COMPARATIVE ANALYSIS OF PERFORMANCE OF PASSIVHAUS AND FEES STANDARD IN CONTEXT OF THE UK 2016 "ZERO CARBON" TARGET

by

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5 September 2011

A Dissertation submitted in part fulfilment of the

Degree of Master of Science Built Environment:

Environmental Design and Engineering

Bartlett school of Graduate Studies

University College London

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ACKNOWLEDGEMENTS:

I would like to thank my supervisor Dr Ian Ridley for his guidance and valuable advice. I would also like to thank Sarah Lewis and Justin Bere from Bere: Architects for their time and useful information related to the case study house.

1. ABSTRACT

The UK “zero carbon” strategy for homes is based on a hierarchical approach. The basis of this approach is Fabric Energy Efficiency (FEE) Standard which aims to limit heating and cooling demand to 39/46 kWh/m^2/yr and gives recommendations on how this should be achieved.

However, the Task Group that worked on defining the FEE standard expressed concern regarding the significant gap which exists between design and actual performance of buildings in the UK and stressed the necessity of additional research on validation of the standard and urgency of moving FEES towards actual rather than designed performance (Zero Carbon Hub, 2010). On the other hand, example of Passivhaus standard shows that such gap is on average reasonably small and that low levels of heating demand can really be achieved on a large scale (Feist, 2007).

The study aims to quantify the range of potential discrepancies between design and actual performance of FEES and Passivhaus standard and determine their implications on the compliance with these standards and establish whether FEES recommendations would actually need to move closer to Passivhaus specification.

Thus, sensitivity analysis of the effect of building fabric deterioration and occupant behaviour, which are considered to be major causes of the gap, is carried out on the case study house, applying specifications of both standards. Analysis of Passivhaus standard confirms results from the practice, indicating that high quality of building fabric, construction and detailing as well as use of MVHR can help significantly reduce this gap. Estimated “actual” performance, which incorporates this gap, results only in slight exceedance (15%) of the Passivhaus heating demand limit.

However, for the FEE standard situation is radically different. Even though it is claimed that FEES recommendations for the building fabric are high enough to enable the compliance even in case of natural ventilation, and that use of MVHR should bring only additional reduction of heating demand below the determined limit, results indicate contrary. In the particular analysed case, even with the use of MVHR the limit can be easily exceeded. Concerns of the Task Group prove to be justified considering that the estimated gap between predicted and “actual” performance is very high, 85% higher consumption in case of natural ventilation, and is thus highly likely to jeopardise compliance with the determined target and indirectly the “zero carbon” goal. Thus, revision of FEES recommendations is considered to be necessary, using good example of Passivhaus as guidance.

2. INTRODUCTION AND AIMS OF STUDY

Driven primarily by the issue of climate change, but also fuel poverty and energy security, in 2007 the UK proclaimed an ambitious plan of achieving new “zero carbon” housing from 2016 (Department for Communities and Local Government, 2007). It is considered that the UK is currently internationally leading by setting a “zero carbon” policy for residential buildings to be implemented in near future (ZCH, 2009). Originally it was believed that mitigating all CO2 emissions only by on-site renewables or by directly connected infrastructure would be achievable. However, in 2008 the Task Group appointed by UK-Green Building Council concluded that this would be physically unachievable in majority of cases (DCLG, 2008). Thus, the latest definition, which is the result of the Task Group recommendation is more complex and is based on a hierarchical approach to achieving “zero carbon” by (ZCH, 2009):

1. Ensuring an energy efficient approach to building design
2. Reducing CO2 emissions on-site via low and zero carbon (LZC) technologies and connected heat networks
3. Mitigating the remaining carbon emissions with a selection of Allowable Solutions

The basis of this hierarchy is energy efficient approach to building design which is based on passive measures only. This is defined within the Fabric Energy Efficiency Standard (FEES) which aims to limit heating and cooling demand to reasonable levels so that LZC technologies can be used in an efficient way and thus guarantee certain achievement of Carbon Compliance and consequently “zero carbon”. According to FEES maximal space heating and cooling energy demand should be (ZCH, 2009):

- 39 kWh/m^2/yr for apartments and mid terrace houses
- 46 kWh/m^2/yr for end of terrace, semi detached and detached houses

The standard does give recommendations regarding the levels of efficiency of building fabric needed for the compliance with aforementioned heating and cooling demand limit. However, these are not obligatory, as it is regarded that various combinations of building fabric properties can assure compliance.

Considering that FEE standard represents the first and basic step in the strategy to achieve Carbon Compliance and “zero carbon”, it is considered to be highly important that such basis is set right. However, although the Task Group that defined the FEES acknowledged there is currently a gap between design and actual performance, it was concluded that “only a design standard could be set at this time” (ZCH, 2009, p.11).

The building performance evaluation practice has shown that this gap between predicted or “design” and actual performance can be very big and that it partially originates from failures in detailing, building construction and in deterioration of building fabric and services (Wingfield, et al., 2009; Branco, et al., 2004; Clevenger, et al., 2007). However, it is established that occupant behaviour also contributes considerably and that its impact can be at least equally high as the effect of building’s physical properties (Vringer, 2005; Gram-Hanssen, et al., 2010). Considering that none of these aspects are taken into consideration when defining of FEES was carried out, it is regarded that resulting gap could be high enough to compromise the achievement of “zero carbon”. This concern is also reflected in final recommendations by Zero Carbon Hub which stress that "further work is urgently required to understand and narrow this gap" (ZCH, 2010, p. 11) and that it is of crucial importance to move the FEE standard towards actual rather than design performance.

On the other hand, German Passivhouse standard shows that high quality of building fabric, construction and detailing, together with use of MVHR can help reduce this discrepancy and allow for very low levels of energy consumption to be achieved in practice.

Thus, the aim of this study is to establish what could be expected to be a reasonable range of differences between design and actual performance of dwellings built to comply with FEES and Passivhaus, when both deterioration of building fabric and occupant behaviour are taken into consideration, and determine the implications of this gap on the compliance with these standards. Main aim is to determine whether this discrepancy is high enough to seriously compromise FEE standard and meeting heating and cooling demand limit and thus indirectly also the achievement of "zero carbon".

Furthermore, based on comparative analysis of FEES and Passivhaus standard, the intention is to establish whether significantly higher standard, more similar to Passivhaus would in reality be necessary to set adequate basis for the "zero carbon" future and accordingly give recommendations for revision of FEE standard.

3. LITERATURE REVIEW

3.1 Low energy housing regulations and standards

3.1.1 Defining Zero Carbon

The UK definition of the "zero carbon" has been changing continuously. The latest concept is more complex than original and is based on a hierarchical approach (Figure 1) to achieving "zero carbon" by:

1. Ensuring an energy efficient approach to building design
2. Reducing CO2 emissions on-site via low and zero carbon technologies and connected heat networks
3. Mitigating the remaining carbon emissions with a selection of Allowable Solutions
(ZCH, 2009)

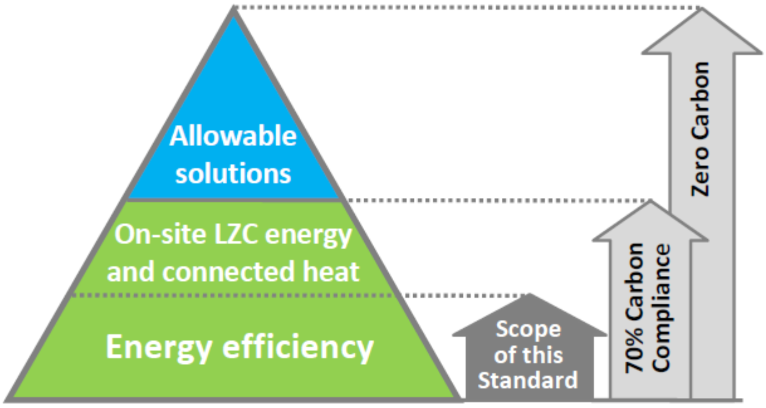


Figure 1- Zero carbon hierarchy (ZCH, 2009, p. 6)

Energy efficiency refers only to passive measures and is defined within the FEES which will be discussed in more detail later.

The Carbon Compliance level was initially set at a 70% reduction in regulated CO2 emissions compared to 2006 Building Regulations (ZCH, 2009). However, in the end of 2010, Zero Carbon Hub recommended that compliance should be expressed in absolute values rather than percentage, as such can be misleading (ZCH, 2010). Thus, minimum Carbon Compliance emission levels are determined to be (ZCH, 2010):

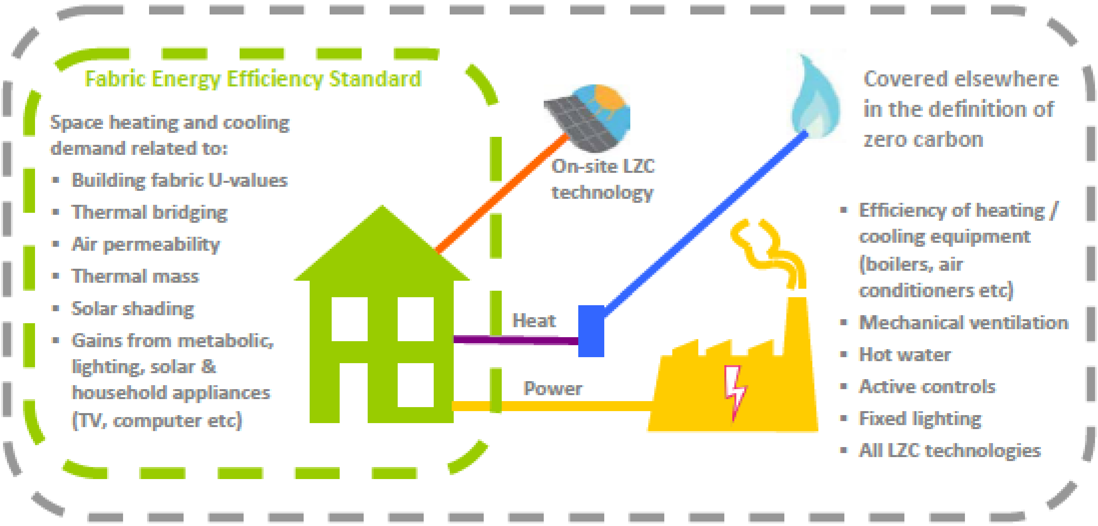
- 10 kg CO2(eq)/m^2/yr for detached homes
- 11 kg CO2(eq)/m^2/yr for terraced and semi-detached homes
- 14 kg CO2(eq)/m^2/yr for low rise flats

The final offsetting of remaining CO2 emissions is expected to be achieved through "allowable solutions". These are not yet completely defined, but will most probably be based on off-site solutions (ZCH, 2010).

3.1.2 Fabric Energy Efficiency Standard (FEES)

In order to ensure the feasibility of achievement of aforementioned "zero carbon" target, a specialist Task Group was set up to give recommendations for minimum fabric energy efficiency standard for future "zero carbon" dwellings. FEES is a performance standard which means that an overall energy performance is defined, rather than a selection of individual specifications. It is claimed that this results in greater flexibility in achieving the required performance through a variety of design solutions (ZCH, 2009). The scope of this standard focuses only on passive measures related to building fabric (Figure 2). Full implementation is expected in 2016.

Figure 2- Task group definition of the scope of the Fabric Energy Efficiency Standard (ZCH, 2009, p. 8)



Setting too high criteria which would demand application of Passivhaus standard was rejected because of the concerns related to the buildability of houses up to such specification by 2016. Finally, as a result of the SAP energy modelling and financial and technical analysis, maximal space heating and cooling energy demand was established to be (ZCH, 2009):

- 39 kWh/m2/yr for apartments and mid terrace houses
- 46 kWh/m2/yr for end of terrace, semi detached and detached houses

Figure 3- Examples of recommendations for construction specifications sufficient to meet the Fabric Energy Efficiency Standard (ZCH, 2009, p. 11)

	Dwelling type			
	4-storey apt. block	Mid terrace	End terrace / Semi	Detached
Target Fabric Energy Efficiency Standard (kWh/m²/yr)[f]	39	39	46	46
Wall U-value (W/m²K)	0.18	0.18	0.18	0.18
Floor U-value (W/m²K)	0.18	0.18	0.18	0.14
Roof U-value (W/m²K)	0.13	0.13	0.13	0.11
Window U-value (W/m²K)	1.4	1.4	1.4	1.3
Air permeability (m³/m²/hr @ 50Pa)	3	3	3	3
Thermal bridging y-value (W/m²K)	0.05	0.05	0.05	0.04

Even though use of MVHR has proven by modelling to result in lower heating demand, it is regarded that making it mandatory would limit design flexibility. Thus, recommendations for building fabric efficiency are considered to be high enough to guaranteed compliance with the limit regardless of the type of ventilation. Use of MVHR is expected to result in heating demand lower than 39/46 kWh/m2 limit and will be rewarded within the Carbon Compliance calculations.

3.1.3 Passivhouse standard

The Passivhouse is a rigorous, voluntary building standard conceived in Germany in 1988 as a result of collaboration between Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist, present director of the Passivhouse Institute (Feist, 2007).

It is based on the principle of primarily minimizing the heat loss through highly insulated, airtight and thermal bridging free construction. Heating demand is further minimized by means of passive solar heating and reduction of ventilative heat losses through use of mechanical ventilation with heat recovery (MVHR). As a result, heating demand is so low that the conventional heating system can be omitted and needed heat provided by pre-heating the air supplied by ventilation system.

In order to achieve Passivhaus certification, a building needs to meet three basic criteria (Feist, 2007):

- Specific Space Heat Demand max 15 kWh/m^2
- Entire Specific Primary Energy Demand max 120 kWh/m^2
- Pressurization Test Result max 0.6 h-1@50Pa

The building performance is assessed using Passivhaus Planning Package (PHPP).

3.2 Design versus actual performance

The building performance evaluation practice has shown that there often tends to be a significant gap between the predicted and actual building performance. Failures in detailing, building construction and deterioration of building fabric and services partially cause this discrepancy. However, many researchers have shown that this can be predominantly accounted for by complex nature of occupant behaviour, which can significantly affect the energy consumption (Hitchcock, 1993; Vringer, 2005; Gram-Hanssen, et al., 2010).

In the research about the effect of occupant behaviour by Guerra Santin, et al. (2009) it is concluded that:

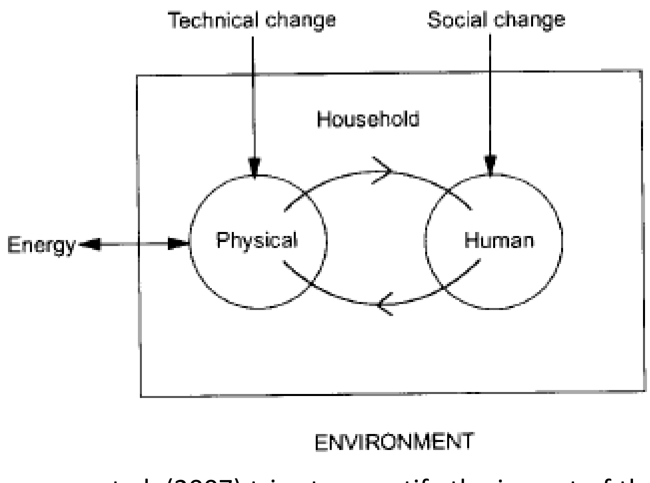
"The impact of the building's thermal characteristics on space heating demand has been well studied, quantified and validated. However there is little work that incorporates the impact of consumer behaviour. Studies have shown that occupant behaviour might play a prominent role in the variation in energy consumption in different households, but the extent of such influence is still unknown." Guerra Santin, et al. (2009, p.1)

Thus, the extent of the effect of these issues will further be analyzed in more detail, when possible separately on the UK and Passivhaus examples.

3.2.1 Occupant behaviour

Hitchcock (1993) emphasizes that the complex nature of domestic energy use is determined by two main aspects of the household: human and physical. He states that so far *"the engineering models describe only physical subsystem of the household system, whereas social models can only model the human subsystem and occupant behaviour"* (Hitchcock, 1993, p. 153). Due to the complexity and quantity of variables within these subsystems, it becomes obvious that purely engineering models will usually fail in precise energy predictions. Thus, Hitchcock stresses great importance of development of integrated energy model which would encompass both subsystems and thus give more reliable and realistic predictions of energy use.

Figure 4- Basic household system (Hitchcock, 1993, p. 3)



Research by Clevenger, et al. (2007) tries to quantify the impact of the uncertainties originating from the assumptions about the occupant behaviour on the predictions of domestic energy consumption. By testing a range of values for parameters which are expected to characterise the occupant behaviour, it is identified that the energy consumption changes by more than 150% compared to the base scenario representing a typical occupant (Clevenger, et al., 2007). Thus, it is suggested that “occupant files” similar to “weather files” should be created and used in simulations in order to, at least crudely, reflect significant variations in the profiles of use of buildings which in reality exist.

Research by Vringer (2005) showed that occupant behaviour can have the same scale of impact on energy consumption as mechanical parameters such as equipment and appliances, and can result in immense variations in energy consumption in dwellings with similar physical and mechanical properties (up to double).

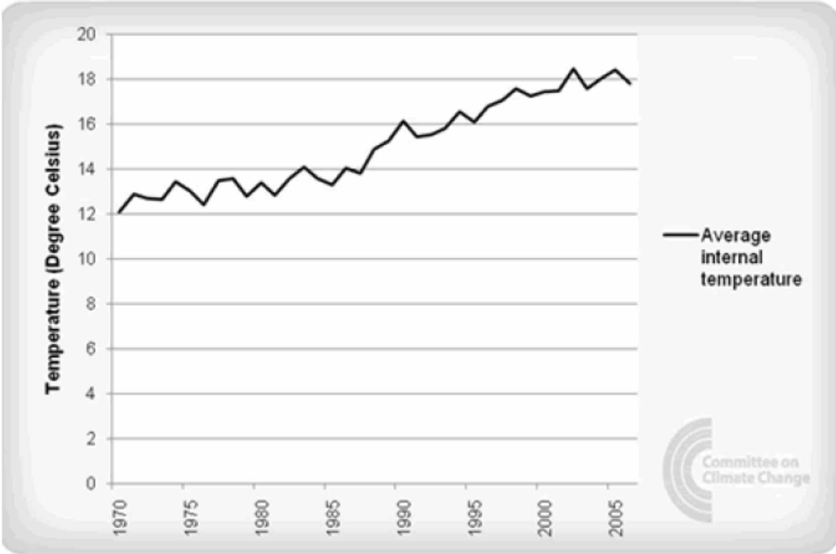
Research of Gram-Hanssen, et al. (2010) shows that some occupants can have even more than three times higher heating demand for their houses than their neighbours who live in the same type of dwelling, even when the building fabric is very energy efficient and robust. This is mainly caused my different thermostat settings and window opening behaviour. Furthermore, even if the energy consumption for heating and cooling is very low, occupant can use great amounts of energy for appliances.

3.2.1.1 Temperature set points

The World Health Organisation currently recommends main living area temperatures to be 21°C whereas for the rest of the home 18°C (DTI, 2002). There can of course be large differences in temperature set points between dwellings which can cause significant variations in heating demand. The range of these variations largely depends on the dwelling heat loss.

However, there seems to be widespread tendency of increase of temperatures in homes which is in some cases related to application of central heating but is also often caused by increase of dwelling energy efficiency and is in such case defined as “take back factor” or “rebound effect” (Longstreth and Topliff, 1990). There is much evidence from the building performance evaluation that supports this. Studies based on census survey data, carried out by Haas, et al. (1998) identified that in analysed Belgium dwellings after application of energy efficiency measures heating demand actually increased for 31% due increase of temperature set points. Similar study in Austria found that “rebound-effect” due to building retrofit varies from 1.5% to 30% (Guerra Santin, et al., 2009). In Switzerland, experimental study carried out over 3 years in multi-family buildings by Branco, et al. (2004), showed that the actual energy use was 50% higher than the estimated, primarily due to increased temperature set points.

Increase of energy consumption in the UK domestic sector in the 1970-2000 period was also largely caused by the increase of internal temperatures, from 13^{o}C in 1970 to 18^{o}C in 2000 (DTI, 2002). Even though it is expected that this increasing trend will stabilize, evidence from Germany indicates that average internal temperature in highly energy efficient passive houses is 22°C (Feist, et al., 2005). Based on national statistic data and results from various studies, Utley and Shorrock (2008) have estimated that the average internal temperature during winter months in the UK dwellings was 19.14°C in 2001 and that it is expected to stabilise at approximately 21°C with possible additional increase of 2 °C for well insulated homes.



Graph 1-Increase of average internal temperatures in the UK dwellings since 1970 (DTI, 2002, p. 54)

3.2.1.2 Window opening behavior

Range of ventilative losses due to different window use can be very high. Great discrepancies between predicted and actual building performance often occur because typical simulation tools cannot adequately predict occupant behaviour regarding window opening patterns. Attempts have been made to determine factors which influence window opening behaviour in order to be able to more reliably estimate opening patterns and thus the effect on heating energy consumption.

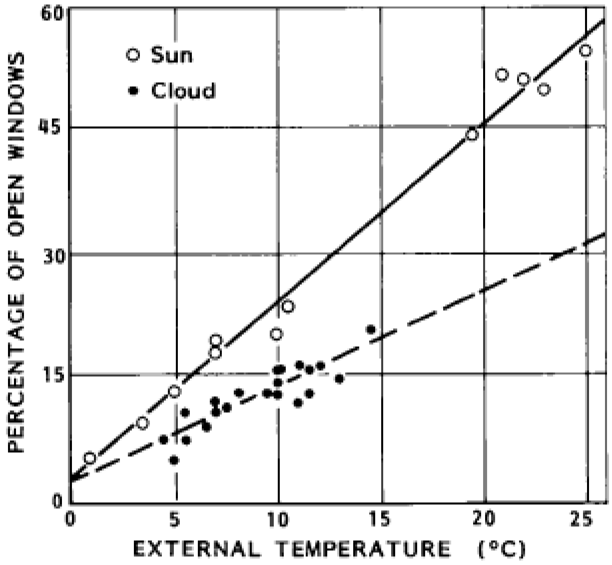
Main variables which affect the window opening behaviour are well known from the work of Air Infiltration and Ventilation Centre (AIVC) and since the 7th AlVC conference (Dubrul, 1988). These are summarised in the Table 1.

Table 1- Possible driving variables for window opening and closing (Fritsch, et al., 1991, p.1)

External variables	Internal variables	"Human" parameters
Outdoor temperature	Indoor temperature	Time of the day
Solar radiation	Odors	Type of day
Wind velocity	Contaminants	Type of building
Rain	Moisture	Habits
Noise		etc.
Odors and pollutants		

However, several researches have established that the most influential parameter is external temperature (Fritsch, et al., 1991).

A study carried out by AIVC (Dubrul, 1988), based on monitoring of dwellings in several EU countries including UK, established that there is a clear linear correlation between the area of window open and external temperature. Correlation however also varied depending on whether conditions were sunny or overcast. Furthermore, a study of Occupant Controlled Ventilation within UK Dwellings (Fox, 2008) resulted in very similar findings.



Graph 2-Window opening as a function of outdoor temperature and sunshine (Dubrul, 1988, p. 28)

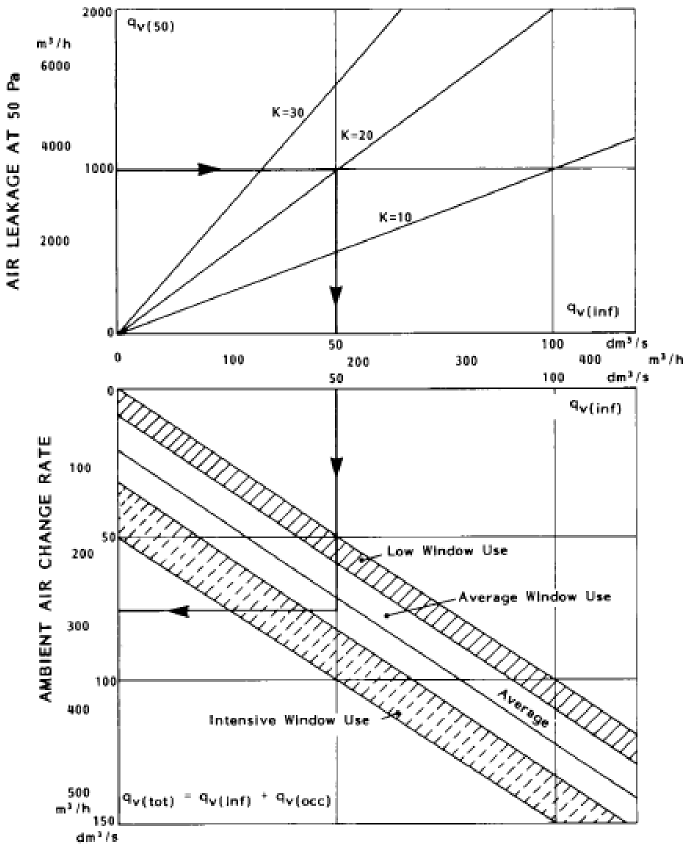
3.2.1.2.1 Estimating average winter ventilations rates due to window opening

As part of the research about Inhabitant Behaviour with Respect to Ventilation coordinated by AIVC, Kvinsgaard (1985) carried out measurements of increase in ventilation rates due to winter window opening in 25 Danish dwellings. Similar was done on Beligian social housing by Wouters (1986) and in Switzerland by Faist et al. (1988) (Table 2).

Table 2- Comparison of the results for Danish, Belgian and Swiss projects (Dubrul, 1988, p.35)

Source	Country	Description	n_{occ} (ach)
Kvisgard et al	Denmark	Single-family dwellings • naturally ventilated • mechanically ventilated	 0.32 0.34
Wouters and De Baets	Belgium	Single-family dwellings Apartments	0.31 0.21
Faist et al	Switzerland	Apartment	0.25

From these studies a normograph for determining typical heating season ventilation rate was constructed.



Graph 3- Normograph for determining typical heating season ventilation rates in dwellings (Dubrul, 1988, p.36)

Based on the nomograph, simplified categorisation of additional average seasonal ventilation rates due to window opening was suggested (Dubrul, 1988):

- Low window us: 0.0 to 0.1 ACH
- Average window use: 0.1 to 0.5 ACH
- High window use: 0.5 to 0.8 ACH

It is stressed that the value of 0.8 ACH is of course not the absolute maximum but that it is rarely exceeded.

3.2.1.2.2 The effect of winter window opening on heating demand

Based on aforementioned approximation of window use, corresponding increase of heat loss for dwellings with tree levels of insulation is calculated for the French and Belgium climatic region (Dubrul, 1988).

Table 3- Comparison of transmission and ventilation losses (Dubrul, 1988, p.41)

Average U-value (W/m²K)		Transmission losses (W/K)		Ventilation losses (W/K)		Ventilation losses as percentage of total losses (%)	
House	Apartment	House	Apartment	House	Apartment	House	Apartment
2.0	4.0	500	160	85	68	15	30
0.7	1.4	175	56	85	68	33	55
0.4	0.8	100	32	85	68	46	68

The percentage of ventilative heat loss as a percentage of total heat loss is summarised in Table 3. As expected, it is noticeable that importance of the ventilation heat loss compared to overall heat loss rises as the fabric energy efficiency increases. Thus, the percentage of heating energy demand due to window opening becomes very significant (Table 4, Table 5), indicating the importance of window opening behaviour particularly in low energy buildings.

Table 4- Percentage of total heating demand due to widow use in houses (Dubrul, 1988, p.43)

U (W/m²K)	T_i °C	Low window use	Average window use	High window use
2.0	17	2	5	11
0.7	18	6	15	28
0.4	19	9	23	40

Table 5- Percentage of total heating demand due to widow use in apartments (Dubrul, 1988, p.43)

U (W/m²K)	T_i °C	Low window use	Average window use	High window use
7.0	18	5	13	25
1.4	19	15	33	52
0.8	20	20	45	64

3.2.1.1 Use of appliances

Increase of use of appliances has a twofold effect on overall energy consumption, on the one hand by increasing electricity consumption and on the other reducing heating demand due to increase of internal gains.

In the UK, energy consumption by lighting and appliances increased for 157% in the 1970-2000 period, primarily due to increase of income (DTI, 2002). On the other hand, due to improvement of efficiency the pace of increase has lowered, resulting in annual average of 1.3% for appliances, in the 1990-2008 period (DTI, 2002). This increase also occurs due to the so called "snap-back effect" which is identified when as a result of applied energy efficiency programmes or use of more efficient appliances, occupants buy more of them (Goetschel, et al., 1995).

3.2.1 Building fabric deterioration

Heating energy consumption is highly dependent on building fabric heat loss. Furthermore, apart from ventilative heat losses through window opening, it is also influenced by uncontrollable losses through infiltration, which is also related to building fabric quality. Thus it is important to quantify, using the UK examples of relatively new, high quality homes built up to various high fabric efficiency standards, which level of difference between design and actual performance of the building fabric can be expected to occur in practice.

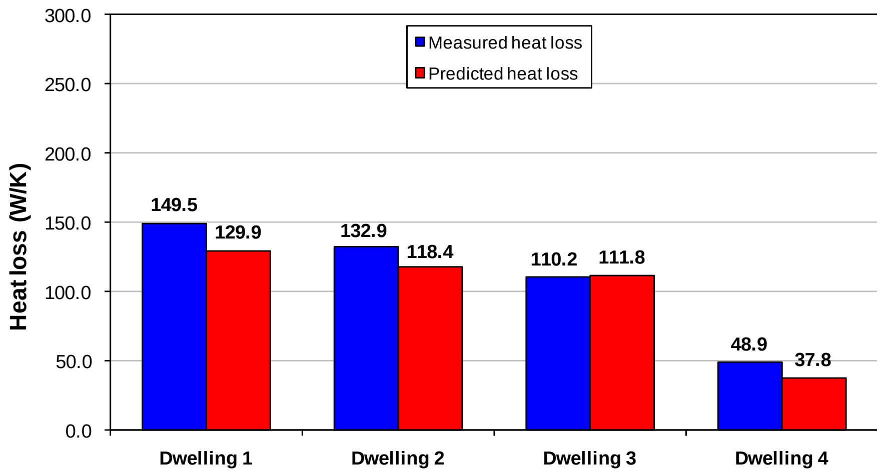
3.2.1.1 Heat loss

This gap is expected to occur primarily due to inadequate quality of building construction and materials, detailing and thus thermal bridging, as well as workmanship and deterioration of the construction through time.

The Good Home Alliance (GHA, in press) carried out monitoring of highly sustainable new homes, in order to determine the extent of difference between the predicted and actual performance. All houses were designed to achieve a whole house heat loss significantly better than the 2006 Part ADL1a building regulations, particularly dwelling 4. The analysed dwellings are built up to following high standards:

- Dwelling 1- Code for Sustainable Homes (CfSH) 4
- Dwelling 2- CfSH 4
- Dwelling 3- CfSH 5
- Dwelling 4- “Eco Homes Excellent” Post Construction Review rating

Results for the fabric heat loss indicate that the differences in predicted and measured values ranges from -2% to 42% (Table 6), with the greatest difference measured in the dwelling 4 which was designed to achieve exceptionally low level of heat loss (GHA, in press).



Graph 4- Measured versus predicted whole house heat loss (Johnston, 2011 cited in GHA, in press, p. 9)

Table 6- Difference between predicted and actual fabric heat loss (based on GHA, in press)

Dwelling	Predicted fabric heat loss coefficient (W/K)	Actual fabric heat loss coefficient (W/K)	% increase of fabric heat loss
1	102.5	122.1	19
2	102.7	117.2	14
3	100.7	99.1	-2
4	26.8	37.9	41

Furthermore, results of co-heating tests carried out in 16 dwellings built up to various low energy standards, including CfSH, EcoHomes, etc., carried out by Wingfield, et al. (2009), show more radical differences which reach even 120%. However, analysis showed that the big difference is to the great extent caused by unexpectedly high heat loss through the party wall, whereas it was originally assumed that such heat loss is minimal.

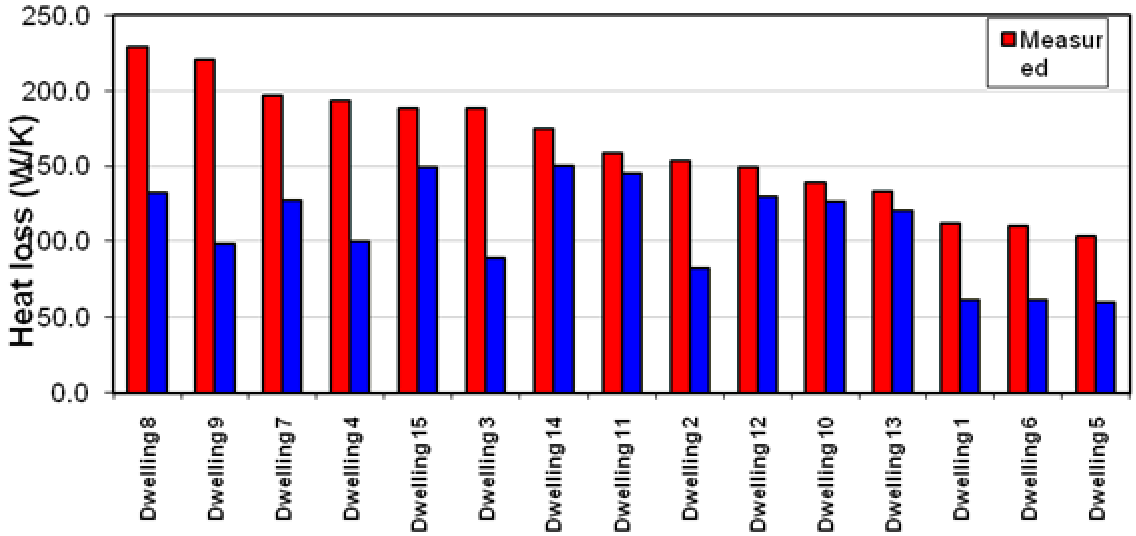


Figure 5- Measured and predicted whole house heat loss in 16 new low energy dwelling (Wingfield, et al., 2009, cited in GHA, in press, p. 25)

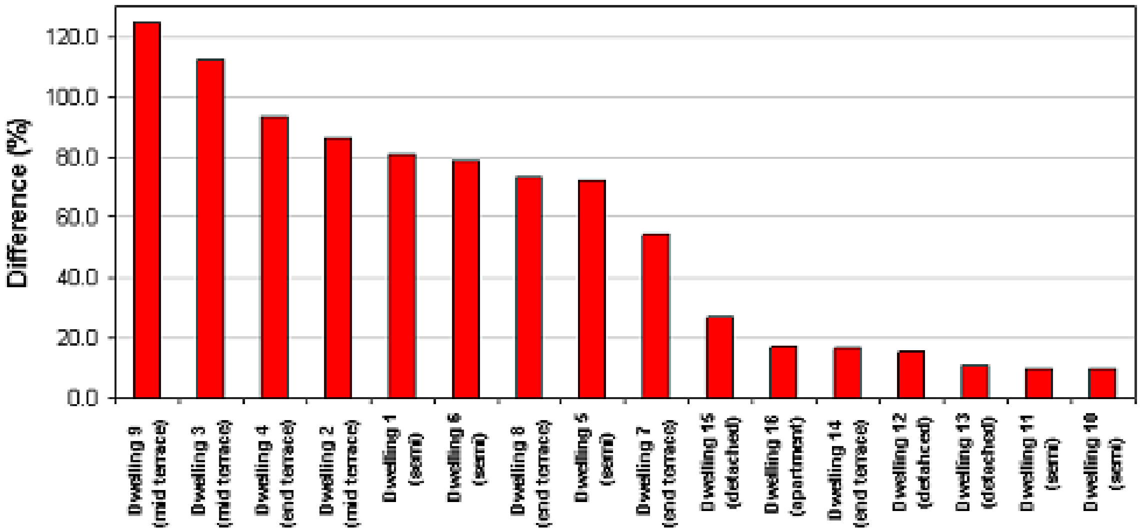


Figure 6- Difference (%) between measured and predicted whole house heat loss in 16 new low energy dwelling (Wingfield, et al., 2009, cited in GHA, in press, p. 24)

3.2.1.2 Air permeability

The difference in designed and measured air permeability is not only influenced by the workmanship and quality and precession of construction, which can ideally be controlled and improved so that mistakes are minimised. Various research (Wingfield, et al., 2007; Elmroth and Lodgberg, 1980) show that air leakage increases over time primarily due to cracks caused by drying out and settlement of the foundations and deterioration of materials which are factors that cannot be easily or at all controlled. This was also confirmed by research undertaken on samples of UK dwellings (Warren and Webb, 1980) which showed that increase of air leakage especially occurred during the first year, in the particular cases reaching up to 83% higher values. Furthermore air leakage can also be significantly increased by unpredictable penetrations of the air barrier by the building occupants.

Performance evaluation of the Elm Tree Mews housing which was designed as high-quality low carbon housing intended to reach 40% CO2 reductions compared to dwellings constructed to the 2006 Building Regulations, shows significant gap (Bell, et al., 2010). The original aspiration was to achieve 3 $m^3/h.m^2$@50Pa whereas mean measured air permeability was 7 $m^3/h.m^2$@50Pa (Bell, et al., 2010).

Furthermore, Wingfield, et al (2004) carried out a research on a small number of UK dwellings which were designed to achieve relatively low levels of air permeability for the UK standards of 5 $m^3/h.m^2$@50Pa. While in masonry dwellings (E, F and G) air permeability was relatively low due to the internal wet-plastered finish which acts as an air barrier, in timber framed dwellings (A, B, C, D) it ranged from 7.64 to 9.45 $m^3/h.m^2$@50Pa., which was significantly above the 5 $m^3/h.m^2$@50Pa target (Table 7).

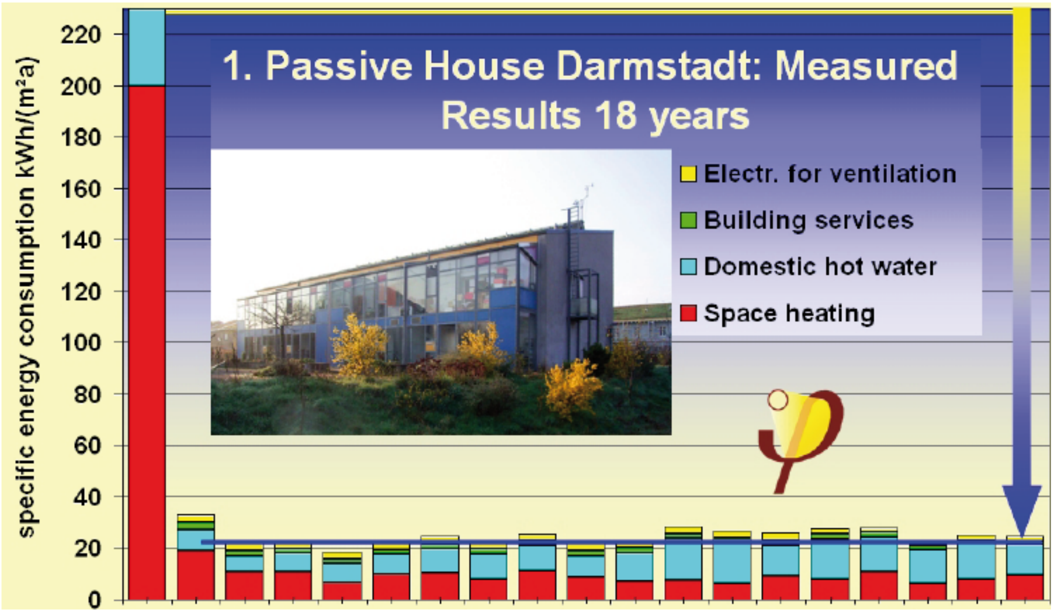
Table 7- Air permeability results for the UK dwellings analysed in research by Wingfield, et al (2004, p. 6)

Dwelling	Pressurisation Test ($m^3/h.m^2$)	Depressurisation Test ($m^3/h.m^2$)	Mean ($m^3/h.m^2$)
A	7.64	7.42	7.53
B	8.58	8.14	8.36
C	9.45	9.46	9.46
D	7.95	7.69	7.82
E	6.71	6.30	6.51
F	4.92	4.64	4.78
G	3.81	3.78	3.80

On the other hand, evaluation of the actual performance of 44 dwellings within the Stamford Brook, development which were designed according to the Environmental Performance Standard (EPS08) which is up to 15% in advance of the 2006 Building Regulations, showed that air permeability was on average lower than the EPS requirement, 4.45 m3/(h.m2)@50Pa compared to 5 $m^3/(h.m^2)$@50Pa target (Wingfield, et al., 2009).

3.2.2 Passivhouse performance

The first Passivhaus built in Darmstadt Kranichstein 19 years ago has been constantly monitored and has always had very low energy consumption (Graph 5) (Feist, 2007).



Graph 5- Energy consumption of the first Passivhaus in Darmstadt Kranichstein over the last 18 years (Feist, 2007, p.3)

Another study by Feist, et al. (2005) which compared the performance of dwellings built up to Low Energy Houses (LEH) standard and Passivhaus standard in Kronsberg, Germany also showed that Passivhaus dwellings are performing very well. LEH is less strict standard than Passivhaus, which sets the heating demand limit to 50 kWh/m^2 (Feist, et al., 2005). The study shows that variations in energy consumption due to occupant behaviour are significantly smaller in Passivhaus dwellings. It is estimated that in the LEH houses, increase of heating demand due to ventilative losses and window opening behaviour ranges from 20 to 100 kWh/m^2, whereas maximal increase in the Passivhaus dwelling is only 17 kWh/m^2. Furthermore, increase of temperature set points for 1K causes increase in heating demand of 7-11 kWh/m^2 in the LEH houses, and only 1.7 kWh/m^2 in Passivahaus dwellings. Finally, it was concluded that the effect of occupant behaviour in analysed Passivhaus dwellings is on average relatively negligible, considering that the average heating demand is 16 kWh/m^2, which is only 1 kWh/m^2 higher that the limit.

Furthermore, research about the impact of user behaviour carried out on two dormitories built up to Passivhaus standard in Austria and Germany, showed that maximal increase of space heating demand, due to occupant behaviour is 18% (Engelmann, et al., 2008). This was caused primarily by increased temperature set points (mean 23.3°C compared to design 20°C) and window opening behaviour. Even though the percentage might seem high, the absolute value of approximately 5 kWh/m^{2}a is actually quite small.

Table 8-Average heating load and standard deviation for the Low Energy Houses and Passivhaus estate in Kronsberg (Feist, et al., 2005, p. 79)

Project (data including summer heating)	Estimate for the expected value μ: Average heating consumption (complete year) in kWh/(m²a))	Estimate for the standard deviation σ of the associated distribution: gauge for the range of individual values conditional on the occupants in kWh/(m²a)
Low Energy Houses Kronsberg, 1999/2000	64,8	±42,5 (65%)
Passive Houses Hannover-Kronsberg 1999/2000	16,0	±6,7 (42%)

Higher variations in heating demand are however noted in Passivhaus dwellings analysed within the CEPHEUS project (Cost Efficient Passive Houses as European Standards) which evaluated the performance of 221 dwellings in 14 Passivhaus buildings in five EU countries (Graph 6) (Schnieders, 2003). It was established that the gap was not caused by deteriorations of building fabric. Air tightness measurements showed that most of them are performing very well, with only couple of exceptions (Table 9) demonstrating that very low levels of air permeability are achievable for all types of constructions and also on a large, mass scale. However, very precise details have show to be the key (Schnieders, 2003).

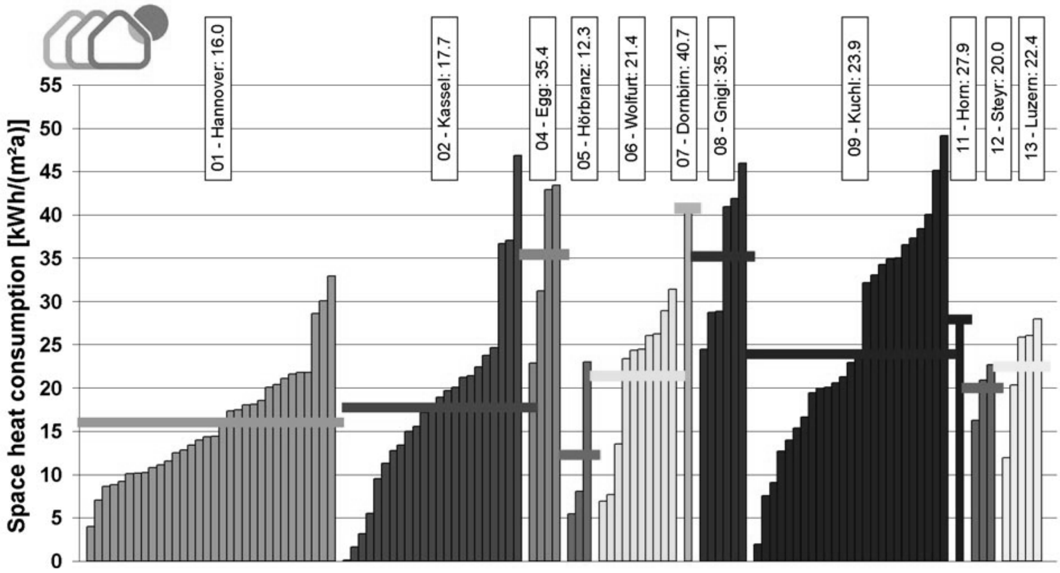
Table 9-Measured building leakage for the CEPHEUS projects as built (Schnieders, 2003, p. 344)

Project	01-Hannover	02-Kassel	03-Gothenburg	04-Egg	05-Hörbranz	06-Wolfurt	07-Dornbirn	08-Gnigl	09-Kuchl	10-Hallein	11-Horn	12-Steyr	13-Luzern	14-Rennes
Construction type	mixed	solid	timber	solid	solid	mixed	timber	timber	mixed	mixed	mixed	solid	timber	mixed
Mean n_{50} / h^{-1}	0,30	0,35	0,31	0,51	0,47	0,33	1,1	0,97	2,2*	0,58	0,61	1,6**	0,57	11**

* In 09-Kuchl, a large internal leakage is probably the reason for the high n_{50}-value.

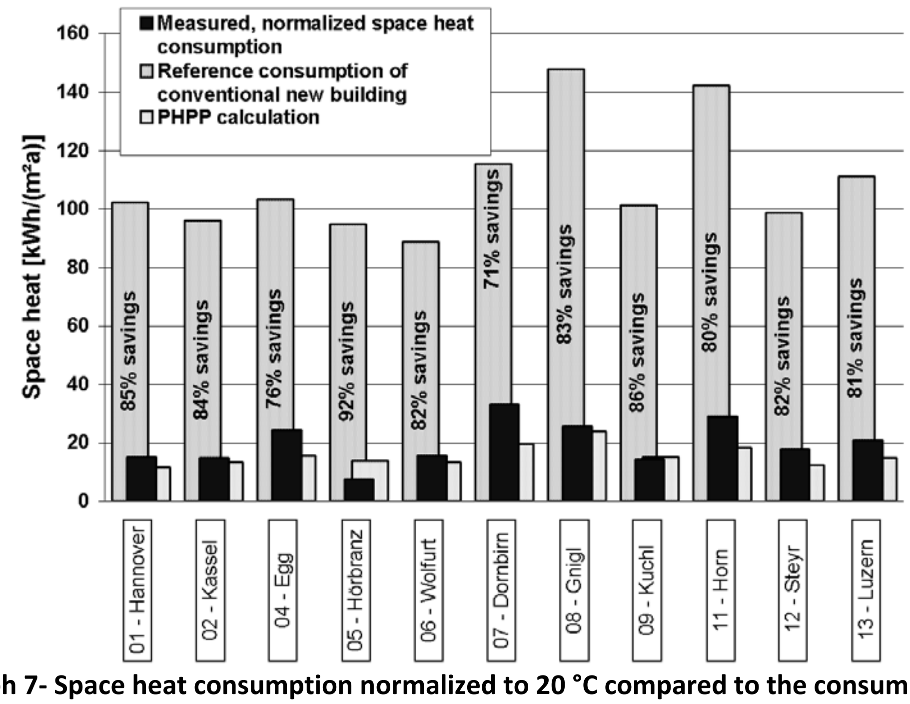
** For these projects, only values from preliminary airtightness measurements were available at the time of analysis. In the meantime, remedial work has been carried out; however, new measurement results are not available.

It was however, determined that variations in heating demand are primarily caused by wide range of temperature settings. Average internal temperature was measured to be 21.4°C, compared to design value of 20°C. However, regardless of such variations, average heating demand is still very low-20 kWh/m^2. Moreover, higher consumption in noted primarily in unoccupied or newly occupied dwellings, which additionally accounts for discrepancies.



Graph 6- Measured space heat consumption of CEPHEUS buildings (for every project mean is displayed as a horizontal bar) (Schnieders, 2003, p. 345)

After normalising the measured energy consumption for the difference in assumed and real temperatures, energy performance showed to be very similar to one predicted by PHPP (Graph 7).



Graph 7- Space heat consumption normalized to 20 °C compared to the consumption of conventional new buildings and to the values calculated by PHPP (Schnieders, 2003, p. 346)

Further research by Feist (2007) shows that average internal temperature in highly energy efficient Passive houses is 22°C and indicates that this tends to be dominant cause of discrepancy between design and actual heating demand, considering that predictions by PHPP are based on assumption of 20^{0}C. However, compared to other low energy dwellings, variations in Passive houses are significantly smaller (Feist, 2007).

On the other hand research about occupant behaviour in Passivhauses by Ebel (2003) as well as Reis and Erhorrn (2003) showed that due to use of MVHR, window use is on average minimal indicating that discrepancies between predicted and actual heating demand due to window opening should not be high.

3.3 Summary

The UK building practice shows that even in the case of new low energy dwellings significant discrepancies still exist between the design and as-built quality of the building fabric. Furthermore, occupant behaviour contributes considerably to increase of the gap between predicted and actual performance. General tendency of increase of temperatures in highly efficient dwellings has significant effect on increase of heating demand. However, in Passive houses this effect is considerably smaller due to reduced fabric heat loss. Furthermore, importance and effect of window opening behaviour in low energy dwelling becomes proportionally higher considering that fabric loss is significantly reduced, unless window use is reduced due to use of MVHR.

Thus, it becomes clear that, without seriously talking into consideration the occupant behaviour and potential deterioration of building fabric in energy modelling which forms the basis for determination of FEES, potential of significant underestimation of real energy use and failure on the road to “zero carbon” is very possible.

4. CASE STUDY RANULF ROAD PASSIVHAUS- DESIGN VERSUS ACTUAL PERFORMANCE

Ranaulf Road is the first certified Passivhaus in London, designed by Bere Architects, with estimated annual heating demand of 13.4 kWh/m^2.

It is two-storey, detached house with lightweight wooden structure. It has extensive high performance triple glazing on the main facade with S-W orientation and highly insulated and airtight envelope. These characteristics, together with use of highly efficient (90%) MVHR enable such low levels heating demand. The house does not have a conventional heating system and heating is achieved primary through heat recovery, and additionally if needed by preheating the air.

As such it is part of the Technology Strategy Board (TSB) monitoring scheme, which aims to aid closing the gap between design and actual performance. A series of tests are carried out in order to make sure that the actual performance meets the design intentions.

4.1 Airtightness

Results of the blower door test indicate that the Passivhaus limit of 0.6ACH@50Pa is met with 0.44 ACH@50Pa (Stamp, 2011). Additional test based on the CO_2 decay method confirmed those results giving 0.38 ±0.08 ACH@50Pa (Stamp, 2011). Thus, in terms of airtightness, house is performing as it is designed.

Table 10- Design and actual infiltration

	INFILTRATION (ACH@50Pa)
DESIGN TARGET	
Passivhaus limit	0.6
ACTUAL PERFROMANCE	
Blower door test	0.44
CO2 decay test	0.38 ±0.08

4.2 Co-heating test

Total heat loss coefficient of the house, incorporating both fabric and infiltration losses, is estimated by PHPP to be 63.6 W/K. Co-heating test carried out by Stamp (2011) gives significantly lower results- the overall heat loss was estimated to be 35 ± 15 W/K. When infiltration losses are taken out of the overall heat loss, resulting fabric heat loss coefficient is only 33.4 ± 12 W/K.

Even though, due to short duration of the test as well as atypically high temperatures during the monitoring period these results incorporate great deal of uncertainty, considering that they are significantly lower than those estimated by PHPP, they should indicate that the house is at least not performing worse than predicted.

Table 11- Heat loss coefficients

	TOTAL HEAT LOSS COEFFICIENT (W/K)
PHPP as designed	63.6
Co-heating test	35+-15

4.3 Appliances consumption and internal gains

As part of the TSB monitoring, detailed metering of the electricity consumption is carried out.

When metabolic heat gains are taken into consideration, this results in overall average internal heat gains of approximately 3.9 W/m^2 which is significantly higher than PHPP assumed 2.1 W/m^2, indicating that heating demand would be overestimated by PHPP.

Table 12- Metered electricity consumption and corresponding heat gains

	ELECTRICITY CONSMUPTION (W/m2)
Lights	0.84
Sockets	1.45
Hob	0.02
Oven	0.00
Auxiliary	1.00
TOTAL GAINS FROM ELECTRICITY CONSUMPTION*	**3.31**
TOTAL GAINS (including metabolic)*	**3.92**

*only electricity that is consumed within the thermal envelope is considered and thus MVHR and blinds are excluded

**for estimation of metabolic gains refer to Appendix (Table 63)

4.4 The BUS survey

The BUS survey conducted with one out of two members of the household gives information about the occupant behaviour. The temperatures are usually kept in the 20-22^{0}C range during winter, which is higher than the PHPP assumed 20^{0}C. The occupant shows understanding of the principles of MVHR and importance of minimisation of natural ventilation which is almost not used at all during winter period. Thus, such behaviour shows to be in line with typical behaviour of Passivhaus occupant.

5. METHODOLOGY

Considering that the research question is related only to houses that will be built in the future, from 2016, estimating characteristic of various examples of new dwelling was considered to be arbitrary. Thus, newly built, first certified Passivhaus in London is chosen as an adequate example, representative in terms of form, style and construction of those to be built in near future.

Recommendations for FEES, which is expected to form the basis for delivering “zero carbon” housing, are based on steady state modelling in SAP which cannot take into consideration all aspects of occupant behaviour. Thus, dynamic thermal modelling is necessary and TAS is considered as a more adequate tool.

First of all the base model of the house is constructed in TAS. This is explained in more detail in section 5.1. In order to be able to answer the research question, the analysis is carried out both on the model of the original house which complies with the Passivhaus standard, and on the model of the same house with applied FEES recommended specification (Table 17, Table 18).

Based predominantly on the literature review, parameters which largely contribute to the gap between design and actual performance are determined to be:

Building fabric

- Increase of fabric heat loss
- Thermal bridging*
- Increase of air permeability

Occupants

- Variation in temperature settings
- Window opening behaviour
- Variation in use of appliances
- Variation in occupant density and family structure (Appendix, section 11.1.2)

*Thermal bridging is separately analysed as one of typical reasons of increase of fabric heat loss

Subsequently, realistic range of values is determined for each of these parameters (section 5.2), predominantly based on the analysed case studies.

Next step is to carry out a sensitivity analysis of the variations in heating demand due to determined variations in aforementioned parameters which in reality influence the dwelling performance.

It needs to be stressed that FEES determined 39/46 kWh/m^2 to be annual limit for heating and cooling demand together. However, considering that the case study house does not have cooling system, as well as that the Energy Saving Trust Housing Energy Model which is used to predict probable future scenarios of energy consumption in the UK domestic sector assumes that cooling is not used (DTI, 2002), only heating load is taken into consideration. Heating demand is expressed on the annual basis.

Considering that the UK building practice shows that the gap between design and actual performance is more often caused by multiple factors (Bell, et al., 2010; Wingfield, et al., 2004) the final step is to create reasonable scenarios of more realistic dwelling performance by combining the effect of the individual parameters. Typical values for selected parameters are defined later on (chapter 6.3.1, 6.3.2) as their choice depends partially on their impact on heating demand and thus on the results of sensitivity analysis. Based on these scenarios "actual" performance of FEES and Passivhaus standard is examined and compared and ultimately it is determine whether compliance with FEES heating demand limit can on average be realistically expected.

Finally, based on results, recommendations for improvement of FEES are given.

5.1 Base models

Considering that the Passivhaus certification of the case study house was based on the PHPP model, calibration of the PHPP and TAS inputs is carried out in order to make them comparable.

5.1.1 Climate file/data

For TAS modelling CIBSE London TRY weather file is used. This climate data does not correspond completely to London climate data used in PHPP. Thus, adjusted set of climate data based on the average monthly temperatures and average monthly incident solar radiation from CIBSE TRY was created and used in PHPP.

Table 13- Incident solar radiation from CIBSE London TRY weather file used for PHPP climate data

Incident solar radiation kWh/(m^2 month)												
Orientation	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
North	7.9	13	23.8	34	48.5	57.4	52	41.5	28.4	18	18	5.8
East	11.3	18.5	35.1	53	65.9	80.3	71.8	62.9	46.1	27.6	27.6	8.5
South	32.4	38.3	57.6	64.5	69.8	73.2	71.9	72.2	69.6	53.6	53.6	26.7
West	15.5	23.1	45.3	58.3	78.7	89.8	84.9	75.8	53.1	35	35	11
Global	23	33	68	101	137	145	141	122	86	52	26	15

Table 14- Average monthly ambient temperature from CIBSE London TRY weather file used for PHPP climate data

Average monthly ambient temperature (^{0}C)											
Jan	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
6.2	6.3	7.1	8.7	12.3	16	18.5	17.9	15.1	11.8	8.7	6.2

5.1.2 Geometry

3D TAS model of the house was created, based on the architectural drawings (refer to Appendix, section 11.4) and checked to correspond with PHPP.

Due to the planning height restrictions part of the ground floor is dug into the ground. This is simulated in TAS by zones which have the thermostat set to temperatures which correspond to average seasonal ground temperatures from PHPP.

Table 15- Ground temperature in PHPP

Ground Temperature	T (^{0}C)
for Heat Load Sheet	12.9
for Cooling Load Sheet	16

Table 16-Ground temperature from PHPP used in TAS during corresponding periods

Period*	T (^{0}C)
Heating	12.9
No heating	16

*refer to Table 21 for definition of heating and no heating periods

5.1.3 Building fabric

The main difference between the two standards are the U-values, air permeability and thermal bridging. For the PH model, real materials (refer to Appendix, section 11.3.1) with corresponding design U-values and measured air permeability are used (Table 17). Thermal bridging which is in PHPP defined separately is incorporated within the U-values in TAS.

Table 17-Building fabric properties of the case study Passivhaus

<table>
<tr><td rowspan="10">U-values</td><td rowspan="10">W/m^{2}K</td><td rowspan="2">Wall</td><td>lower (WL)</td><td>0.12</td></tr>
<tr><td>upper (WU)</td><td>0.11</td></tr>
<tr><td>Floor</td><td></td><td>0.1</td></tr>
<tr><td rowspan="2">Roof</td><td>flat (RF)</td><td>0.067</td></tr>
<tr><td>sloping (RS)</td><td>0.11</td></tr>
<tr><td rowspan="5">Window/door *</td><td>balcony door 1 (BD1)</td><td>0.73</td></tr>
<tr><td>balcony door 2 (BD2)</td><td>0.79</td></tr>
<tr><td>entrance door (ED)</td><td>0.81</td></tr>
<tr><td>window 1 (W1)</td><td>0.93</td></tr>
<tr><td>window 2 (W2)</td><td>0.89</td></tr>
<tr><td rowspan="2">Air permeability</td><td>m^3/h.m^2@50Pa</td><td colspan="3">0.27</td></tr>
<tr><td>ACH@50Pa</td><td colspan="3">0.44</td></tr>
</table>

* window/door U-values with incorporated thermal bridging; thermal bridging of the rest of the construction on average minimal (refer to the Appendix, section 11.3.2)

For the FEES model, same type of construction and materials are used, but with different U-values, thermal bridging and air permeability which correspond to FEES recommendations for detached house (Table 18).

Table 18-FEES recommendations for the building fabric properties for a detached house (ZCH, 2009)

U-values*	W/m^2K	Wall	0.18
		Floor	0.14
		Roof	0.11
		Window	1.3
Air permeability	$m^3/m^2/hr@50Pa$		3
	ACH@50Pa		4.9
Thermal bridging**	W/m^2K		0.04

* without thermal bridging
**added to the U-values for TAS simulations

5.1.4 TAS zoning and internal conditions

Spaces are zoned according to their use.

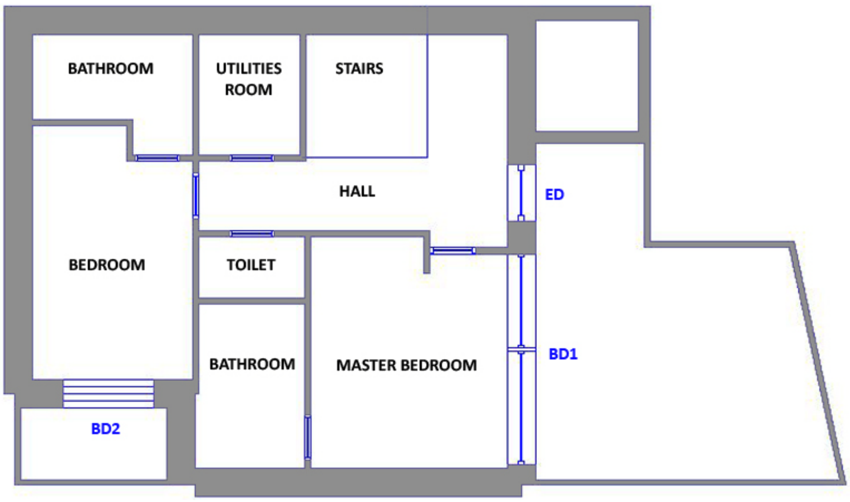


Figure 7-TAS zoning- ground floor (with marked different window types)

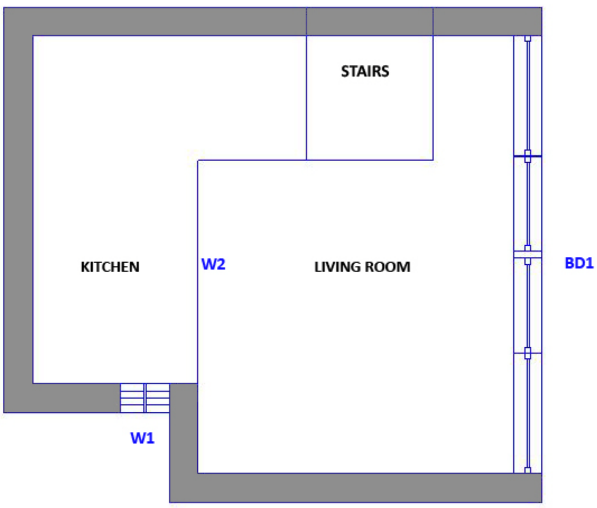


Figure 8-TAS zoning- first floor (with marked different window types)

Standard average internal heat gain value for dwellings of 2.1 Wh/m2, which is used for PHPP and Passivhaus certification (Feist, 2007) is also applied in TAS, in all zones.

Passivhaus (PH) model is considered to have MVHR with 90% efficiency, which corresponds to the case study house. Heat recovery is modelled in TAS by reducing the ventilation rate for the corresponding percentage of the efficiency of heat recovery during winter. Ventilation rate was taken as the standard rate from PHPP with 0.4 ACH. In zones which have only extract no ventilation is applied (Table 22).

Considering that use of MVHR is not considered within the scope of FEE standard, initial FEES base model has natural ventilation which is simulated by constant ventilation rate of 0.3 ACH which corresponds to average window use according to AIVC classification (Dubrul, 1988). Ventilation rate of zero is applied only in enclosed zones without openings (IC4, Table 20, Table 22, Figure 7).

In both TAS models thermostat is during heating period set to 20^{0}C in all zones, which corresponds to temperature settings in PHPP. Based on monitoring of low energy dwellings which indicate a tendency of equalisation of temperatures in leaving and sleeping areas (Feist, 2007) it is assumed that temperatures are distributed evenly within the space.

Table 19- Internal conditions for TAS for PH base model -zones with inlet (IC1) and zones with only extract (IC2)

	Internal conditions 1 (IC1)	Internal conditions 2 (IC2)
Infiltration (Table 17)	0.44 ACH@50Pa	0.44 ACH@50Pa
Ventilation rate (MVJR)	0.4 ACH	0 ACH
TAS ventilation rate (90% heat recovery)	0.04 ACH	0 ACH
Heat gains	2.1 W/m^2	2.1 W/m^2
Heating period thermostat settings	20 ^{0}C	20 ^{0}C

Table 20- Internal conditions for TAS for initial FEES base model

	Internal conditions 3 (IC3)	Internal conditions 4 (IC4)
Infiltration (Table 18)	4.9 ACH@50Pa	4.9 ACH@50Pa
TAS ventilation rate	0.3 ACH	0 ACH
Heat gains	2.1 W/m^2	2.1 W/m^2
Heating period thermostat settings	20 ^{0}C	20 ^{0}C

Table 21- Heating and no heating period

	Period	Thermostat (^{0}C)
Heating*	1.10.-3.3.	20
No heating	4.3.-30.9.	/

*length of the heating period in TAS and PHPP are equal

Table 22- TAS zones with corresponding internal conditions

Zones	Base model internal conditions	
	PH	FEES
Master bedroom	IC1	IC3
Bedroom		
Living room		
Kitchen		
Hall		
Stairs		
Bathroom/toilets	IC2	IC4
Utilities room		

5.2 Defining the range of values for sensitivity analysis

5.2.1 Occupant behaviour

5.2.1.1 Temperature settings

Monitoring of low energy dwellings indicates a tendency of equalisation of temperatures in leaving and sleeping areas (Feist, 2007) and thus uniform temperature setting is used. Wide range of thermostat settings is tested in order to estimate the magnitude of the effect of such change. It is considered to be unreasonable that during the heating period temperatures would be outside 18-25^{0}C range. However, within this range, most typical values are considered to be:

- 18 °C as average temperature in UK dwellings in 2000 (DTI, 2002)
- 21 °C as WHO recommended main living area temperature and estimated future stabilisation temperature in the UK after a steady increase (Utley and Shorrock, 2008)
- 22 °C as average internal temperature in passive houses in Germany (Feist, et al., 2005)
- 23 °C as estimated potential stabilisation temperature in the UK after a steady increase for highly insulated homes (Utley and Shorrock, 2008)

5.2.1.1 Window opening behaviour

Considering that simulation of the window opening behaviour is a complex issue, three different approaches are considered. These are simulations of window use based on:

- Ventilation rate
- Correlation of window opening and external temperature (Appendix, section 11.1.1.1)
- Window opening area needed for IAQ (Appendix, section 11.1.1.2)

Approximation of window opening behaviour by corresponding average winter ventilation rate is based on extensive research carried out by Air Infiltration and Ventilation Centre (AIVC) in 1988 on several EU countries including UK about inhabitant behaviour with respect to ventilation (Dubrul, 1988).

Different windows use intensities are approximated by corresponding ranges of air change rates (ACH) (Table 23).

Table 23- Average window ventilation rates due to window use (based on Dubrul, 1988)

WINDOW USE	ACH
Low	0-0.1
Average	0.1-0.5
High	0.5-0.8

Table 24- Expected range of window use for FEES and PH house

<table>
<tr><th colspan="2">WINDOW USE</th></tr>
<tr><th>FEES</th><th>PH</th></tr>
<tr><td>Low</td><td rowspan="3">Low</td></tr>
<tr><td>Average</td></tr>
<tr><td>High</td></tr>
</table>

The whole range of values from 0 to 0.8 ACH is tested in order to estimate the range of corresponding heating demand. However, considering that research shows that window opening in Passivhauses is due to use of MVHR on average minimal (Ebel, 2003; Reis and Erhorrn, 2003, Feist, 2007), it will be considered that this corresponds to low window use (0.1ACH) from AIVC classification and that higher window use is atypical (Table 24).

5.2.1.2 Appliances, lighting and auxiliary electricity

Considering that heat gains based on results of energy consumption metering of the case study house as well as PHPP and SAP estimates for corresponding household size are all different, three scenarios will be examined. It is considered that these scenarios reflect different intensity of appliances use.

First scenario is based on very moderate PHPP assumptions (Feist, 2005) of appliances use. Highest efficiencies are assumed. Other scenario is based on SAP estimations of use of appliances for corresponding household size (SAP, 2005). These are significantly higher. In between those two are the monitoring results from the case study house (refer to the Appendix, Table 62, Table 63). Thus, it can be considered that these typical values correspond to three different intensities of appliances and other electricity use within house, PHPP representing low use and SAP high.

Table 25- Average overall heat gains for different appliances use scenarios

APPLIANCES USE SCENARIOS	SOURCE	OVERALL AVERAGE HEAT GAIN** (W/m^2)
Low	**PHPP**	2.1
Medium	**Monitored***	3.9
High	**SAP**	5.6

*Results of metered energy consumption were obtained in the end of work on dissertation and could thus not be used for the base case

** Metabolic heat gains are included; number of people is constant in all of the scenarios and corresponds to the real occupancy of two

5.2.2 Building fabric deterioration

5.2.2.1 Fabric heat loss

For estimation of potential realistic increase of fabric heat loss, values based on discrepancies between design and actual performance of the UK low energy dwellings are used. They are based on results of GHA monitoring of 4 highly energy efficient homes and results for 16 co-heating tests carried out by Wingfield, et al. (2009), on dwellings built up to various low energy standards (Table 26).

Table 26- Percentage of fabric heat loss increase* in dwellings analysed by Wingfield, et al. (2009) and GHA dwellings (GHA, in press)

Wingfield, et al. (2009)	
DWELLING	% INCREASE OF HEAT LOSS **
1	122
2	112
3	92
4	88
5	81
6	79
7	72
8	71
9	52
10	28
11	18
12	18
13	29
14	10
15	9
16	9
Mean	56
Std. dev.	38.6
Mean+2std. dev.	146

GHA (GHA, in press)	
DWELLING	% INCREASE OF FABRIC HEAT LOSS
1	19
2	14
3	-2
4	41
Mean	18
Std. dev.	17.8
Mean+2std. dev.	60

* Increase of fabric heat loss is simulated by the increased U-values (refer to the Appendix, Table 65, Table 66)
** Even though results from 16 dwellings include infiltration losses, actual air permeability of analysed dwellings is on average better than predicted and thus total increase of heat loss can be attributed to increase of fabric heat loss

From each set of results two typical values are used. These are:

- Mean
- Mean ± 2.33 std.dev.

Assuming that the distribution is normal, 99% of the cases should fall within mean±2.33std.dev. Thus mean+2.33std.dev is considered to be maximal possible value.

Considering that "maximal" value for GHA results is approximately the same as mean of other set of results, only 60% deterioration will be tested.

Two sets of results are intentionally not merged to produce only one set of mean and extreme values considering that Wingfield, et al. (2009) monitoring data are not completely regular and representative. This is due to the fact that a very big discrepancy between design and actual fabric heat loss is partially caused by underestimation of heat loss through the party walls. Thus, GHA values will be considered as values that are more probable to occur, whereas others as more extreme ones.

Table 27- Estimated typical values for percentage of increase of heat loss

		% INCREASE OF HEAT LOSS	
	No. of samples	**Mean**	**Mean±2.33 std.dev.**
GHA	4	18	60
Stamford Brook	15	56	146

5.2.2.2 Thermal bridging

It is considered that if the construction details match with the UK Accredited Construction Details, the thermal bridging y-value should be approximately 0.08 W/m^2K (SAP, 2005). If this is not the case and no particular attention is paid to detailing, the y-value is typically not expected to be higher than 0.15 W/m^2K (SAP, 2005). However, if any attention is paid to detailing, it is considered that with the FEES design y-value of 0.04 W/m^2K, thermal bridging in reality is highly unlikely to exceed 0.12 W/m^2K. Considering that for the Passivhaus design target is almost thermal bridge free construction and thus great attention is paid to detailing, y-value of 0.08 W/m^2K is considered as the worst case scenario. Thus 0.04-0.12 W/m^2K range is tested.

5.2.2.3 Air permeability

A wide range of different air permeability values is tested in order to determine the magnitude of the effect of its increase. The values range from 0.25 $m^3/h.m^2$@50Pa (0.4 ACH@50Pa) which approximately corresponds to the measured value of the case study house, up to 10 $m^3/h.m^2$@50Pa which is a limiting value for new dwellings according to Building Regulations Part L1 (2010).

However, in order to be able to estimate what can be considered as a reasonable realistic discrepancy between designed and actual air permeability, examples of relatively new UK energy efficient housing are used. These include:

- Stamford Brook low energy dwellings (Wingfield, et al., 2009)
- Elm Tree Mews designed as high-quality low carbon housing intended to reach 40% CO2 reductions compared to dwellings constructed to the 2006 Building Regulations (Bell et al., 2010)
- the UK dwellings which were designed to achieve relatively low levels of air permeability for the UK standards of 5 m3/h.m2 @ 50Pa analysed in the research by Wingfield, et al. (2009)

Differences between design and actual permeability in analysed groups of dwellings are summarised in the Table 28.

Table 28- The difference between design and actual permeability in analysed low energy dwellings

		AIR PERMEABILITY ($m^3/h.m^2$@50Pa)		MEAN % OF INCREASE OF AIR PERMEABILITY
	no. of dwellings	design target	measured mean	
Elm Tree Mews	/	3	7.01	134%
Stamford Brook	44	5	4.45	-11%
Wingfield et al.	7	5	6.89	38%

From these results three typical values are used:

- Mean of the mean percentages of increase
- Mean of the mean percentages of increase + 1 std.dev. of the mean percentages of increase

For determination of the maximal allowed air permeability in Building Regulations Part L1 (2010), safety margin of 1 standard deviation of the measured tested dwellings is used as a representative of discrepancy between design and actual values. Furthermore, if the distribution is normal, 68% of cases should fall within ±1 standard deviation.

- Mean of the mean percentages of increase + 2.33 std.dev. of the mean percentages of increase

This value is taken as an absolute maximum considering that for assumed normal distribution 99% of the values fall within ±2.33 standard deviations from the mean.

Table 29- Estimated typical values for percentage of increase of air permeability with corresponding air permeability

	INCREASE OF AIR PERMEABILITY	AIR PERMEABILITY ($m^3/h.m^2$@50Pa)	
		FEES	PH
BASE	/	3.00	0.25
MEAN	54%	4.6	0.4
MEAN+1 STD.DEV.	127%	6.8	0.6
MEAN+2.33 STD.DEV.	225%	9.7	0.8

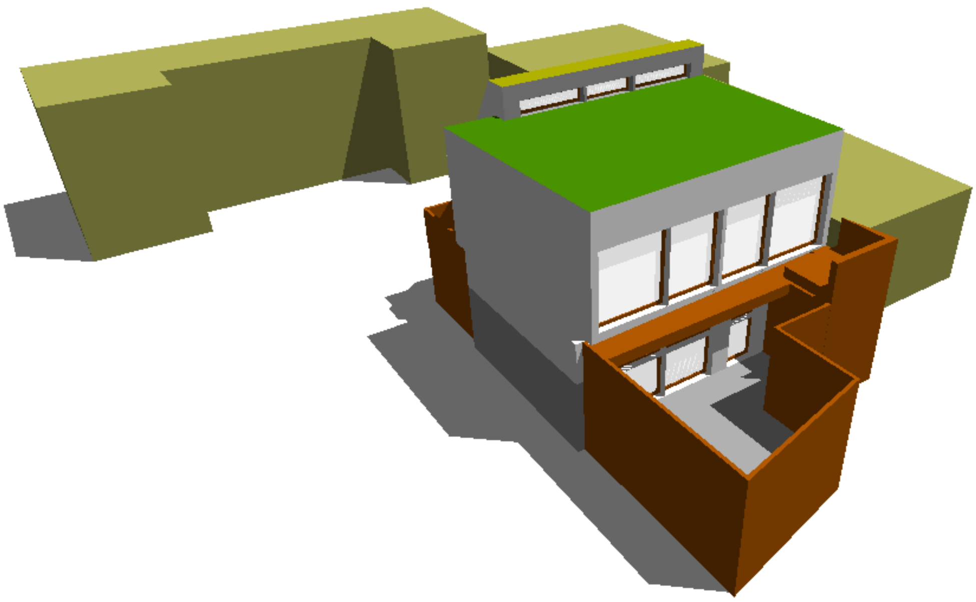
Instead of these exact values, the closest round values for air permeably of FEES house (5, 7 and 10 $m^3/h.m^2$@50Pa) will be used for sensitivity analysis.

6. RESULTS AND ANALYSIS

6.1 Base model

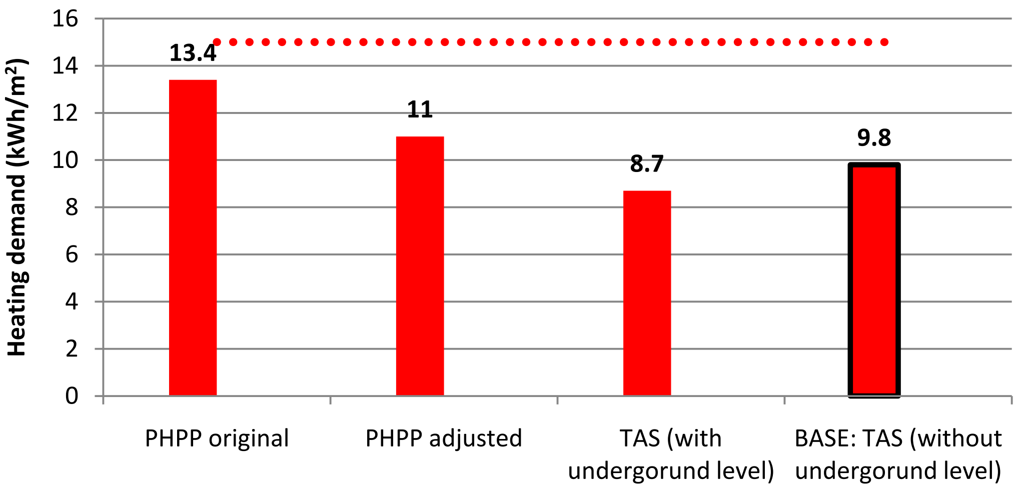
The original PHPP estimated space heating demand is 13.4 kWh/m^2. When inputs are adjusted so that TAS and PHPP match as much as possible, corresponding heating demand estimated by PHPP is 11 kWh/m^2, whereas by TAS 8.7 kWh/m^2. Considering that these two tools are based on significantly different principles, such difference is regarded as reasonable and not too high.

Figure 9- TAS 3D of the base model



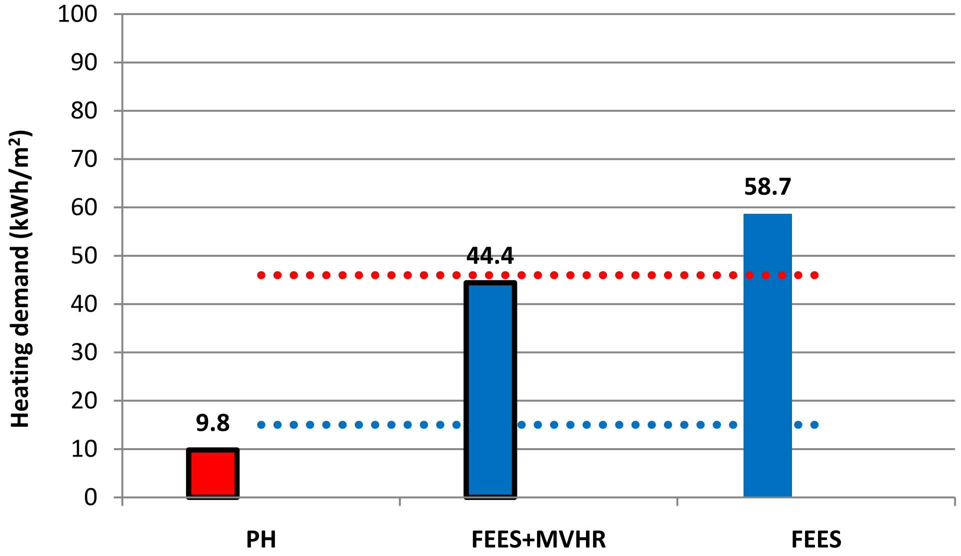
However, as it is considered that underground level is a feature that is not typical of an average house, it is removed so that the results could be more representative of general housing stock. This gives the final base model of the case study Passivhaus (PH) with the corresponding heating demand of 9.8kWh/m2 which still complies with the Passivhaus standard.

Graph 8- Calibration of the PHPP and TAS model of the Passivhaus (PH)



Heating demand of initial FEES base model with natural ventilation is significantly higher (58.7 kWh/m^2). Even though according to FEE standard, recommendations for fabric efficiency should be sufficient for compliance in case of NV, this is not the case. Thus, considering that use of MVHR proves to be necessary for compliance it will be included in the final FEES base case resulting in heating demand of 44.4 kWh/m^2 (Graph 9). Implications of use of NV will be separately analysed and discussed.

Graph 9- PHPP and FEES base model heating demand



*in all following graphs showing heating demand of FEES and PH models:
- the base models are be marked with black border
-FEES heating demand limit of 46 kWh/m^2 is marked with red dashed line

6.2 Sensitivity analysis

6.2.1 Occupant behaviour

6.2.1.1 Temperature settings

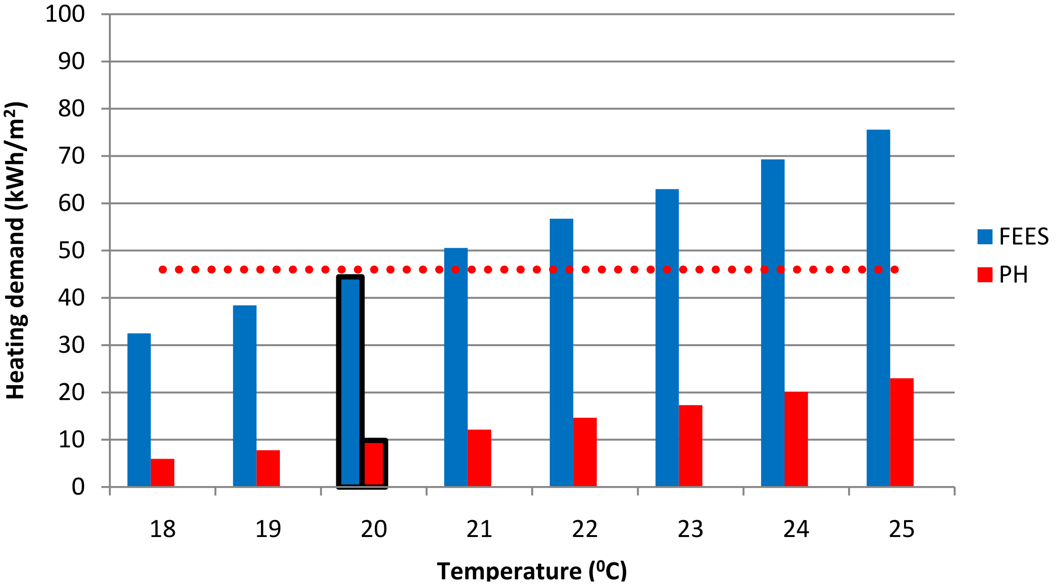
Simulation results indicate that if temperature setting increases from the base 20^{0}C for only 1^{0}C, to 21^{0}C which is advised by WHO as the optimal temperature in living areas (Utley and Shorrock, 2008), heating demand of the FEES house increases for 6.2kWh/m^2 thus already exceeding 46kWh/m^2 limit (Table 30), compared to only 2.2kWh/m^2 increase in PH model.

If temperatures are set to 23^{0}C, which is predicted to be most probable temperature in future highly energy efficient houses in the UK (Utley and Shorrock, 2008), heating demand for FEES house goes to 63kWh/m^2 compared to only 17.3kWh/m^2 for PH house, which in such case only slightly exceeds the Passivhaus limit of 15kWh/m^2.

Table 30- Heating demand of FEES and PH models for corresponding thermostats settings

T (^{0}C)	HEATING DEMAND (kWh/m^2)	
	FEES	PH
18	32.5	5.9
19	38.4	7.8
20 (BASE)	44.4	9.9
21	50.6	12.1
22	56.8	14.6
23	63.0	17.3
24	69.3	20.1
25	75.6	23.0

Graph 10- Effect of thermostat settings on heating demand of FEES and PH house



6.2.1.2 Window opening behaviour

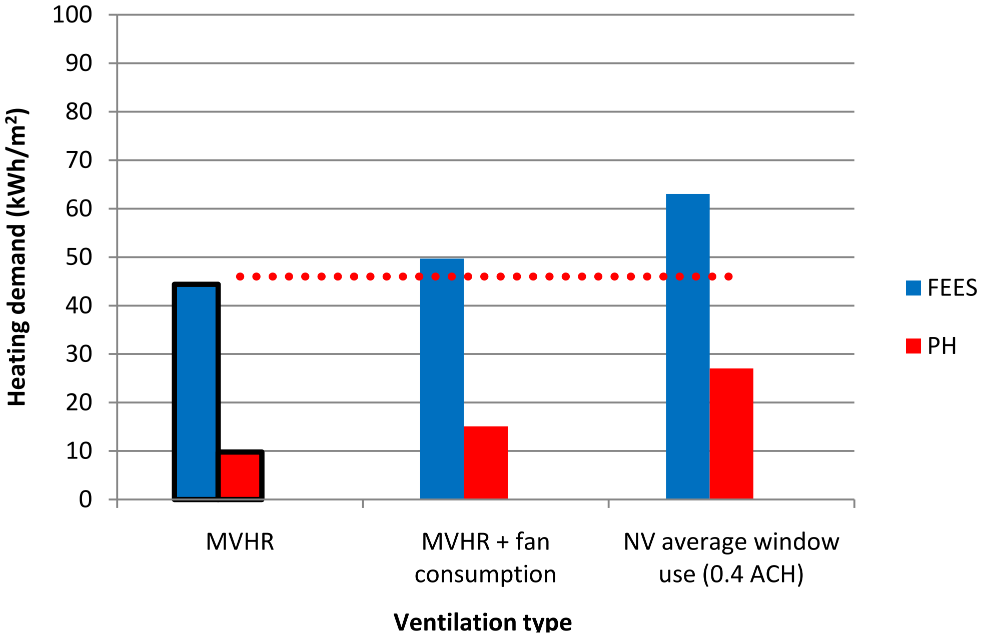
First of all, speaking of ventilation, it needs to be taken into consideration that in the heating load of the base case, energy consumption of the MVHR unit is not taken into consideration. Even though it can be argued that mechanical ventilation energy consumption should be considered separately, heat recovery does represent basic mean of heating the house and it does cause slightly higher energy consumption of the MV unit due to higher specific fan power needed in case of implemented heat recovery. Thus, if this additional energy consumption is taken into consideration (Table 31) base case heating demand increases for 5.3 kWh/m2 which results in slight exceedance of both FEES and Passivhaus heating demand limit (Table 32).

Table 31- Energy use by MVHR (referred to as fan consumption)

APPLICATION	ENERGY DEMAND* (kW/m2)
Winter mechanical ventilation	3.7
Defroster HX	1.6
TOTAL	**5.3**

*source PHPP

Graph 11- Comparison of MVHR ventilation with natural ventilation with the same effective ventilation rate of 0.4ACH



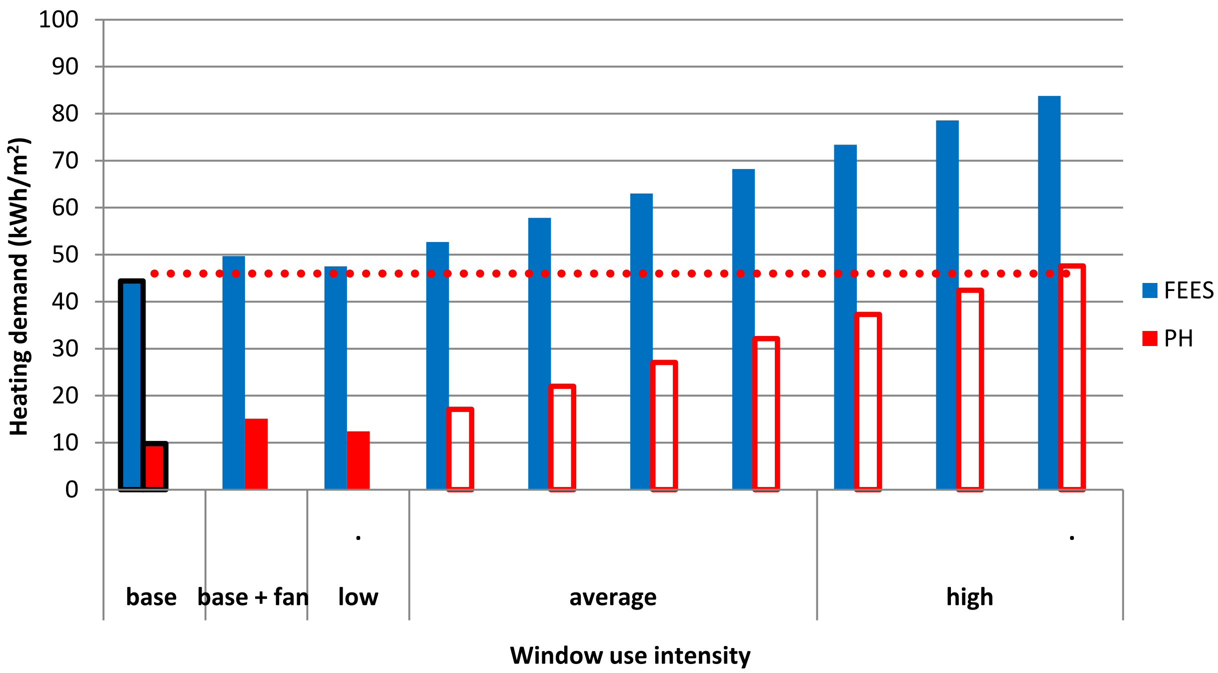
Further comparison of MVHR and natural ventilation indicates that only in case of low window use (ACH=0.1), heating load is lower than in case of MVHR with included fan consumption. However, even in such case of natural ventilation, heating demand of the FEES house model still exceeds the limit of 46 kWh/m^2 (Table 32). Moreover, with such air change rates IAQ would not be satisfactory. For any more intensive window use, corresponding heating load would be higher than in case of MVHR (Graph 12).

Table 32- Heating demand of FEES and PH models for corresponding window use scenarios

		ACH	HEATING DEMAND (kWh/m^2)	
			FEES	PH
MVHR	BASE	0.4	44.4	9.8
	BASE +MVHR consumption	0.4	49.7	15.1
NV window use	low	0.1	47.5	12.4
	average	0.2	52.7	17.1
		0.3	57.8	22.0
		0.4	63.0	27.1
		0.5	68.2	32.2
	high	0.6	73.4	37.3
		0.7	78.6	42.4
		0.8	83.8	47.6

In case of average window use with corresponding ACH of 0.4, heating load is almost 20 kWh/m^2 higher than in the base case where same ventilation rate is provided by MVHR (Graph 11). In case of the most intensive window use heating load almost doubles compared to the MVHR base case.

Graph 12- Effect of different window use intensities on heating demand



*bars without the fill just show the trend but are not considered to be realistic cases of deterioration

If MVHR was not used in the Passivhaus, ventilative losses due to window opening would cause approximately the same increase of heating demand as in FEES house. However, according to various research (Ebel, 2003; Reis and Erhorrn, 2003, Feist, 2007) window use in Passive houses in on average minimal and is thus estimated to cause less than 3kWh/m^2 increase of heating load (Graph 12) (low window use, 0.1 ACH).

Considering that simulations of window opening behaviour based on other two approaches gave similar results to the aforementioned, these are summarised in Appendix (section 11.1.1.1 and 11.1.1.2).

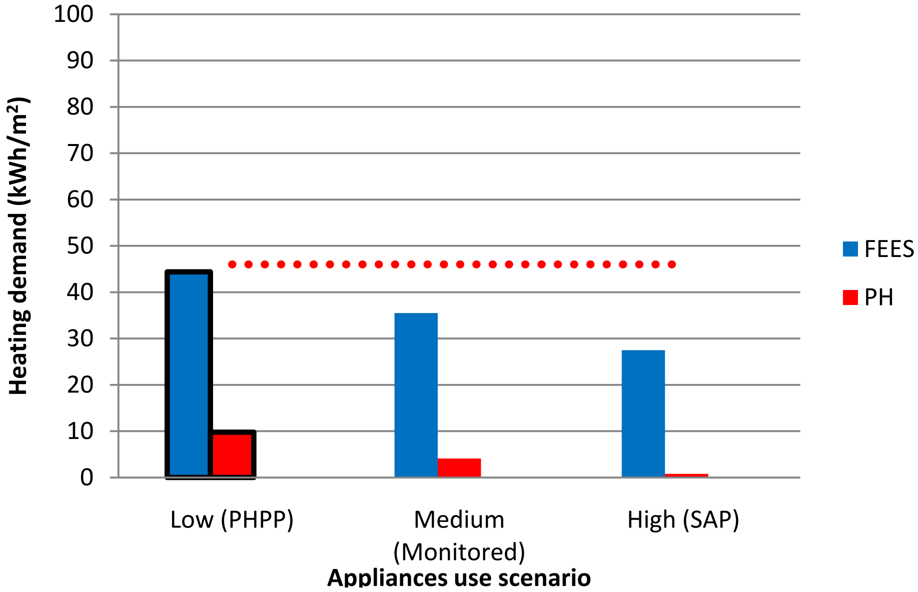
6.2.1.3 Appliances, lighting and auxiliary electricity

Considering that the base case was based on the most moderate PHPP estimation of appliances use, the base model is one with the highest heating demand (Graph 13). In case of the "medium" appliances use scenario and actual heat gains of the case study house (Table 33), heating demand of the FEES model is approximately 10kWh/m^2 lower. In case of the of the highest SAP estimate of appliance use, heat gains are so high that the heating demand in PH house is basically negligible.

Table 33- Heating demand for corresponding appliances use scenarios

APPLIANCES USE SCENARIOS	INTERNAL HEAT GAIN (W/m^2)	HEATING LOAD (kWh/m^2)	
		FEES	PH
Low	**PHPP (2.1)**	44.4	9.8
Medium	**Monitored (3.9)**	35.5	4.1
High	**SAP (5.6)**	27.5	0.8

Graph 13- Effect of different appliances use scenarios on heating demand



6.2.2 Building fabric deterioration

6.2.2.1 Fabric heat loss

Simulation results indicate that even for the most modest prediction of average heat loss increase (MEAN_GHA), FEES house is underperforming as it exceeds the heating demand limit of 46 kWh/m^2. Conversely, for the same increase in the PH house case, heating demand is still lower than the Passivhaus limit. Only for the most extreme estimated increase of heat loss (MAX_W) PH house reaches the same level of performance as FEES house without deterioration (Graph 14).

Graph 14- Effect of heat loss increase on the heating demand

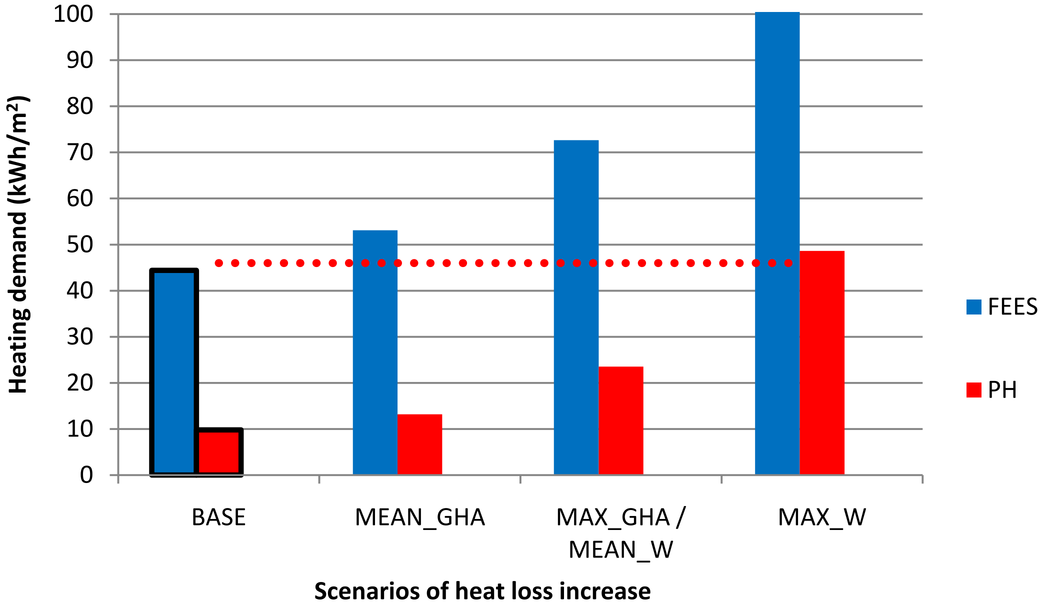


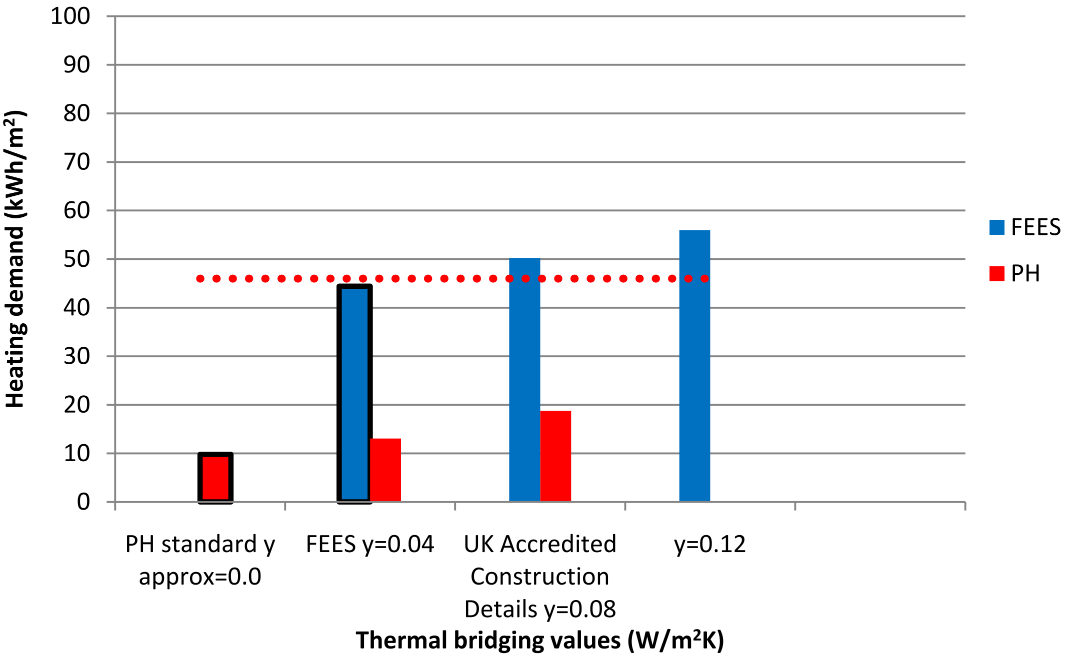
Table 34- Heating demand for FEES and PH house for corresponding estimated typical values for percentage of increase of heat loss

	% INCREASE OF HEAT LOSS	HEATING DEMAND (kWh/m^2)	
		FEES	PH
BASE	0%	44.4	9.8
MEAN_GHA	18%	53.1	13.2
MAX_GHA / MEAN_W	60%	72.7	23.5
MAX_W	146%	100.5	48.6

6.2.2.2 Thermal bridging

In case of FEES house model, again only slightly higher actual thermal bridging would be sufficient to exceed the heating demand limit whereas for the worst estimated deterioration with y=0.12 W/m^2K it would exceed the limit for 20%.

Graph 15-FEES and PH house model heating demand for range of thermal bridging values



On the other hand, if in the PH house, thermal bridging goes up to 0.04 W/m^2K Passivhaus compliance would still not be compromised (Table 35).

Table 35- Heating demand of FEES and PH models for corresponding thermal bridging values

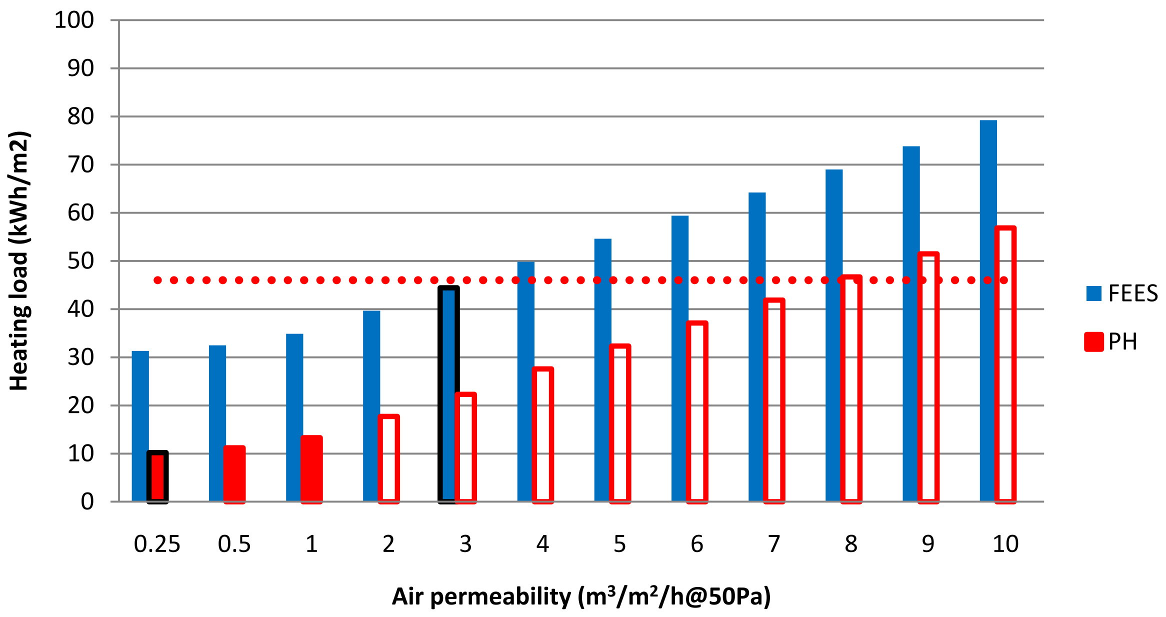
THERMAL BRIDGING (W/m^2K)	HEATING DEMAND (kWh/m^2)	
	PH	FEES
BASE	**9.8**	**44.4**
0.04	13.1	44.4
0.08	18.8	50.2
0.12	/	56.0

In the worst case scenario with y=0.08 W/m^2K, even though heating demand would almost double to 18.8 kWh/m^2, Passivhaus limit would not be significantly exceeded, and house would still be performing very well.

6.2.2.3 Air permeability

Results indicate that even for a relatively small difference between design and actual value and increase of air permeability from 3 to 4 $m^3/h.m^2$@50Pa, heating demand would already exceed the FEES limit (Table 36). In case of estimated mean increase to 5 $m^3/h.m^2$@50Pa, heating demand would increase for 10 kWh/m^2. In what was estimated to be most extreme "realistic" case of discrepancy with approximate air permeability of 10 $m^3/h.m^2$@50Pa, which also corresponds to current Building Regulations maximum, heating demand would significantly escalate to 79.2kWh/m^2 exceeding the limit for approximately 70%. The effect of estimated possible increase of air permeability in the FEES house is thus very high as in the "worse" case it can result in up to 35kWh/m^2 higher demand than the base case.

Graph 16- Effect of air permeability on heating demand of FEES and PH house



*bars without the fill just show the trend but are not considered to be realistic cases of deterioration

On the other hand, PH model is very robust to such increase due to its very low initial airpermeability. Even for the estimated "worse case" increase, corresponding air permeability would be less than 1 $m^3/h.m^2$ @50Pa (Table 29). Even if the air permeability reached 1 $m^3/h.m^2$@50Pa, which is highly unlikely, heating load would increase for only 4 kWh/m2 compared to the base case, and would still be very low, achieving the Passivhaus compliance.

Table 36- Tested air permeability values with corresponding heating demand of FEES and PH house model

TYPICAL VALUES	AIR PERMEABILITY ($m^3/h.m^2$@50Pa)	HEATING DEMAND (kWh/m^2)	
		FEES	PH
PH BASE	**0.25**	**31.3**	**9.8**
	0.5	32.5	11.2
	1	34.9	13.3
	2	39.6	17.7
FEES BASE	**3**	**44.4**	22.3
	4	49.8	27.6
FEES MEAN INCREASE	**5**	**54.6**	32.3
	6	59.4	37.1
FEES MEAN+1 STD.DEV	**7**	**64.2**	41.9
	8	69.0	46.7
	9	73.8	51.5
FEES MEAN+2.33 STD.DEV (BUILDING REGULATIONS)	**10**	**79.2**	**56.9**

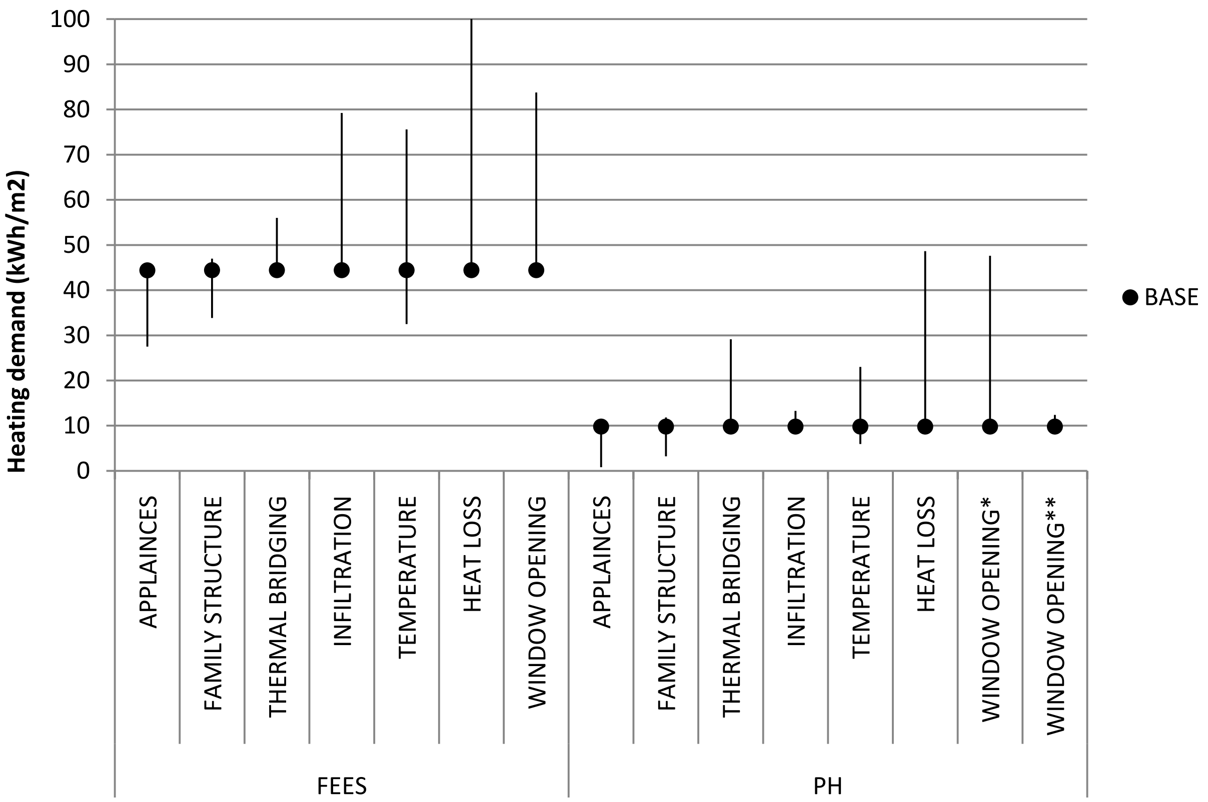
6.3 Final scenarios

In order to fully answer the research question it is necessary to estimate the combined effect of previously analysed parameters.

Table 37- All parameters used for sensitivity analysis

CATEGORY	PARAMETER
Building fabric deterioration	Fabric heat loss
	Thermal bridging
	Air permeability
Occupant (behaviour)	Temperature settings
	Window opening
	Use of appliances
	Occupant density and family structure (Appendix, section 11.1.2)

Graph 17 –Heating demand variations for all tested individual parameters



*Effect of window opening behaviour in case MVHR was not used- not realistic for Passivhaus standard
**Estimated effect on window opening together with MVHR (based on results of research (Ebel, 2003; Reis and Erhorrn, 2003, Feist, 2007) which indicates minimal window use in Passivhauses due to use of MVHR)

6.3.1 Choice of varying parameters

Some parameters will be excluded from the final scenarios due to reasons summarised in Table 38.

Table 38- Parameters excluded from the final scenarios

PARAMETER	CRITERIA
Thermal bridging	accounted for within the increase of overall fabric heat loss
Occupant density and family structure*	2 occupants most representative of the UK family size (national average 2.31 (Beaumont, 2011))
Use of appliances**	on the road to “zero carbon” reduction of use of appliances should be one of the aims, thus variation of heat gains due to increased appliances consumption will be excluded

*Appenidx, section 11.1.2
** the range of the effect of such variations is further analysed in the Appendix, section 11.2.1

Finally, scenarios are separated in two types, one with use of MVHR and the other with natural ventilation, so that final comparison of these two ventilation types can be carried out and importance of MVHR discussed.

6.3.2 Typical values for scenario construction

From the range of values used in sensitivity analysis, two sets of new values are chosen (Table 39):

- MEDIUM values - expected to be occurring more often in reality
- HIGH values- more extreme ones, in terms of causing higher energy consumption

Table 39- The range of tested values for selected parameters with marked MEDIUM and HIGH values

	BASE	RANGE OF TESTED VALUES							
TEMPERATURE (^{0}C)	20	18	19	20	21	22	23	24	25
WINDOW OPENING NV (ACH)*	MVHR(0.4)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
HEAT LOSS INCREASE (%)	0 (as desined)	18			60		146		
AIR PERMEABILITY INCREASE (%)	0 (as desined)	54			127		225		

MEDIUM value
HIGH value**

*only for natural ventilation scenarios; for the MVHR scenarios base ventilation rate with use of heat recovery is applied
** HIGH values are not the most extreme values from the tested range, but rather more moderate and sensible as it was considered that the probability of many extremes coinciding is not very high

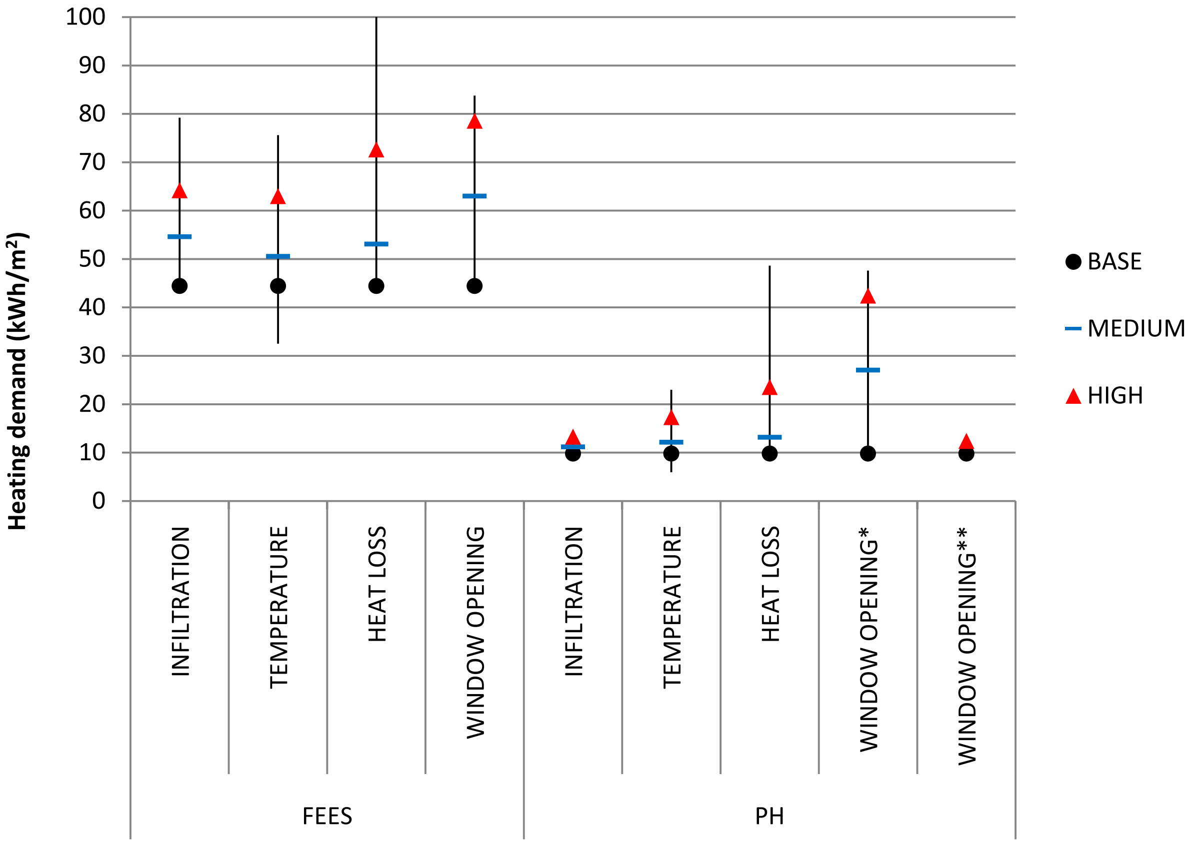
Corresponding criteria on which they were chosen are summarised in the table (Table 40).

Table 40- Summary of criteria for choice of typical MEDIUM and HIGH values for corresponding parameters

CATEGORY	SCENARIO	VALUE	CRITERIA
TEMEPERATURE (°C)	BASE	20	PHPP default temperature
	MEDIUM	21	WHO recommended main living area T and estimated future stabilisation T in the UK increase (Utley and Shorrock, 2008)
	HIGH	23	estimated potential stabilisation temperature in the UK highly insulated homes (Utley and Shorrock, 2008)
WINDOW OPENING (ACH)	BASE	0.4 (MVHR)	standard ventilation rate for MVHR in PHPP
	MEDIUM	0.3	average window use (Dubrul, 1988)
	HIGH	0.6	high window use (Dubrul, 1988)
HEAT LOSS INCREASE	BASE	0%	as designed
	MEDIUM	18%	MEAN_GHA
	HIGH	60%	MEAN_GHA+2.33 STD.DEV.
AIR PERMEABILITY INCREASE	BASE	0	as designed
	MEDIUM	54%	MEAN
	HIGH	127%	MEAN+2.33 STD.DEV.

Corresponding heating demand, due to change of base values to medium or high, can be seen on Graph 18.

Graph 18 -Heating demand for corresponding medium and high values of selected individual parameters



*Effect of window opening behaviour in case MVHR was not used- not realistic for Passivhaus standard
**Estimated effect on window opening together with MVHR (based on results of research (Ebel, 2003; Reis and Erhorrn, 2003, Feist, 2007) which indicates minimal window use in Passivhauses due to use of MVHR)

6.3.3 Scenarios-results and discussion

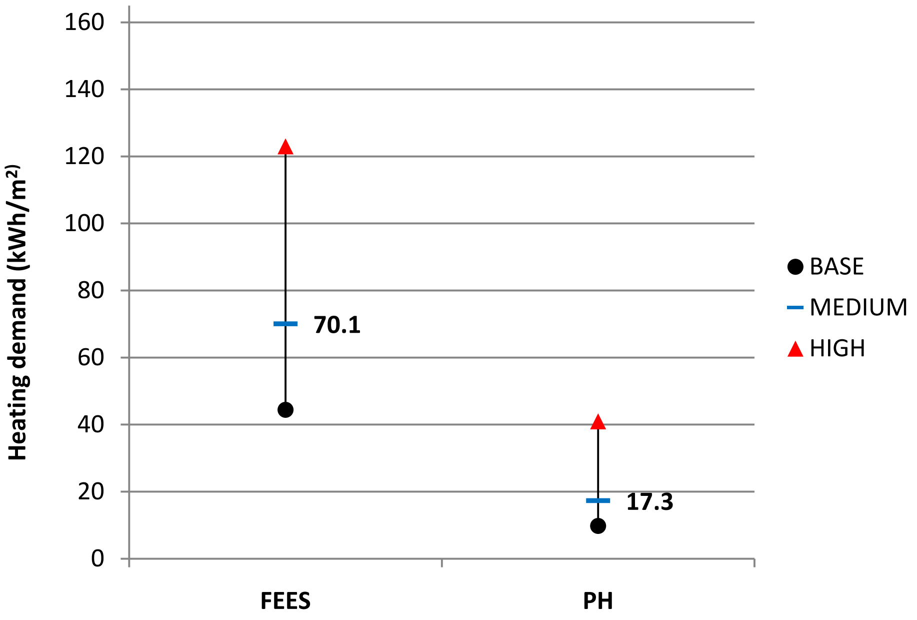
6.3.3.1 MVHR

Even in the case of use of MVHR, FEES house is significantly underperforming and exceeding the determined limit.

Even in the moderate medium scenario, heating demand reaches 70 kWh/m^2 which is more than 50% higher than the predicted heating demand as well as the FEES limit. In the high scenario, FEES house heating demand increases extremely to 123kWh/m^2.

On the other hand, even in this high scenario, PH house is meeting the FEES limit and performing better than original base model of FEES house, whereas in the medium scenario only slightly exceeding the Passivhaus limit of 15kWh/m^2.

Graph 19- Scenarios of heating demand for FEES and PH house with MVHR

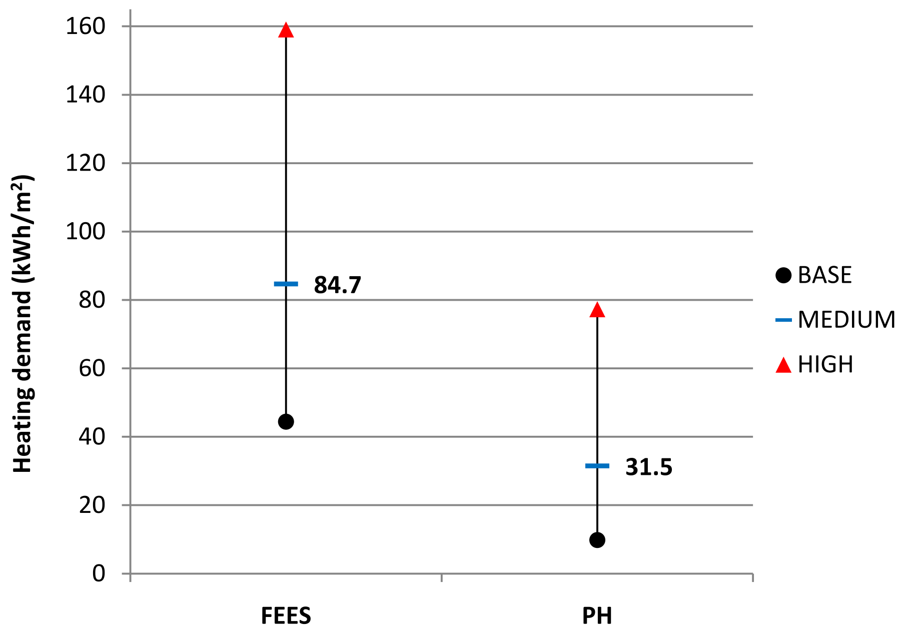


6.3.3.2 Natural ventilation

When, instead of MVHR natural ventilation, which is originally assumed within the FEE standard, is used, situation is significantly worse. In the medium scenario FEES house heating demand almost doubles compared to the base case with MVHR and exceeds the FEES limit for even 85%.

If within the Passivhaus standard MVHR was not obligatory and natural ventilation was used, heating demand would triple. However, as aforementioned, window use is in Passive houses in general minimal and thus this option is not considered to be representative for this standard.

Graph 20- Scenarios of heating demand for FEES and “PH house” with natural ventilation



7. LIMITATIONS

Even though results are based only on one case study house, taking into consideration that the house is optimised for passive solar heating, and without any significant constrains regarding the plot and adjacent buildings that might increase its energy consumption, it is justified to assume that a typical newly built house would not, in these terms, be better than this one. Thus, such analysis should not result in overestimation of heating load for typical house built up to FEES standard.

8. DISCUSSION

Within the FEE standard it was claimed that recommendations are high enough to allow the flexibility in terms of choice of ventilation type and that use of MVHR will not be necessary for the compliance. However, analysis indicates contrary. Even the initial base case of the FEES house showed that in case of natural ventilation recommended building fabric efficiency is not high enough to enable compliance with the determined heating demand limit. Thus, rather than being a voluntary feature which would reduce the heating demand below 39/46 kWm^2, MVHR actually proved in the particular case to be necessary for the compliance.

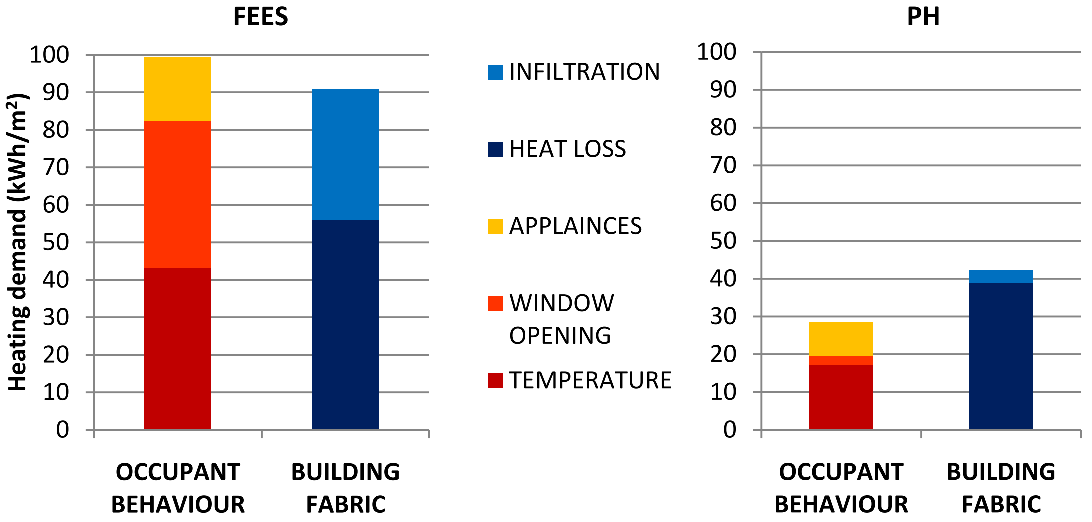
Such difference between estimate of base model heating demand by TAS and FEES prediction based on SAP modelling is in particular case partially originating from different assumptions of internal heat gains which are considered to be related to assumed intensity of use of appliances. It was considered to be more reliable to form the base model applying heat gain estimates used for PHPP and Passivhaus certification as they are based on actual data of monitored energy consumption and moreover, considering that practice shows that the difference between PHPP estimated and actual heating demand is relatively small (Ebel, 2003; Reis and Erhorrn, 2003; Feist, 2005). On the contrary, in the UK building practice such gap is very big which can partially originate from overestimation of internal heat gains.

Sensitivity analysis of the effect of different heat gains prove that this issue has a significant impact on estimation of heating demand as it causes considerable variations for FEES house, up to approximately 17 kWh/m^2. Considering that real heat gains obtained by metering of energy consumption in the case study house are significantly lower than SAP (2005) estimates, use of gains assumed for by SAP would thus result in significant underestimation of real heating demand, approximately 10kWh/m^2, which is not negligible and can have serious implications on actual compliance with the FEES heating demand limit. This is particularly important considering that SAP is used as main tool for defining FEES standard. On the other hand, real gains are higher than PHPP estimates used for the base case. This indicates that in terms of heat gains, hating demand is slightly overestimated. Considering that it can be difficult to accurately predict actual internal heat gains, it is considered that underestimation of heat gains is a better option in terms of estimation of heating demand.

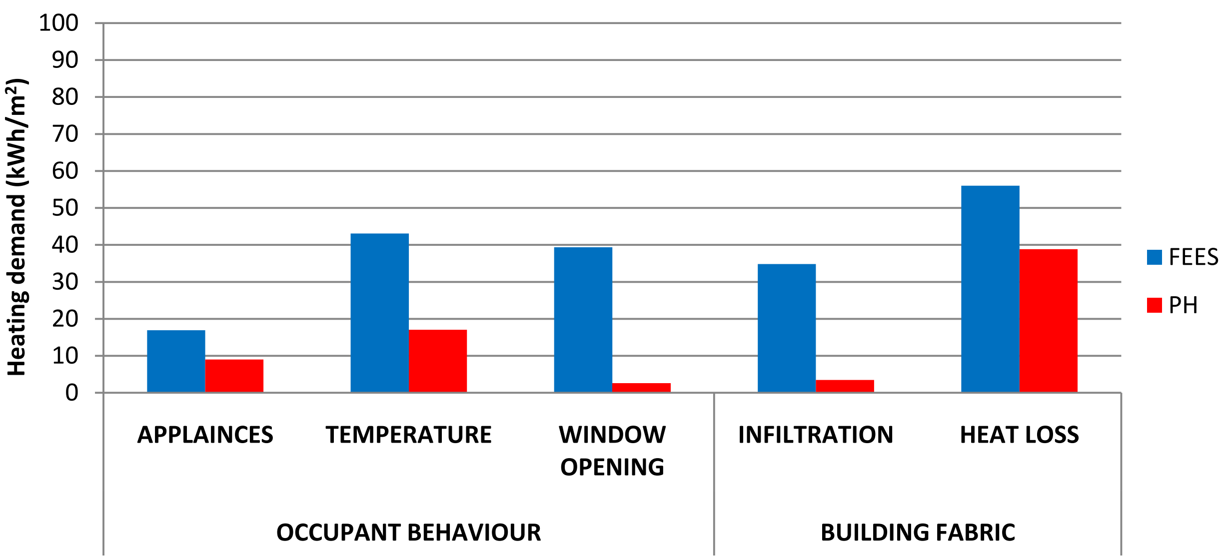
As expected, comparative analysis of Passivhaus and FEE standard showed that deterioration of building fabric has significantly higher impact on the performance of the FEES house, whit maximal estimated variation of heating demand two times higher than for PH house (Graph 21), which is result of significantly lower quality of building fabric (U-values, thermal bridging, air permeability).

Additionally, results also confirm findings from previous research (Hitchcock, 1993; Vringer, 2005) and indicate that occupant behaviour can have equally high impact on heating demand as building fabric quality (Graph 21). This is particularly the case with the FEES house. Increase of internal temperature settings alone, from 20^0C to 23^0C, which is estimated by Utley and Shorrock (2008) to be potential future stabilisation temperature in the UK highly insulated homes, causes 20kWh/m^2 increase in heating demand. This shows that if existing tendency of increase of thermostat set points in low energy dwellings continues, it can compromise successfulness of FEE standard. Furthermore, window opening behaviour can cause heating load to even double compared to the base case, in case of high window use (0.8ACH). Such big scale of the effect of occupant behaviour gives it exceptional importance considering that it is relatively unpredictable and rarely considered within energy modelling, consequently making it one of major causes of significant discrepancy between predicted and actual performance. Thus, this issue can have very serious implications on actual compliance with FEE standard.

Graph 21- Accumulative presentation of estimated maximal realistic variations in heating demand due to occupant behaviour and deterioration of building fabric



Graph 22- Comparison of estimated maximal realistic variations in heating demand due to occupant behaviour and deterioration of building fabric for FEES and PH house



On the other hand in the Passivhaus occupant behaviour shows to have lower impact than deterioration of building fabric (Graph 21). The same range of change of thermostat settings as well as variation of internal heat gains have significantly lower impact on heating demand of PH house, again due to lower fabric and infiltration heat loss. Furthermore, due to occupant awareness of beneficial effect of heat recovery, window use in Passive houses is on average minimal (Ebel, 2003; Reis and Erhorrn, 2003, Feist, 2007). When such window opening behaviour, representative of Passive houses is implemented in the sensitivity analysis it was estimated to cause negligible increase of less than 3 kWh/m^2. Thus, this makes Passivhaus standard considerably more robust to occupant behaviour than FEES with natural ventilation, with estimated maximal variation in heating demand due to occupant behaviour 3.5 times lower than in FEES house. Consequently, performance of Passivhaus is significantly more robust not just to physical deterioration but also to occupant behaviour.

Very good performance of Passivhaus standard is also confirmed by estimated final scenario for "realistic" actual performance (medium scenario) which indicates that, even when all types of analysed deteriorations and occupant behaviour are taken into consideration, PH house is only slightly exceeding Passivhaus heating demand limit (15%).

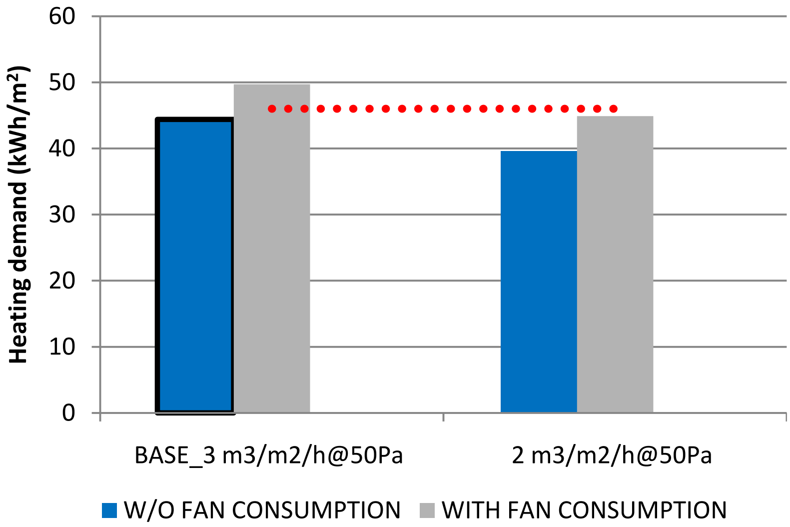
Conversely, final scenarios show that situation with FEES standard is radically different which was expected considering that the initial sensitivity analysis of the effect of individual parameters already showed that deterioration or increase of only one of them is sufficient for the heating demand limit to be exceeded, even in case MVHR is used. Analysis of the combined effect of moderate building fabric deterioration and occupant behaviour (medium scenario) showed that estimated realistic gap between design and "actual" performance of the FEES house with MVHR is not at all negligible as it results in approximately 50% exceedance of the FEES limit. As expected, in case of naturally ventilated house, which is in accordance with the scope of FEES, the gap is significantly worse-85%. This higher difference is caused by additional effect of window opening behaviour.

Furthermore, comparative analysis of natural and mechanical ventilation options in final estimated scenarios shows that use of MVHR significantly contributes to very good energy performance of the PH house. If natural ventilation was used instead of MVHR, heating demand would almost double, from 17.3 to 31.5kWh/m^2 (medium scenario). Such heating demand indicates that real U-values of the case study Passivhaus would be more adequate to ensure compliance with FEES target in case of natural ventilation, even when certain deteriorations are taken into consideration, which is impossible with current recommended FEES U-values even in the ideal base case. However, due to use of natural ventilation infiltration would need to be higher than current 0.44 ACH@50Pa of the case study house in order to ensure sufficient IAQ. In order to eliminate potential negative health impact due to inadequate air quality, air permeability of at least 5 m^3/h.m^2@50Pa is recommended (Ridley, et al., 2003).

Moreover, comparison of Passivahaus and FEES standard points out to air permeability levels as another very important issue which is related to choice of ventilation and has very significant implications on heating demand. The Task Group that worked on defining the FEES intentionally recommended relatively high universal level of air permeability (3 m^3/h.m^2@50Pa), claiming it to be flexible enough for both natural and mechanical ventilation with heat recovery (ZCH, 2009). Major concern was not to compromise the IAQ by too airtight building fabric. However, aforementioned research (Ridley, et al., 2003) shows that air permeability of at least 5 m^3/h.m^2@50Pa is necessary in case of natural ventilation. Furthermore, results indicate that such flexibility is not beneficial neither in case of mechanical ventilation due to implications on heating demand. Recommendations for low energy housing (Johnston, et al., 2011) also indicate that different infiltration rates should be used for different ventilation strategies, advising maximum 3ACH@50Pa (2 m^3/h.m^2@50Pa) for mechanical extract ventilation and 1ACH@50Pa (0.6 m^3/h.m^2@50Pa) in case of MVHR. Results show that by lowering the air permeability from maximal FEES recommended 3 to 2 m^3/h.m^2@50Pa would actually be sufficient to compensate for energy used by fans (Graph 23). Furthermore, if FEES house with MVHR actually had advised air permeability of 0.6 m^3/h.m^2@50Pa (Johnston, et al., 2011) this would result in approximately 25% reduction of heating load, or even 30% if Passivhaus level of approximately 0.25

$m^3/h.m^2$@50Pa is achieved. This would significantly increase the chances of compliance with FEES limit. On the other hand, if Passivhaus had the maximal air permeability advised by FEE standard, heating load would double diminishing beneficial effect of heat recovery. However, Passivhaus certification represent a guarantee of low air permeability as it ensures that maximal measured post-construction infiltration rate is 0.6ACH@50Pa, which corresponds to approximately 0.4 $m^3/h.m^2$@50Pa, thus ensuring that such cases do not occur.

Graph 23- Comparison of FEES house heating demand for different air permeability, with and without MVHR energy consumption



Thus, results clearly show that combination of both low air permeability and MVHR allows Passivhaus standard to achieve such low levels of heating demand. High levels of air permeability advised by FEES, in conjunction with MVHR significantly decrease the effectiveness of heat recovery and reduce energy savings which could be achieved at no particular additional cost if air permeability was lower. Analysis also indicates that air permeability levels advised by FEES are actually neither adequate for MVHR nor for natural ventilation.

Results obtained by energy modelling are in line with actual monitoring results from the practice (Schnieders, 2003; Feist, 2005; Feist, 2007) which indicate very good average performance of Passivhaus standard. Results obtained by the same methodology however clearly indicate that in case of FEES standard estimated gap between design and “actual” performance can be very high and that FEES recommendations for building fabric are not sufficient to guarantee compliance of actual dwelling performance with the determined heating demand limit, even if MVHR was included in the scope of the standard. Consequently, the achievement of “zero carbon” gaol can be seriously compromised at this initial, basic stage. Thus, revision of FEES recommendations for the building fabric efficiency seems to be necessary.

9. CONCLUSIONS AND RECOMMENDATIONS

Although it is considered that the UK is currently leading by setting the most ambitions "zero carbon" goal for residential buildings from 2016 (ZCH, 2009), constant redefining of "zero carbon" is only one of the reflections of uncertainties in actual achievement of such target. Moreover, even though it is acknowledged that in the UK building practice significant gap between design and actual performance exists, FEES which forms the basis of the "zero carbon" strategy is defined as a design standard (ZCH, 2009). Even the Task Group which worked on defining the standard stresses the urgency of moving FEES towards actual rather than designed performance (ZCH, 2010). Thus, this further increases the doubt in possibility of real "zero carbon" future.

The sensitivity analysis of performance of FEES house shows that aforementioned concerns are justified and points out to couple of important issues.

Significant discrepancy between assumed and actual heat gains in the case study house indicates that more attention should be paid to this issue. In terms of prediction of heating demand it is considered to be a better option to slightly underestimate rather than overestimate internal gains. It is regarded that the example of PHPP, which is based on very modest assumptions of heat gains, should be followed and used also in SAP modelling as this can eliminate one of potential causes of the gap between design and actual performance. Moreover, even though increase in appliances use leads to increase of internal heat gains and reduction of heating demand, it needs to be taken into consideration that this decrease in one aspect of energy use is only caused by increase in the other. Moreover, although the UK still shows slight annual increase of appliances energy use, considering that on the way to achieving "zero carbon" there should be an integrated approach to reduction of overall energy consumption in the dwellings including appliances, this tendency should also be reflected in heating demand predictions through heat gain estimates, which should be closer to those used for Passivhaus certification.

Furthermore, even when wrong estimates of internal gains are taken out of the analysis, the gap between design and actual performance caused by mistakes and deterioration of building fabric and by occupant behaviour, is estimated to be sufficiently high to seriously compromise compliance with FEES heating demand limit and consequently potentially achievement of "zero carbon" dwellings. Thus, in order to narrow this gap, an integrated approach to energy consumption reduction is considered to be necessary as well as revision of FEES recommendations.

Considering that the results indicate that occupant behaviour can have equally high impact on heating demand of FEES house as building fabric properties, addressing both "human" and "physical" aspect (Hitchcock, 1993) of the household energy consumption is considered to be of crucial importance. Thus, informing the occupants on how to adequately use the house, e.g. indicating the importance of the thermostat settings and reasonable window opening behaviour, is of equal importance for the "zero carbon" strategy as the fabric quality.

Additionally, increase of quality of construction, detailing and skilfulness of workmanship is also very important to minimize the gap.

On the other hand, certain gap is still expected to occur considering that practice shows that certain level of fabric deterioration cannot be controlled as it depends on age and construction technique (Wingfield, et al., 2007; Elmroth and Lodgberg, 1980). Moreover, even though occupant behaviour can be modified up to a certain extent, it is influenced by many complex factors which still make it relatively unpredictable. Thus, it is regarded to be of crucial importance to also incorporate these aspects in energy modelling and consequently give revised recommendations for higher building fabric efficiency, which would ensure that actual performance of a dwelling complies with the FEES heating demand limit.

Speaking of revision of FEES it is considered that it would also be beneficial to incorporate the consideration of ventilation type within the standard as performance of particular ventilations type is highly related to building fabric properties, in particular air permeability, and thus only bearing in mind what kind of ventilation will be used, optimal recommendations can be given. Analysis of one example of FEES recommended specification shows that advised air permeability would actually be inadequate both for natural ventilation and mechanical ventilation with heat recovery. Furthermore, comparison of Passivhaus and FEES indicated that use of MVHR together with low air permeability is very important for achievement of low levels of heating demand. Thus, it is considered that this issue can be resolved in two ways.

One way is to incorporate MVHR within the standard and make its use compulsory, in which case significantly lower air permeability closer to Passivhaus standard should be advised in order to maximally exploit beneficial effect of heat recovery. In this case only small improvement of U-values would be sufficient. Examples of Passive houses (Feist, 2005; Schnieders, 2003) show that use of MVHR can also be beneficial for reduction of the impact of occupant behaviour, assuming they would be adequately informed about the importance of minimal window use. Thus, this could also help narrow the gap between design and actual performance by decreasing an unpredictable effect of window opening behaviour.

If it is regarded as unreasonable to expect that use of MVHR can be made obligatory on the national level, MVHR should be at least strongly advised and various forms of incentives applied to stimulate its use. However, if in accordance with the initial Task Group recommendations both natural and mechanical options will be possible, it is deemed to be necessary to give different set of recommendations for building fabric efficiency, corresponding to the type of ventilation. In a naturally ventilated dwelling, in order to guarantee sufficient IAQ, significantly higher air permeability should advised (at least 5 $m^3/h.m^2$@50Pa, (Ridley, et al., 2003)). In such case U-values that approximately correspond to those of the case study Passivhaus would be necessary to compensate for ventilative losses and ensure compliance with the FEES limit. Such lower U-values would also reduce the impact of occupant behaviour through increase of thermostat setting which proves to be very high in current FEES house model.

However, it is obvious that in both financial and energy aspect, use of MVHR represent a better option as it offers quite cheap and efficient reduction in heating demand. Amount of insulation needed to compensate for vantilative losses in case of natural ventilation, would result in significantly higher capital cost for achievement of approximately the same heating demand.

However, there is a technical issue related to buildability of such high specification. Although German practice shows that very low levels of air permeability are absolutely feasible, achievement of such low levels in the UK construction practice is rarely the case, where inadequate detailing and skilfulness of workmanship can be considered as one of the major constrains. Improvements in this field also have financial implications. However, it is considered that investment in the improvements of the quality of workmanship and construction can bring long-term benefits as it would allow optimal use of heat recovery and thus contribute to abundant and cost effective energy savings and furthermore to the achievement of “zero carbon” goal. Moreover, beneficial effect of MVHR is twofold as its adequate use can also insure good IAQ.

Ultimately, if heating demand of new houses is not sufficiently reduced this will further also have a financial impact on ZLC technologies needed to satisfy such demand. Thus, the basis of “zero carbon” should not be so fragile and investments and improvements should be done at this initial stage to make sure that such ambitious goal can actually be achieved in reality.

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11. APPENDIX

11.1 Sensitivity analysis

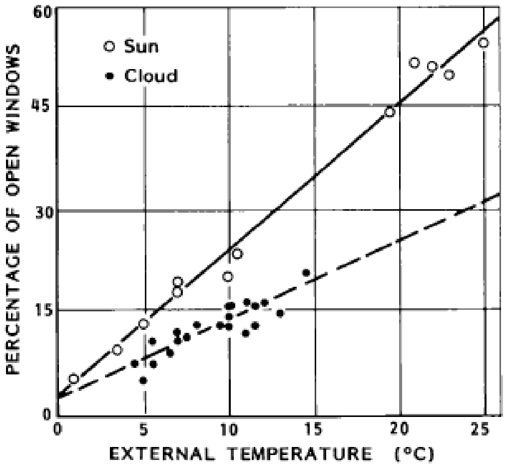
11.1.1Window opening behaviour

11.1.1.1 Correlation of window opening and external temperature

Determining the range

As a result of aforementioned AIVC research a correlation between window use and external temperature is established and determined (Graph 24). Considering that correlation differs depending on whether weather is sunny or cloudy, new linear regression was interpolated between excising two. This resulted in 54% of the window open at 32^{0}C, whereas window starts opening at 0^{0}C.

Graph 24- Window opening as a function of outdoor temperature and sunshine (TN23, 1988)



In each of the spaces which have windows, one typical window is chosen. Actually only the kitchen has the windows, whereas all other spaces have sliding/tilting doors. Thus, aforementioned function related to the external temperature is applied to the kitchen window, due to its reasonable size. For control of window opening by external temperature in TAS zdcem function is used.

It was regarded that during winter, due to their large areas, balcony doors would only be tilted for approximately 5cm which resulted in maximal area of 0.1 m^2. Thus, after restricting the opening area, the door in the living room was assigned also with the external temperature function. In the bedrooms balcony doors are kept constantly open, tilted also for 5cm, during the occupied period, as it was considered that no adjustments are possible while occupants are asleep. Outside the occupancy period all windows are closed.

Tree scenarios, which differ in the number and type of open windows/doors used are tested. In all of them bedroom door are always used, due to necessary provision of adequate IAQ. Variations exist in terms of use of windows in living room and kitchen. Considering that the upper floor with kitchen and living room is open plan space, it is considered that for the ventilation of this space three main combinations are probable, with windows open:

- Only in kitchen
- Only in living room
- Both in kitchen and living room

When the kitchen window is open, it is assumed that it is used to provide ventilation for the living room also, and thus it is used during the occupancy period of the living room.

Table 41- Scenarios of window use

SCENARIO	SPACE	SCHEDULE	T(^{0}C)	%/A(m2)
1	bedrooms	23-6	0-10	0.1 m2
	living room	18-22	0-10	0.1 m2
2	bedrooms	18-22	0-10	0.1 m2
	kitchen	17-22	0-32	54%
3	bedrooms	23-6	0-10	0.1 m2
	kitchen	17-22	0-32	54%
	living room	18-22	0-10	0.1 m2

Results

It needs to be stressed that according to the Passivhaus standard use of MVHR is mandatory and that thus window use is minimal. However, analysis of potential effect of window opening is also carried out for the PH house in order to estimate how big the effect on heating demand would be if MVHR is not used.

As expected, use of natural ventilation compared to MVHR causes significant increase of heating load. In case windows are regularly open in all three main spaces, FEES house model is consuming 20kWh/m^2 more than the allowed maximum, whereas PH house is using approximately 3 times more than the base case with MVHR. However, according to the aforementioned AIVC research, the main ventilation zones in dwellings are bedrooms, whereas the greatest percentage of windows which are never opened are in living rooms. Such case would correspond to scenario 2, in which case however the FEES house is still exceeding the heating demand limit by approximately 10 kWh/m^2. The consumption is similar in case of the living room being ventilated using the kitchen window. This combination is considered to be most likely, at least in the particular house, considering that, due to its more convenient size, kitchen window is more frequently used by the occupant.

Table 42- Scenarios of window use with corresponding heating load for FEES and PH house

SCENARIO	WINDOW USE	HEATING DEMAND (kWh/m2)	
		FEES	PH
BASE	MVHR	44.4	9.8
1	Bedroom + living room	54.8	19.8
2	Bedroom + kitchen	57.5	19.6
3	Bedroom + kitchen + living room	66.8	27.1

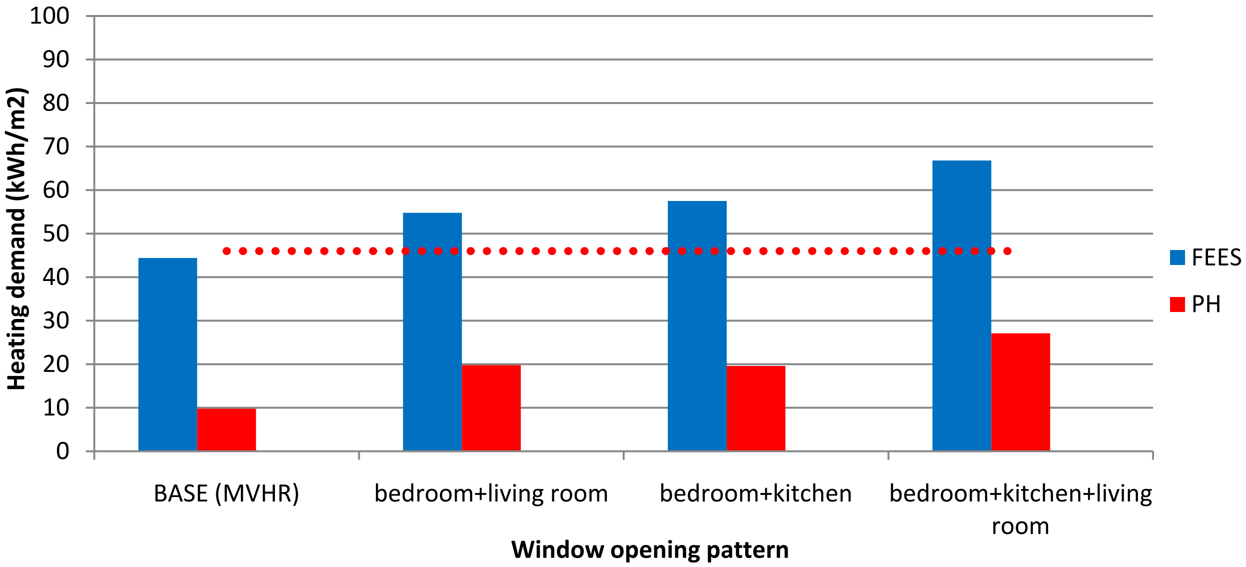
Such simulated window opening behaviour is considered to be very moderate, which confirms comparison with the results of approximation of window use intensities by corresponding ACH based on

AIVC research (Dubrul, 1988). Scenario 3, with one widow moderately used in all main spaces, results in heating load which corresponds approximately to for medium window use with 0.4-0.5 ACH, whereas other two more moderate combinations with one window less used, correspond to 0.2-0.3 ACH range (Table 43).

Table 43- Range of heating load for medium window use

ACH	FEES	PH
0.1	47.5	12.4
0.2	52.7	17.1
0.3	57.8	22.0
0.4	63.0	27.1
0.5	68.2	32.2

Graph 25- Effect of different window use on heating demand of FEES and PH house



Such results indicate that even in case of the most modest window use, the FEES heating load limit would be exceeded and more energy would be consumed than in case of MVHR. Furthermore, it is becomes clear that use of obligatory use of MVHR within the Passivahaus standard significantly contributes to such low levels of heating demand which can hardly be achieved with natural ventilation.

11.1.1.2 Window opening area needed for IAQ

Determining the range

The final way of simulating the window use is based on fixed window opening area which is needed for provision of 8l/s/person. This area is estimated using AM10 (Table 44). Thus, windows are kept constantly open for the corresponding area during the whole occupancy period of corresponding spaces. This simulation corresponds to case where CO2 sensors are used to regulate window opening. This is rarely the case in domestic buildings. However, such results can be indicative of the scale of heating demand needed to ensure adequate IAQ, which is one of major concerns in case of natural ventilation.

Again, bedroom balcony doors are open in all scenarios. Variations exist in terms of use of living room and kitchen window. In the first scenario it is considered that the kitchen window is used only during cooking, whereas in the second it is used for ventilation of the living room also, considering that its size is more convenient. In the third scenario, kitchen window is also left open during the whole occupancy period of the living room, together with the living room balcony door. This is based on the results of the BUS survey which indicated that the kitchen window is most frequently used.

Table 44- Window opening scenarios

SCENARIO	SPACE	SCHEDULE	OPENING A (m2)	% WINDOW A
1	kitchen (cooking)	17	0.087	0.155
	living room	18-22	0.087	0.019
	bedrooms	23-6	0.087	0.020
2	kitchen	17-22	0.087	0.155
	bedrooms	23-6	0.087	0.020
3	kitchen	17-22	0.087	0.155
	living room	18-22	0.087	0.019
	bedrooms	23-6	0.087	0.020

Results

The results of such window opening behaviour are similar to previous set of results. They indicate that even in the case of highest window use scenario "PH house" heating demand is significantly lower than FEES limit, whereas for the lowest window use pattern FEES house demand already exceeds the limit. Although in case of PH model, even minimal window use would causes doubling of heating demand, it is still performing satisfactory compared to FEES house which is severely exceeding the limit with 64.1 kWh/m2.

Thus, again results show that compliance with the FEES target seems impossible with the current advised building fabric properties and natural ventilation.

Graph 26- Effect of different window use on heating demand of FEES and PH house (IAQ)

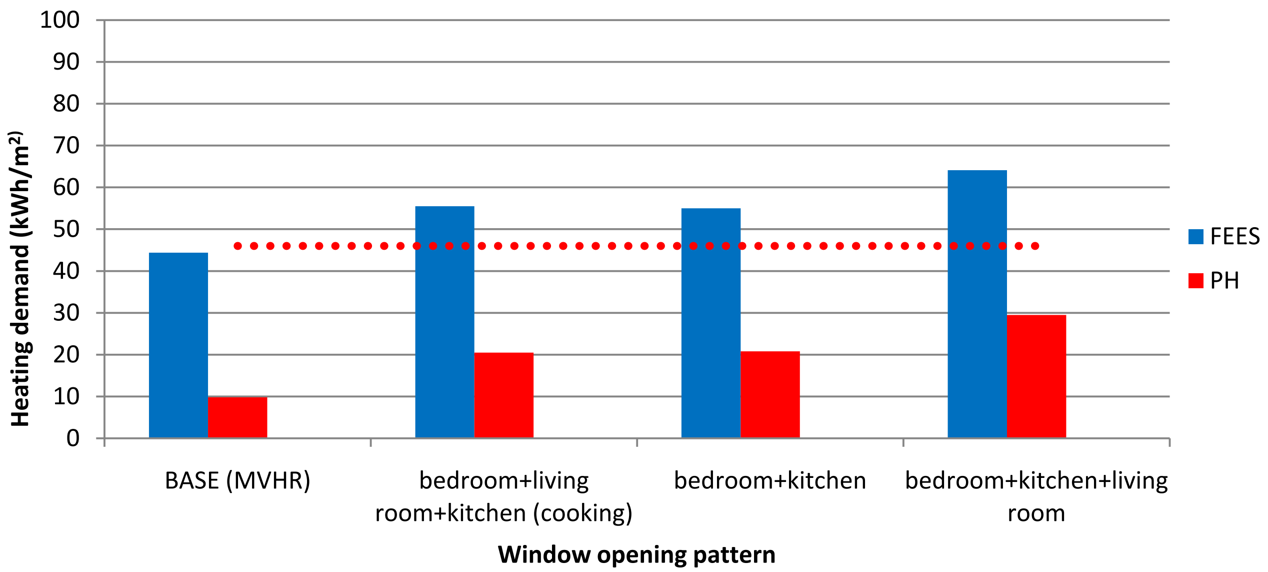


Table 45- Scenarios of window use with corresponding heating demand for FEES and PH house

SCENARIO	WINDOW USE	HEATING DEMAND (kWh/m2)	
		FEES	PH
BASE	MVHR	44.4	9.8
1	Bedroom + living room + kitchen (cooking)	55.5	20.5
2	Bedroom + kitchen	55.0	20.8
3	Bedroom + kitchen + living room	64.1	29.5

11.1.2Occupant density and family structure

Determining the range

The amount of metabolic heat gains from the occupants varies depending on the size of the family as well as its structure, in terms of age and thus time spent at home. In terms of size, household ranging from single to four members, which is considered the maximum for such dwelling, is tested. In terms of time spent at home, occupants are divided in two categories, the first category spending significant part of day outside and the second spending most of the time inside (Table 46).

Table 46- Occupant type categories

CATEGORY	DESCRIPTION
1	working
	studying
2	young children
	unemployed/working at home
	retired

The presence of these two categories at home is characterised in PHPP by availability factor, 0.55 being typical for the first category. For the second category 0.9 is adopted. For each combination average availability factor is estimated. All possible combinations of these two categories for all variations in family size are determined. Change in number of occupants is reflected not only through metabolic gains but also through different use of appliances, consumer electronics, lighting, auxiliary electricity. Cooling effect of evaporation and cold water is also taken into consideration. Using PHPP as a source of average quantities of aforementioned types of energy use and sources of heat gains (Table 64), final average overall heat gain per m^2 is estimated for each combination of family structure (Table 47), and inputted in TAS.

Additionally, average heat gain for average UK family size of 2.31 occupants is also estimated.

Table 47- Heat gains for different family structure

FAMILY STRUCTURE	NO OF OCCUPANTS			AVAILABILITY OF THE OCCUPANT HEAT GAINS (PHPP)			TOTAL AVERAGE HEAT GAIN (W/m2)
	TOTAL	WORKING	AT HOME	WORKING	AT HOME	AVERAGE	
SINGLE	1	1	0	0.55	0.00	0.55	**1.59**
COUPLE	2	2	0	1.10	0.00	0.55	**2.19**
	2	1	1	0.55	0.90	0.73	**2.47**
	2	0	2	0.00	1.80	0.90	**2.75**
NATIONAL STATISTICS	2.31	2.31	0	0.55		0.55	**2.37**
3 MEMBER FAMILY	3	3	0	1.65	0.00	0.55	**2.79**
	3	2	1	1.10	0.90	0.67	**3.07**
	3	1	2	0.55	1.80	0.78	**3.35**
4 MEMBER FAMILY	4	4	0	2.20	0.00	0.55	**3.39**
	4	3	1	1.65	0.90	0.64	**3.67**
	4	2	2	1.10	1.80	0.73	**3.96**
	4	1	3	0.55	2.70	0.81	**4.24**

Results

Maximal variation in heating demand for tested family structure range is approximately 13 kWh/m^2 for FEES house and 9 kWh/m^2 for PH house. Although the absolute difference for the PH house is lower, effect of heat gains is in this case in relative terms actually more pronounced and very significant due to lower fabric heat loss than FEES. In the best case of the four member family, heating load is approximately 70% lower than in the case of the single person household for the PH house model (Table 48). However, effect of internal heat gains is also quite important for the FEES house, considering that only a small change in number of occupants, from couple to singe, results in heating demand of FEES house of 47kWh/m2, exceeding thus the defined limit.

Graph 27- Effect of occupant density and family structure on heating demand

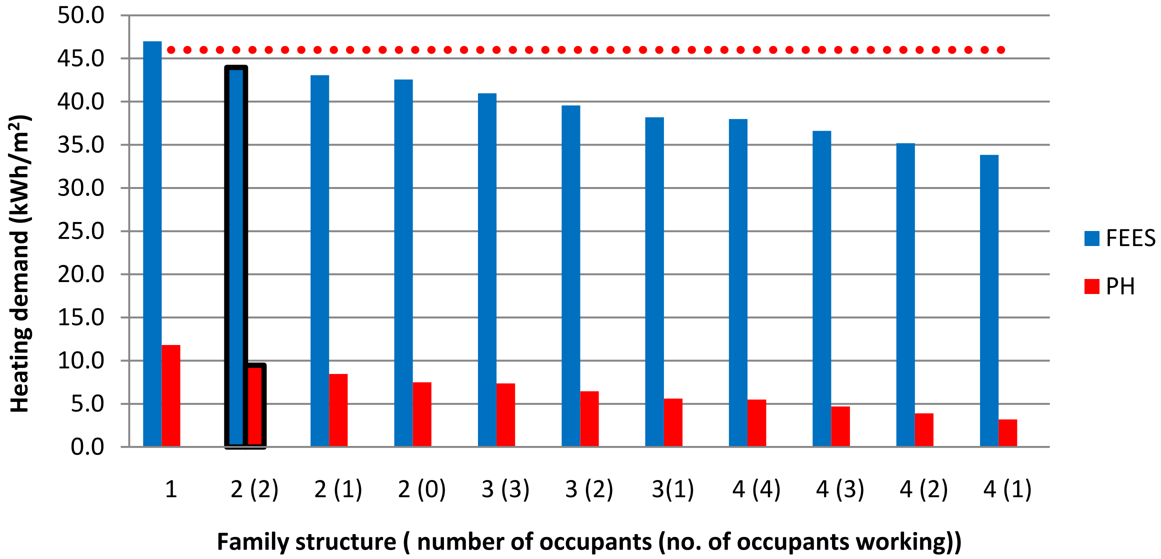


Table 48- Heating load for different family structure

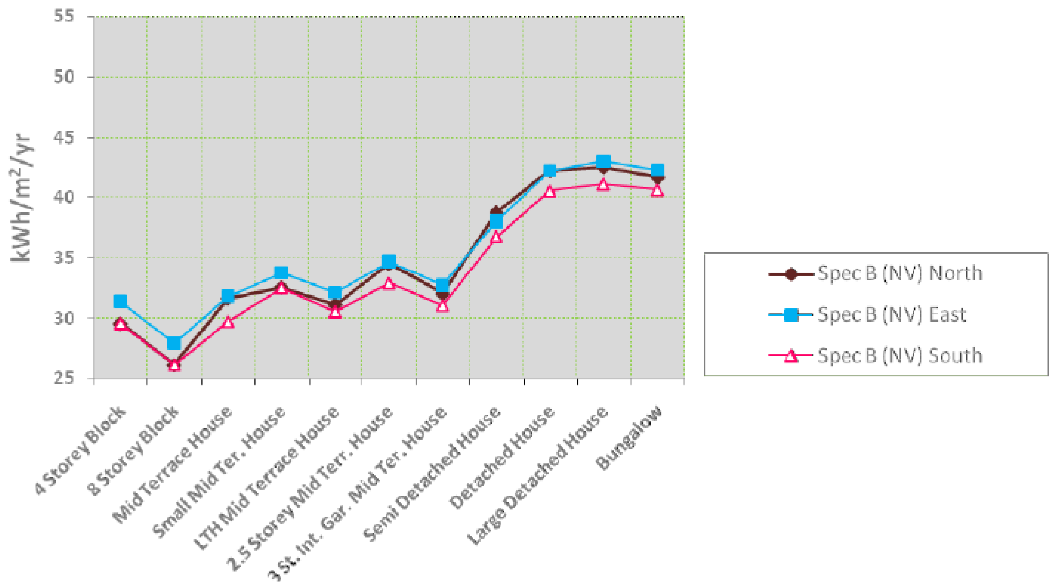
	NO OF OCCUPANTS			HEATING DEMAND (kWh/m2)	
	TOTAL	WORKING	AT HOME	FEES	PH
SINGLE	1	1	0	**47.0**	**11.8**
COUPLE	2	2	0	**44.0**	**9.5**
	2	1	1	**43.1**	**8.5**
	2	0	2	**42.6**	**7.5**
NATIONAL STATISTICS	2.31	2.31	0	**41.2**	**8.8**
FAMILY	3	3	0	**41.0**	**7.4**
	3	2	1	**39.6**	**6.5**
	3	1	2	**38.2**	**5.6**
FAMILY	4	4	0	**38.0**	**5.5**
	4	3	1	**36.6**	**4.7**
	4	2	2	**35.2**	**3.9**
	4	1	3	**33.8**	**3.2**

Thus, number and age of occupant do have a significant impact on energy consumption of the house. Although it is understandable that for the sake of simplicity of modelling national averages or typical family structure are usually used, it needs to be taken into consideration that variations in heating demand are not small and that a safety margin should be left so that the limit is not exceeded even in the "worse" case.

11.1.3Effect of orientation and thermal mass

According to SAP modelling used for determination of FEES, effect of orientation as well as use of thermal mass have minimal effect on heating load and can thus not compromise compliance with the limit when recommended values are used. The range of variation of heating demand is determined to me only ±2 kWh/m^2(ZCH, 2009). Thus, analysis is carried out in order to critically examine such claims.

Graph 28- Variations in heating demand due to change in orientation according to SAP modelling of FEES (ZCH, 2009)



Considering that site constrains can be restricting in terms of use of optimal orientation, the model of the house is rotated in order to estimate maximal variations in heating demand. Variations in cooling load are not within the scope of this study but they are expected to be minimal compared to heating due to use of shading.

Considering that the existing building has a light-weight structure, option with the heavy weight concrete structure, but with the same U-values is tested in order to estimate the effect on heating load.

11.1.3.1 Orientation

Results of the rotation of both models of the house do not confirm the results of the Task Group which were indicating that the maximal variation in the heating demand for different orientations is 2 kwh/m^2.

In the particular case the difference goes up to 7kWh/m2 for the FEES house. It needs to be taken into consideration however, that the case study house is optimised for passive solar heating, with extensive glazing areas on the South. That can account for big N-S orientation difference in heating demand. However, on the other hand, only between S and S-W orientation, which are both considered to be quite good in terms of passive solar heating, the difference reaches 2kWh/m2.

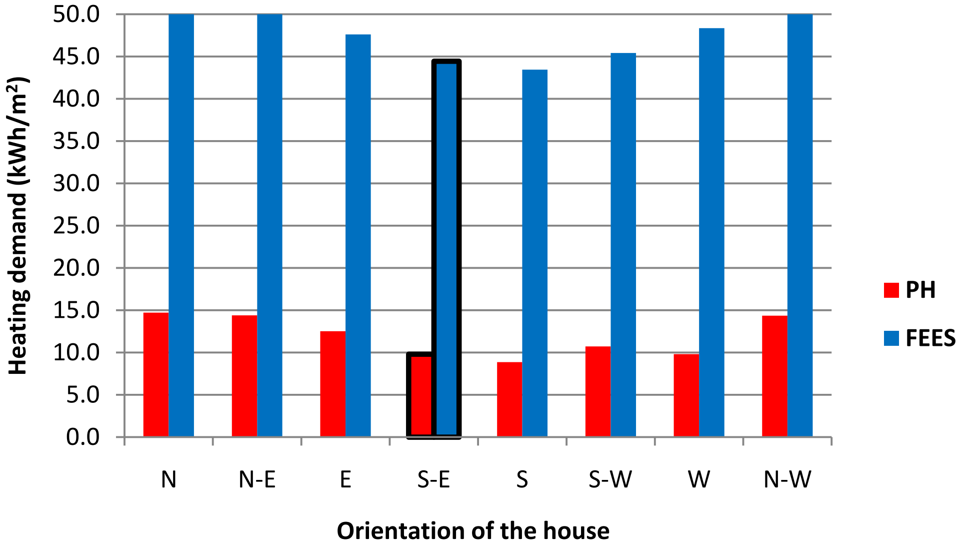
Table 49- Variations in heating demand of FEES and PH house due to change of orientation

ORIENTATION	HEATING DEMAND (kWh/m2)	
	FEES	PH
N	50.5	14.7
N-E	50.0	14.4
E	47.6	12.5
S-E (BASE)	44.4	9.8
S	43.4	8.9
S-W	45.4	10.7
W	48.3	9.8
N-W	50.0	14.3

MAXIMAL VARIATION	7.0	5.8

Thus, it is reasonable to suggest that in case of site constrains when orientation is not most advantageous, compliance with the FEES maximal heating load can be compromised unless lower U-values than advised are used and great attention is paid to optimal use of available orientation. However, even in case of the PH house model, maximal variations are still relatively high-5.8kWh/m2. On the other hand, in this case, due to significantly lower fabric heat loss, maximal heating demand for the worse N orientation is still satisfying even strict Passivhaus heating demand limit of 15kWh/m2.

Graph 29- Variations in heating demand of FEES and PH house due to change of orientation



This indicates that site constrains in terms of building orientation can have much more significant implications on heating demand and that that thus significantly higher quality of building fabric is needed if compliance is to be achieved regardless of these realistic constrains.

11.1.3.2 Thermal mass

One type of concrete structure with internally exposed surfaces is tested. Considering that the exposed surface area was maximal, only thickness of the concrete element was varied. For such construction type 200mm and 300mm concrete structure was considered to be reasonable option. There are however no big differences in the effect of different widths. Maximal variation is approximately the same for both house model- 1.2kWh/m2 which is in accordance with Task Group estimates. Even though variations are not big, use of thermal mass proves to be beneficial for decrease of heating demand.

Table 50- Variations in heating demand of FEES and PH house due to effect of thermal mass

	HEATING DEMAND (kWh/m2)	
	PH	**FEES**
BASE (LIGHTWEIGHT)	9.8	44.4
THERMAL MASS 200mm	8.9	43.7
THERMAL MASS 300mm	8.6	43.2
MAXIMAL VARIATION	1.2	1.2

11.2 Final scenarios

11.2.1Effect of internal heat gains

As the results of sensitivity analysis already indicated, variation in heating demand due to variation in internal heat gains caused by different occupant density or use of appliances can be significant. Their effect on the heating load of both NV and MVHR final scenarios is examined.

Variation in heat gains, based on PHPP and SAP estimates, as well as metered energy consumption which were previously used as representation of different scenarios of appliances use is applied on the final medium and high scenarios. Real heat gains based on monitoring data are exactly in between PHPP and SAP values.

In the medium scenario which is considered to be more realistic approximation of average “actual” performance, maximal variation of heating demand of PH house is approximately 9 kWh/m^2 whereas for FEES house with MVHR even 19 kWh/m^2. The situation is similar for the natural ventilation FEES house model. Thus, such significant difference can have big impact on the compliance with the FEES heating load limit. This is especially crucial when gains are overestimated. Results clearly indicate that estimation of heating demand based on SAP heat gains results in significant underestimations compared to real heat gains of the case study house. This is particularly important in the light of the fact that SAP is the tool used for energy modelling and defining the FEE standard. Although it cannot be considered that heat gains based on monitoring of only one house can be regarded as representative of the average, there seems to be the possibility of overestimation by SAP, when compared also to the values based on Passivhaus calculations.

Graph 30- Effect of internal heat gains on heating demand of FEES and “PH house” with natural ventilation

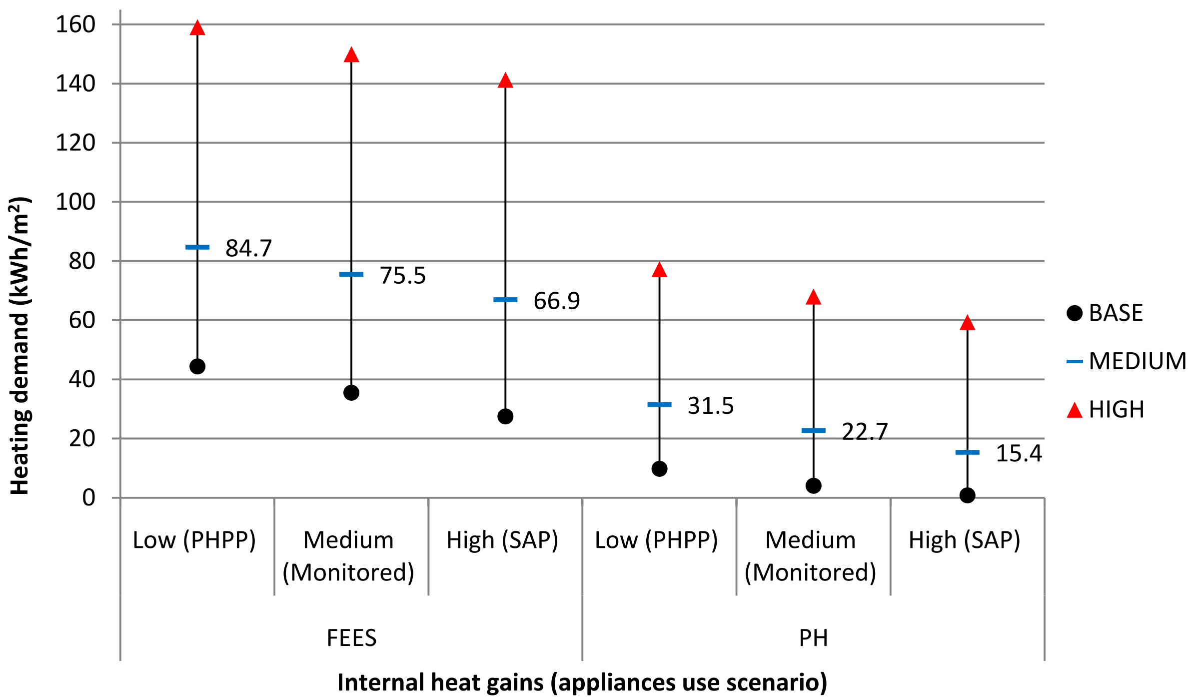


Table 51- Heating demand of FEES and "PH house" with natural ventilation for corresponding internal heat gains (appliances use) scenarios

STANDARD	APPLIANCES USE SCENARIO	INTERNAL HEAT GAIN (W/m^2)	HEATING DEMAND (kWh/m^2)		
			BASE	MEDIUM	HIGH
FEES	Low	PHPP (2.1)	44.4	84.7	159.1
	Medium	Monitored (3.9)	35.5	75.5	149.9
	High	SAP (5.6)	27.5	66.9	141.3
PH	Low	PHPP (2.1)	9.8	31.5	77.3
	Medium	Monitored (3.9)	4.1	22.7	68.0
	High	SAP (5.6)	0.8	15.4	59.4

Graph 31- Effect of internal heat gains on heating demand of FEES and PH house with MVHR

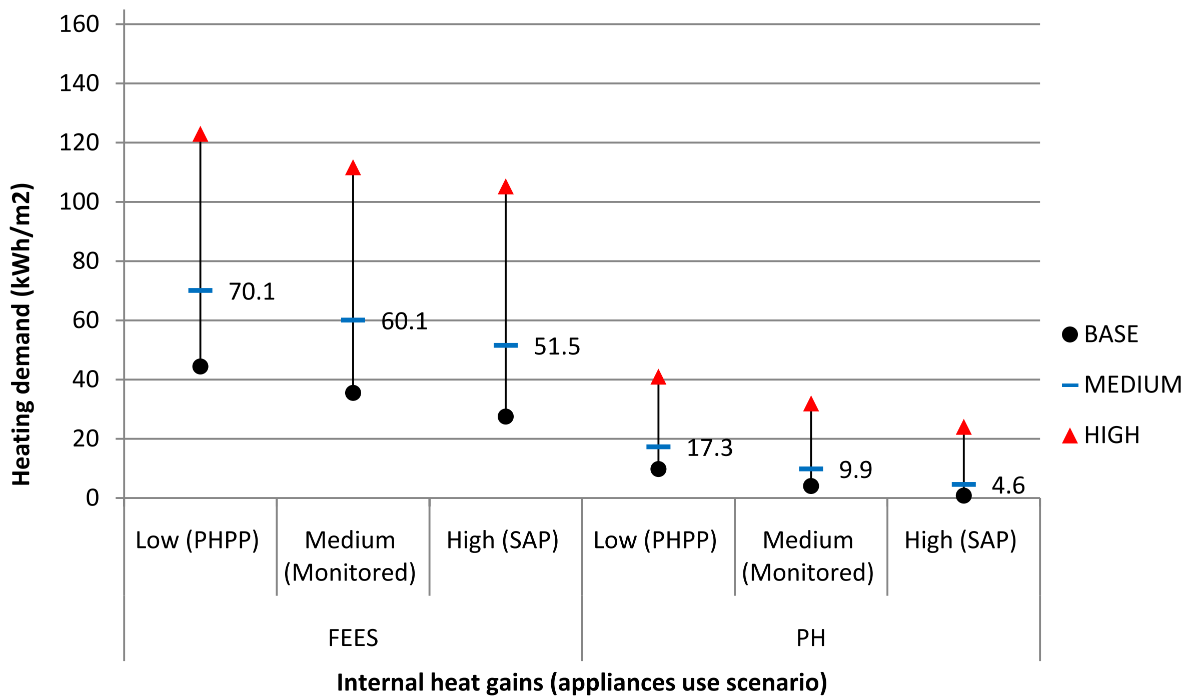


Table 52- Heating demand of FEES and PH house with MVHR for corresponding internal heat gains (appliances use scenario)

STANDARD	APPLIANCES USE SCENARIO	INTERNAL HEAT GAIN (W/m2)	HEATING DEMAND (kWh/m^2)		
			BASE	MEDIUM	HIGH
FEES	Low	PHPP (2.1)	44.4	70.1	123.0
	Medium	Monitored (3.9)	35.5	60.1	111.7
	High	SAP (5.6)	27.5	51.5	105.3
PH	Low	PHPP (2.1)	9.8	17.3	41.0
	Medium	Monitored (3.9)	4.1	9.9	32.0
	High	SAP (5.6)	0.8	4.6	24.0

Such discrepancy can increase the gap between design and actual performance and compromise the compliance with determined target. Thus, safety margin should be defined to account for realistic variations and modelling should also be based on more moderate assumptions about appliances use and thus heat gains.

11.2.2Effect of climate change

Finally, the effect of increase of temperatures due to climate change on decrease of heating demand is estimated for medium scenario, as a representative of typical “realistic” consumption. The intention is to determine the range of effect and establish whether such change could eventually, in near future, lead to actual compliance with the FEES target. Analysis is carried out separately on models with natural ventilation and MVHR, for years 2020, 2050 and 2080, using UKCIP medium high weather files which are based on moderate assumptions about the intensity of climate change.

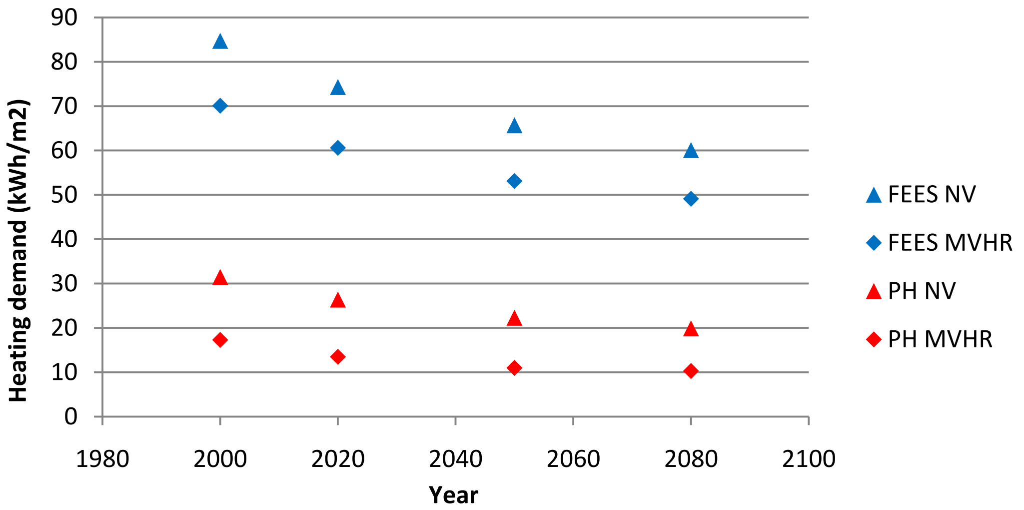
Increase of temperatures has more significant effect on reduction on heating demand of the FEES house model, due to its higher heat loss. The range of the effect is very high for the FEES house, causing reduction of up to 25kWh/m^2 in 2080 for naturally ventilated option. Although this is a significant decrease, it is still not sufficient for compliance with FEES heating demand. Only in case of MVHR, heating demand gets relatively close to the limit, with 49.1kWh/m^2.

Table 53- Effect of climate change on heating demand of medium scenario of FEES and PH house (natural ventilation and MVHR)

MEDIUM SCENARIO	VENTILATION	HEATING DEMAND (kWh/m^2)			
		BASE-2000	2020	2050	2080
FEES	NV	84.7	74.3	65.7	60.1
	MVHR	70.1	60.6	53.1	49.1
PH	NV	31.5	26.4	22.3	19.9
	MVHR	17.3	13.5	11.0	10.3

Even though results indicate that it can be expected that the increase of temperatures will cause substantial decrease in heating demand, it is not justified to base the estimations of heating demand on predictions of distant future, which can even exceed the lifespan of the dwelling built today. Moreover, climate change would on the other hand increase the need for cooling. Furthermore, use of such predictions for justification of potential future better winter performance is particularly not justified considering that exactly the point of the FEES standard and “zero carbon” target is to reduce the CO2 emission and stop or at least lower the pace of temperature increase.

Graph 32- Effect of climate change on heating demand of medium scenario of FEES and PH house (natural ventilation and MVHR)



11.3 Input data for TAS simulations

11.3.1Construction and materials

Table 54- Upper walls

Material	ƛ (W/mK)	Thickness (m)
OSB board	0.13	0.015
rockwool	0.038	0.1
OSB board	0.13	0.015
rockwool	0.035	0.28
farmacell	0.32	0.025
membrane		

Total thickness (m)	**0.435**
U-value (W/m2K)	**0.11**

Table 55- Lower walls

Material	ƛ (W/mK)	Thickness (m)
plasterboard	0.21	0.015
rockwool	0.038	0.1
membrane		
OSB	0.13	0.015
rockwool	0.035	0.24
farmacell	0.32	0.012
cavity drain	0.046	0.005
calitite concrete	1.35	0.2

Total thickness (m)	**0.587**
U-value (W/m2K)	**0.122**

Table 56- Ground floor slab

Material	ƛ (W/mK)	Thickness (m)
finish	0.13	0.036
rockwool	0.038	0.1
rockwool	0.035	0.3
void	0.18	0.02
screed	1.15	0.065
concrete	2.3	0.3

Total thickness (m)	**0.821**
U-value (W/m2K)	**0.103**

Table 57- Terrace

Material	ƛ (W/mK)	Thickness (m)
timber board	0.13	0.14
insulation	0.024	0.13
timber board	0.13	0.06

Total thickness (m)	**0.33**
U-value (W/m2K)	**0.14**

Table 58- Roof flat

Material	ƛ (W/mK)	Thickness (m)
wood panels	0.13	0.14
membrane		
insulation (rigid baunder)	0.026	0.28
rockwool	0.04	0.12
timber board	0.13	0.02
drinage	0.153	0.025
asphalt	0.7	0.001
soil	0.8	0.15

Total thickness (m)	0.736
U-value (W/m2K)	0.067

Table 59- Roof sloping

Material	ƛ (W/mK)	Thickness (m)
plaster board	0.21	0.015
air	0.153	0.025
OSB	0.13	0.015
rockwool	0.035	0.28
farmacell	0.32	0.012
roskwool	0.038	0.1

Total thickness (m)	0.447
U-value (W/m2K)	0.11

11.3.2Thermal bridging

Table 60- Overview of thermal bridging estimations for the case study Passivhaus (PHPP)

Thermal Bridge Description	Length [m]	Y W/(mK)	Heat loss due to thermal bridging (W/K)
1)flat roof-roof window	7.05	0.043	0.3
14)slab upstand	13.40	-0.045	-0.6
4)front roof beam-1f wall	7.90	-0.090	-0.7
6)balcony:door-gf wall	3.84	-0.081	-0.3
13)balcony:doors both sides	3.68	-0.153	-0.6
8)1floor-wall	22.00	0.001	0.0
9)back beam-sloping roof	7.05	0.021	0.1
10)retaining wall-slab	22.78	-0.088	-2.0
12)wall-roof detail	11.76	-0.046	-0.5
32)1f wall-flat roof	1.67	-0.052	-0.1
33)intermed floor courtyard wall-1f slab	4.71	0.044	0.2
34)1f-sloping roof sides	9.33	-0.026	-0.2
35)1f timber stud	2.41	-0.052	-0.1
15)gf corner vertical	2.84	-0.004	0.0
16)gf corner vertical	3.15	0.060	0.2
17)gf corber vertical	2.84	-0.023	-0.1
18)gf corner vertical	2.84	0.032	0.1
19)gf corner vertical	2.84	-0.006	0.0
20)gf corner vertical	2.84	0.056	0.2
21)id.18 gf corner vertical	2.84	0.032	0.1
22)gf corner vertical	2.84	-0.022	-0.1
23)id.22 gf corner vertical	2.84	-0.022	-0.1
24)1f corner vertical	3.79	-0.014	-0.1
25)1f corner vertical	4.37	0.075	0.3
26)1f corner vertical	1.12	-0.016	0.0
27)1f corner vertical	1.12	-0.007	0.0
28)1f corner vertical	4.37	0.055	0.2
29.2)1f corner vertical	3.79	0.000	0.0
30)id.29.2 1f corner vertical	3.79	0.000	0.0
11.1)gf internal 120mm-slab	6.12	0.037	0.2
11.2)gf internal 80mm-slab	7.33	0.035	0.3
11.3)gf internal 120mm-slab	4.59	0.055	0.3
11.8)gf internal 80mm-slab	5.46	0.056	0.3
		Total heat loss due to thermal bridging (W/K)	**-2.7**

Table 61- Summary of thermal bridges of the case study Passivhaus

Thermal Bridge Overview	A (m2)	Y (W/mK)
Thermal Bridges Ambient	129.58	-0.008
Perimeter Thermal Bridges	36.18	-0.072
Thermal Bridges Floor Slab	23.50	0.044

11.3.3 Estimation of values for parameters for sensitivity analysis

11.3.3.1 Heat gains based on monitoring of the case study house

Table 62- Internal heat gains based on monitored data from the case study house

	IHG from electricity consumption (W/m^2)
Kit Sockets	0.8
Hob	0.024
Up Sockets	0.6
Up Lights	0.6
Down Sockets	0.1
Down Lights	0.3
Utility Sockets	0.001
Auxiliary	1.0

Total IHG from electricity	3.3
Rest (Table 63)	0.6
Total IHG	3.9

Table 63- Calculation of heat gains from sources other than electricity consumption

	heat (W)	number	availability	total heat (W)
persons	80	2	0.55	88
evaporation	-25	2	0.55	-27.5

total heat (W)	60.5
A(m2)	99.04
total heat gains (W/m2)	0.6

*assumed that cold water cancels out the heat from hot water

11.3.3.1 Heat gains due to varying occupant density

Table 64- Calculation of overall internal heat gains

Application	Existing (1/0) or number of people*	Norm Consumption		Utilization Factor	Frequency		Useful Energy (kWh/a)	Availability	Used During Time Period (kh/a)	Internal Heat Source (W)
Dishwashing	1	1.2	kWh/Use	1	65	/(P*a)	156	0.3	8.76	2.7
Clothes Washing	1	1.1	kWh/Use	1	57	/(P*a)	125.4	0.3	8.76	2.1
Clothes Drying	1	3.5	kWh/Use	0.875	57	/(P*a)	349.125	0.7	8.76	13.9
Refrigerating	1	0.575	kWh/d	1	365	d/a	209.875	1	8.76	24.0
Cooking	1	0.25	kWh/Use	1	500	/(P*a)	250	0.5	8.76	7.1
Lighting	***1***	***11***	***W***	***2***	***2.9***	***kh/(P*a)***	***127.6***	***1***	***8.76***	***7.3***
Consumer Electronics	***1***	***80***	***W***	***1***	***0.55***	***kh/(P*a)***	***88***	***1***	***8.76***	***5.0***
Household Appliances	***1***	***50***	***kWh***	***1***	***1***	***/(P*a)***	***100***	***1***	***8.76***	***5.7***
Auxiliary Appliances										***75.3***
Persons	***1***	***80***	***W/P***	***1***	***8.76***	***kh/a***	***700.8***	***0.55******	***8.76***	***44***
Cold Water	***1***	***-5***	***W/P***	***1***	***8.76***	***kh/a***				***-5***
Evaporation	***1***	***-25***	***W/P***	***1***	***8.76***	***kh/a***	***-438***	***1***	***8.76***	***-25***

Total Internal Heat	W	157.16
Area	A(m2)	99.02
Total Internal Heat Gains	W/m²	**1.59**

*for calculation of heat gains for different occupant densities number of people is changed in marked rows, starting from lighting to evaporation

**for final calculation of heat gains for different number of occupants as well as family structure (which is reflected in time occupants spend at home), availability factor is changed accordingly (Table 47)

11.3.3.2 Heat loss

Table 65- U-values due to estimated increase of heat loss in FEES house

		Increase of heat loss (%)		
		18	**60**	**146**
	BASE U-value (W/m2K) (with base thermal bridging)	**Resulting U-value (W/m2K)**		
walls	0.11	0.13	0.18	0.27
floor	0.103	0.122	0.16	0.25
roof sloping	0.11	0.13	0.18	0.27
roof flat	0.067	0.079	0.11	0.16
terrace	0.13	0.153	0.21	0.32
balcony door 1	0.73	0.86	1.17	1.80
balcony door 2	0.79	0.93	1.26	1.94
entrance door	0.81	0.96	1.30	1.99
window 1	0.93	1.10	1.49	2.29
window 2	0.89	1.05	1.42	2.19

Table 66- U-values due to estimated increase of heat loss in PH house

		Increase of heat loss (%)		
		18	**60**	**146**
	BASE U-value (W/m^{2}K) (with base thermal bridging)	**Resulting U-value (W/m^{2}K)**		
walls	0.22	0.26	0.35	0.54
floor	0.18	0.21	0.29	0.44
roof	0.15	0.18	0.24	0.37
windows	1.34	1.58	2.14	3.30

11.3.3.3 Thermal bridging

Table 67-Increase of U-values due to thermal bridging for FEES house

building element	thermal bridging y (W/m^{2}K)				
		0.04	0.08	0.12	0.15
	base U-value (W/m^{2}K)	**resulting overall U-value with thermal bridging (W/m^{2}K)**			
wall	0.18	0.22	0.26	0.3	0.33
floor	0.14	0.18	0.22	0.26	0.29
roof	0.11	0.15	0.19	0.23	0.26
window	1.3	1.34	1.38	1.42	1.45

Table 68- Increase of U-values due to thermal bridging for PH house

building element	thermal bridging y (W/m²K)				
		0.04	0.08	0.12	0.15
	base U-value (W/m²K)	resulting overall U-value with thermal bridging (W/m²K)			
walls	0.11	0.150	0.190	0.230	0.260
floor	0.103	0.143	0.183	0.223	0.253
roof sloping	0.11	0.150	0.190	0.230	0.260
roof flat	0.067	0.107	0.147	0.187	0.217
balcony door 1 (BD1)	0.73	0.77	0.85	0.97	1.12
balcony door 2 (BD2)	0.79	0.83	0.91	1.03	1.18
entrance door (ED)	0.81	0.85	0.93	1.05	1.20
window 1 (W1)	0.93	0.97	1.05	1.17	1.32
window 2 (W2)	0.89	0.93	1.01	1.13	1.28

11.3.3.4 Air permeability

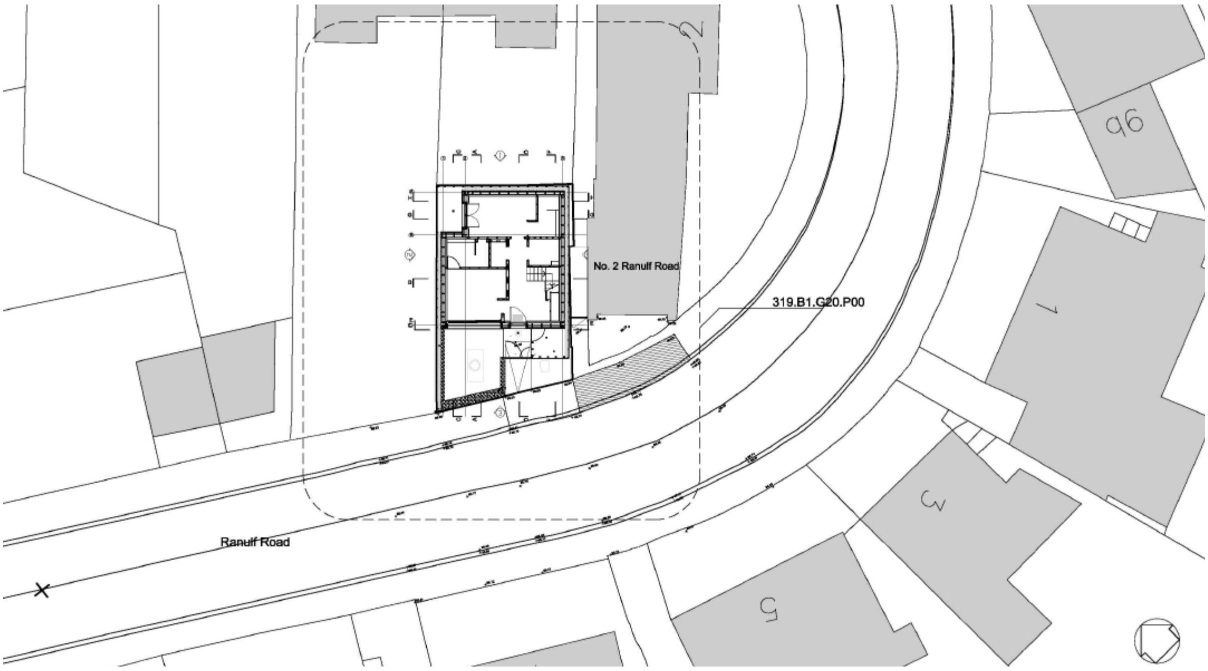
Table 69- Calculation of air change rates for corresponding air permeability

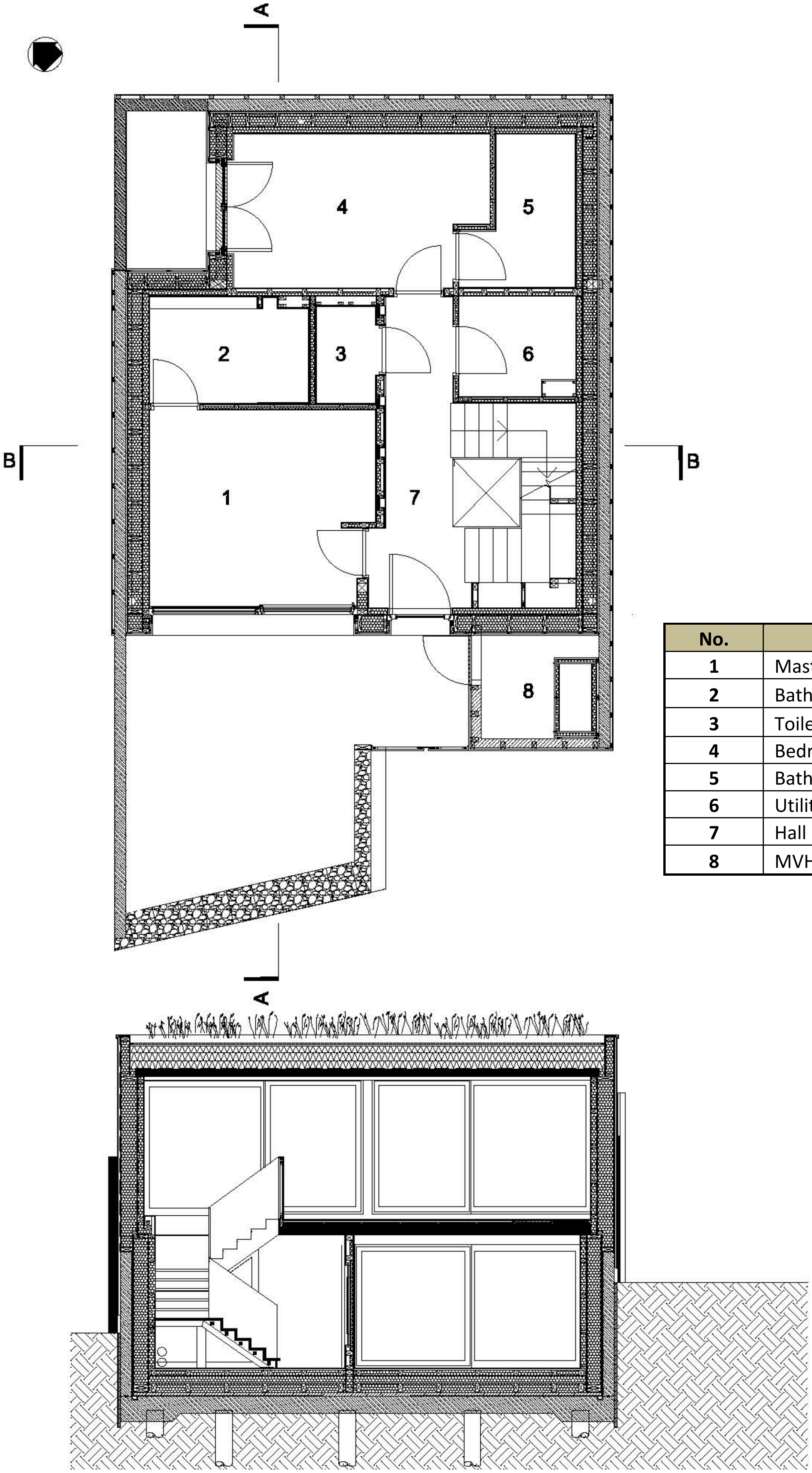
INFILTRATION				
air permeability (m³/h.m²@50Pa)	Internal volume (m³)	Area of building envelope (m²)	ACH@50Pa	ACH
0.25	237.6	388	0.4	0.02
0.5			0.8	0.04
1			1.6	0.08
2			3.3	0.16
3			4.9	0.24
4			6.5	0.33
5			8.2	0.41
6			9.8	0.49
7			11.4	0.57
8			13.1	0.65
9			14.7	0.73
10			16.3	0.82

ACH@50Pa= air permeability * A/ V
ACH=ACH@50Pa/20

11.4 Drawings

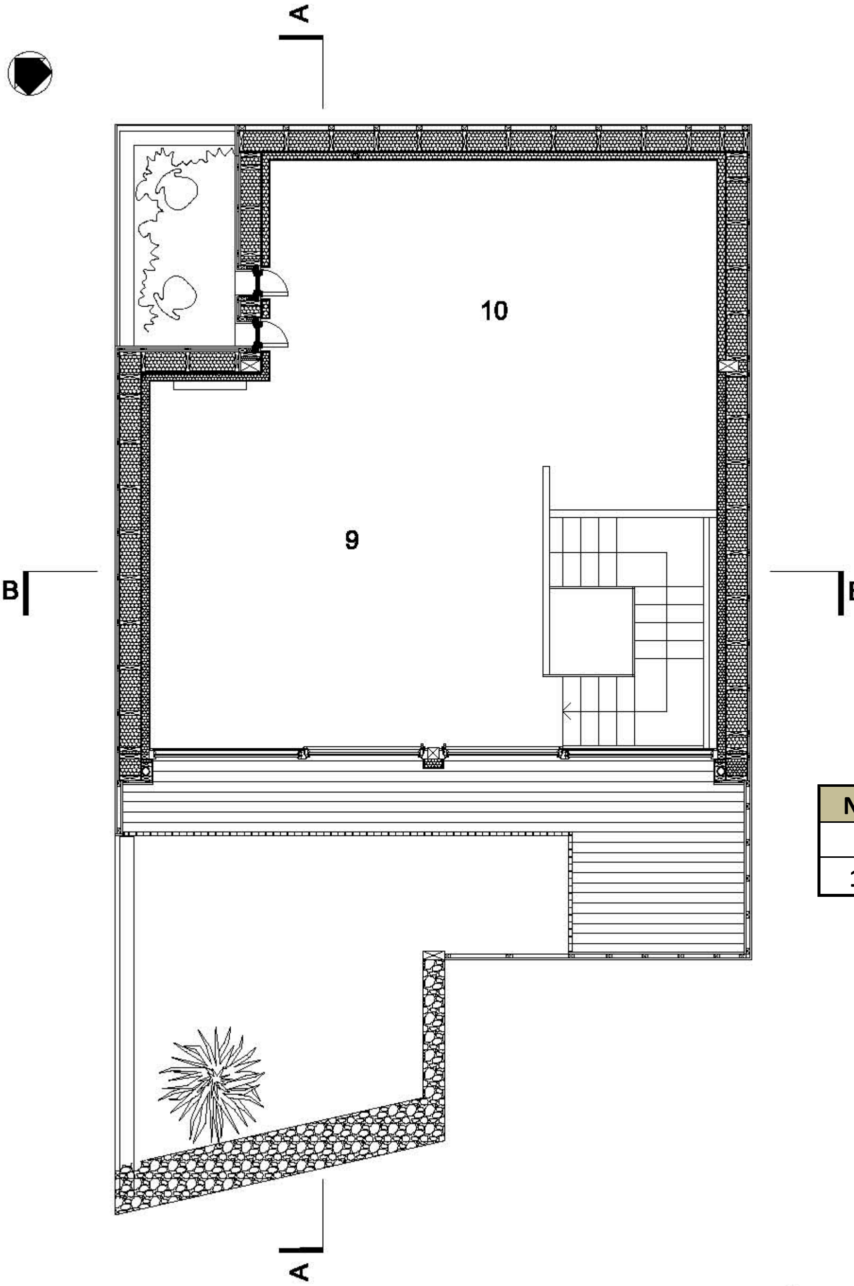
Figure 10- Site plan (Bere: architects, 2009)





No.	Room
1	Master bedroom
2	Bathroom
3	Toilet
4	Bedroom
5	Bathroom
6	Utilities room
7	Hall
8	MVHR

Figure 11- Ground floor and cross-section B-B, S=1:100 (Bere: architects, 2009)



No.	Room
9	Living room
10	Kitchen

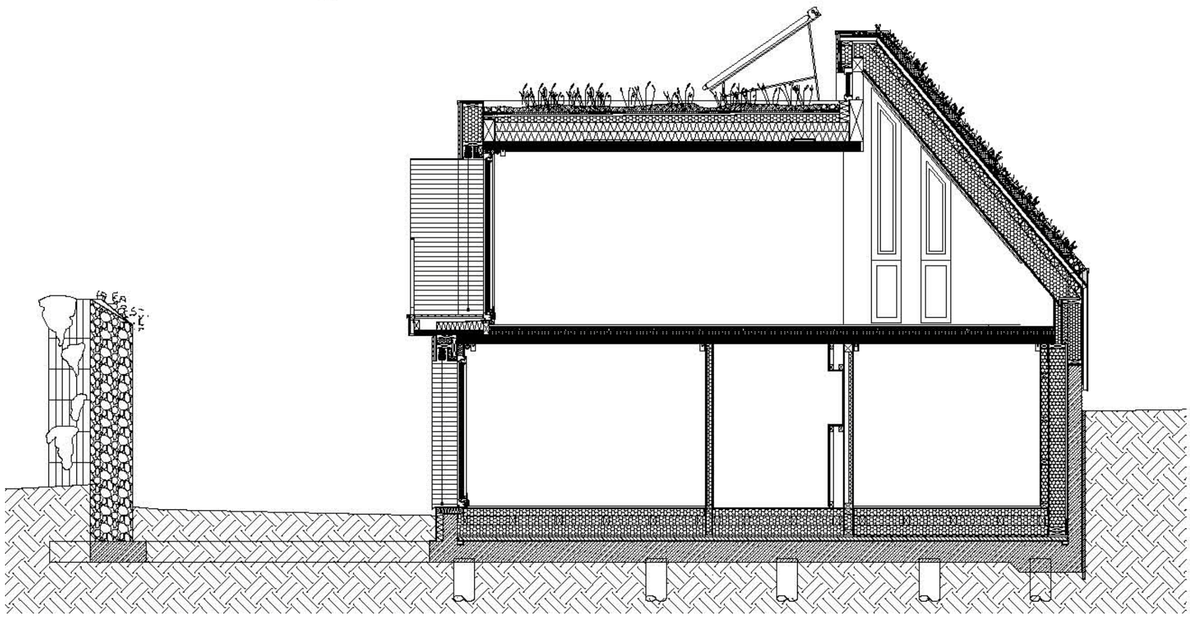


Figure 12- First floor and cross-section A-A, S=1:100 (Bere: architects, 2009)