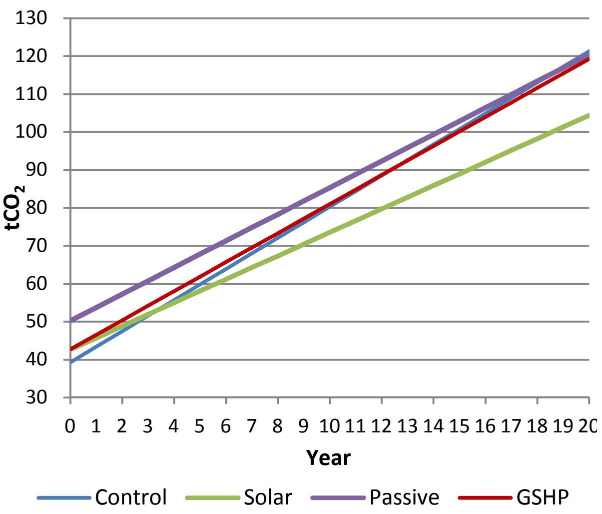

Figure 4.7 modelled embodied CO2 and emissions in use for 20 years.

Figure 4.8 considers energy[34]. Here the story is somewhat different. The GSHP homes consistently use less energy than all the other house types, despite an initial high embodied energy load. The initially high embodied energy is recouped during year 4, compared with the CONTROL home.

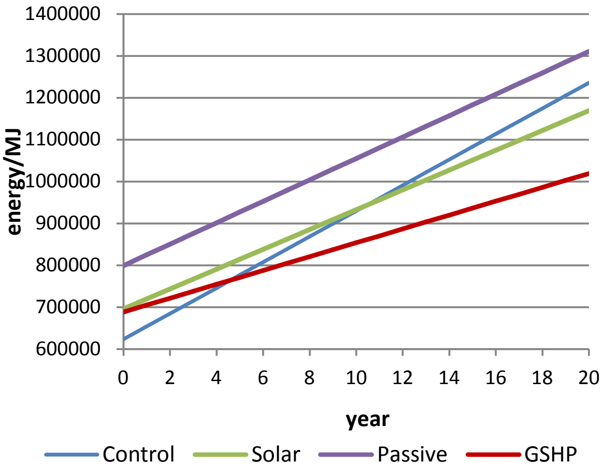

Figure 4.8: Embodied energy and energy in use for 20 years.

The SOLAR homes recoup the initial energy investment during years 10 and 11, compared with the CONTROL. The PASSIVE homes do not recoup their initial energy investment at all during the 20 year period modelled.

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[34] Units of MJ to enable joining of embodied energy and energy in use data

Chapter 5 Conclusions

The GreenGauge Lingwood CONTROL homes showed a significant saving in energy compared with the average UK home and an equivalent meeting minimum building regulations (59% and 7% saving respectively).

The majority of savings were from reduced space heating demand associated with: an efficient boiler; better insulation; and attention to air tightness and ventilation during design and construction.

The addition of micro generation technologies, as demonstrated with the GSHP, SOLAR and PASSIVE homes, resulted in further savings to different degrees.

The energy consumption associated with lighting, appliances and cooking showed no significant difference compared to the average UK household, despite the use of 100% dedicated low energy lighting. The energy consumption associated with these end uses is closely associated with behaviour, personal lifestyle and choice. These households provided their own white goods, most opting for economy of cost of purchase over economy in use (energy efficiency).

The GSHP homes performed well in energy terms, using least overall energy, in kWhs. However, without careful attention to energy tariffs, the running costs are high compared to gas. The environmental costs are also high due to the significant carbon emissions associated with grid electricity.

The SOLAR homes performed well across all three evaluation criteria. Those households that were occupied during the day and with occupants who operated their boiler and solar hot water systems together gained the greatest benefits from having the active solar systems. It was clear that these households would have benefited from guidance in their information packs. Guidance needs to be given in a clear concise manner on operating a combined solar and boiler system.

In cases where PV is specified, clear advice needs to be provided on when to run appliances and a realistic idea of how much the system will generate in easy to understand terms (e.g. full sun at 1pm will produce enough power to run 1 washing machine).

Whilst the PASSIVE homes did show a small improvement in performance compared to the CONTROL the sample groups are too small to elicit whether this was due to occupant behaviour or design. The analysis results indicate that more attention during design needs to be made if passive strategies are to be replicated in further GreenGauge developments.

Strategies, such as sunspaces, thermal mass and pre-heat ventilation, need to be integrated in a holistic manner during the design phase rather than considered as an optional bolt on strategy to a standard house typology.

For all housing types the provision of information to the new occupants was found to be inadequate. The information packs contained manufacturers' manuals and installation guides aimed at professional installers. Most households only gave the packs cursory glances upon moving in and used them as references when the information was needed. Information on using their homes efficiently, in particular relating to the new technologies, was lacking or unusable.

The Housing support teams were also lacking in knowledge and were often unable to answer technology specific questions.

The simplification of the information packs to include basic guides on how to use the GreenGauge home efficiently as well as basic good energy housekeeping would enable the households to make further demand reduction.

Chapter 6 Appendices

Appendix One: NPI (Normalised Performance Indicator)

Many indices have been produced concerning energy consumption. One of them is the NPI (Normalised Performance Indicator), which is a government accredited scheme to assess and allow for the comparisons of energy performances of buildings. It is, put simply, the benchmark to which comparisons of performance are made.

The steps used to produce the NPI were the following:

1. All metered energy units were converted to kWh.
2. Raw annual space heating energy use for space heating was determined.
    - The space heating portion of gas/ electricity was determined by monitoring the gas/electricity consumption during a four week period during July and August divided by number of days and multiplied to a years estimated demand. Assuming there was no space heating demand during this period and hot water consumption patterns did not change seasonally.
3. Energy used for space heating was corrected to account for weather
    - Standard annual degree days divided by annual heating degree days experienced by building
4. Energy used for space heating was corrected to account for exposure influences:
    - An exposure coefficient of 1.0 was used.
5. Energy used for non-heating purposes was determined and added to the corrected space heating data to give the raw non time corrected energy consumption.
6. The raw non time corrected energy was corrected for hours of use to give the normalised total annual energy consumed.
    - Hours of use were determined from survey data by dividing by standard hours of use for housing.
7. Floor area or volume, m^2 or m^3. Determined from plan measurements
8. NPI was then calculated by dividing the normalised energy consumption by floor area.

Appendix Two: Emissions and cost factors

Carbon emissions factors:

The emissions factors used in the analysis and production of this report are those published by DEFRA[35]. Fuel conversion factors for fuels other than grid electricity were by Net CV basis. The carbon factor for grid electricity was based on the rolling average:

- Gas 0.206 kg CO_2 kWh
- Electricity 0.54 kWh kg CO_2 kWh

Cost factors:

The cost factors used in the analysis and preparation of this report are those published by BERR[36,37] in 2008. Average published unit prices were used and not actual prices paid by the occupants. There was some switching behaviour, tariff price changes and lack of information on unit prices paid by householders. Comparison was on an equal basis. The unit prices used were as follows:

- Gas 0.03 pence per kWh
- Electricity 0.1114 pence per kWh

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[35] Department of Environment, Food and Rural Affairs: 2008 Guidelines to Defra's GHG Conversion Factors Update April 2008

[36] Department for climate change Energy statistics Quarterly energy prices tables 2.2.3. and 2.3.3 http://www.berr.gov.uk/whatwedo/energy/statistics/index.html

[37] Department for Business, Enterprise and regulatory reform Energy Statistics Prices Table 2.2.3 Average annual domestic electricity bills in 2008 for selected towns and cities in the UK and average unit costs