



DESIGNER'S HANDBOOK

Designing comfortable
low energy homes
that perform as intended



CONTACTS AND ACKNOWLEDGEMENTS

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Further copies of this guide are available as a PDF download from www.thebuildingshub.co.uk

The Buildings Hub

was formed following the closure of the Zero Carbon Hub in March 2016. The vision is to maintain momentum with industry and government on key areas such as the Performance Gap, overheating, and ventilation & indoor air quality, whilst having a broader remit to help drive change in other areas. We are also seeking to support industry with training and knowledge development.

www.thebuildingshub.co.uk

Pollard Thomas Edwards

uses practical experience and research to complement and inform one another. We contribute to best practice and debate through research, post occupancy evaluation and public speaking. Recent publications have included the Builders' Book, the Services Guide, Superdensity, HAPPI report and research into housing density, overheating, ventilation and the performance gap in homes. As architects, we continue to create the whole spectrum of residential development and other essential ingredients which make our cities, towns and villages into thriving and sustainable places.

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Think Three

are experts in turning aspirations for sustainable development in the built environment into a commercial reality by adding value where it matters and makes a difference. Think Three is a sustainability consultant that embraces the three P's of sustainability, 'People, Places and Profit' to provide a holistic approach to sustainable development.

www.thinkthree.co.uk

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INTRODUCTION

This handbook sets out the key design requirements for delivering comfortable, healthy, low energy homes that perform as intended. It is not a rigid design guide, but seeks to clarify aspects of the energy Performance Gap and provide key recommendations for designers.

The Performance Gap Evidence Review Report by the Zero Carbon Hub highlighted 12 key areas of concern at the concept and detailed design stages. A key theme running through these is the need for skills and knowledge development to ensure that as-built energy performance knowledge is embedded into training for both professionals and operatives.

At the concept design stage, the priority is for the design team to have a greater understanding of the impact of their decisions on as-built energy performance. At the detailed design stage, design teams need the skills and knowledge to successfully take into account a myriad of potentially competing aspects. Important items in terms of helping to reduce the Performance Gap include: buildability, thermal detailing, tolerances, construction systems, properties of materials, site conditions, and energy performance targets. There is often a lack of specialist input, a lack of integration and a lack of communication between the technical team and the site team, which needs to be remedied.

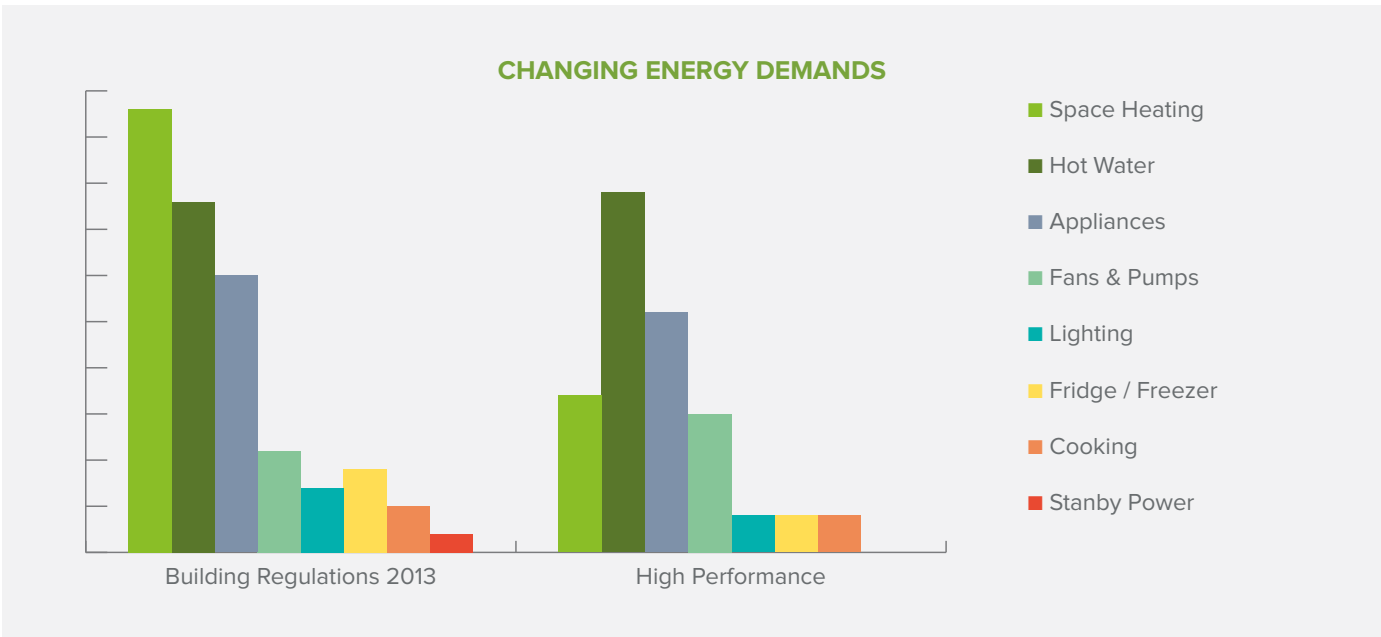


The Performance Gap

The difference between the designed and as-built energy performance of new homes is called the Performance Gap. The Performance Gap can arise in a multitude of ways within the overall house-building process and its existence represents a number of risks to industry, government and consumers. It is therefore important that the Performance Gap is closed.

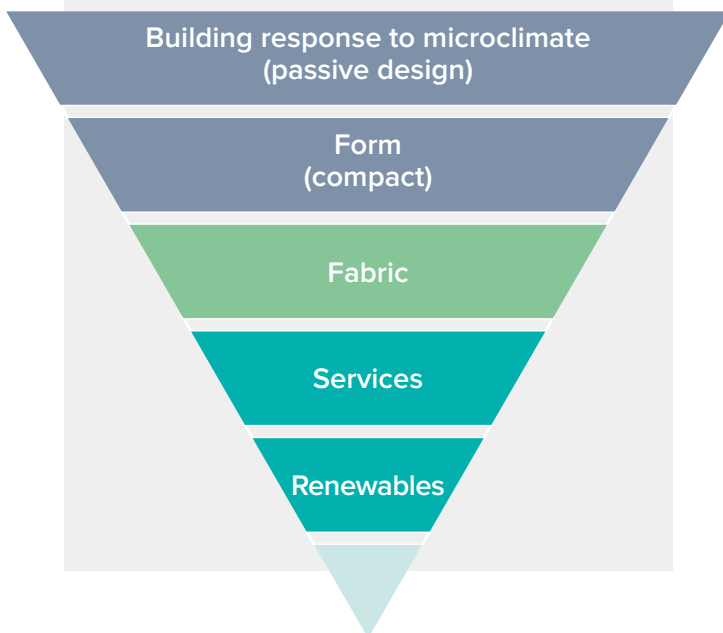
For more information see the Zero Carbon Hub's *Performance Gap Evidence Review Report* and *End of Term Report*, available from the Zero Carbon Hub website, www.zerocarbonhub.org.

This is all in the context of changing energy demands, as homes become more energy efficient. With a low energy home, the dominant energy demands are for hot water and appliances, with reduced requirements for space heating, as illustrated below.

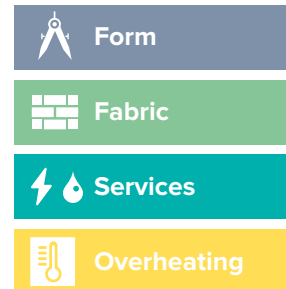


In order to design low energy homes, the following hierarchy should be addressed.

The site and its microclimate should first be analysed. The building design responds to these environmental conditions. Form, fabric and services should be designed and specified to be efficient. The designer should also address the feasibility of renewable energy production on site. As part of this appropriate controls for services and appliances should be specified to minimise unnecessary energy use. Controls are not in the scope of this handbook, but more information is available in the Zero Carbon Hub's *Services Guide*.



The Designer's Handbook is split into four sections:



Each section includes key information and recommendations. Indoor air quality, daylighting and thermal comfort (preventing overheating) are key outcomes that have specific pages to highlight their importance to achieving comfortable and healthy internal environments.

This handbook sets out to combine guidance in terms of reducing the Performance Gap with suggestions for good practice in terms of low energy housing design. Recommendations as to what this means as a performance specification are included, but this is intended only as a guide to inform project-specific aspirations.

The key recommendations can be used as checklists for good practice to prompt discussion within the project team. However, this handbook is not exhaustive in scope, and has not examined all aspects of good practice design.

This handbook is one of a series of good practice guides that are aimed at addressing the Performance Gap and improving the design, procurement and construction quality of new homes. All publications in the series are available for free download from The Buildings Hub website, www.thebuildingshub.co.uk.

LOW ENERGY HOMES

This handbook sets out a model for the key design requirements for delivering comfortable, healthy, low energy homes that perform as intended. The main principles are summarised here.

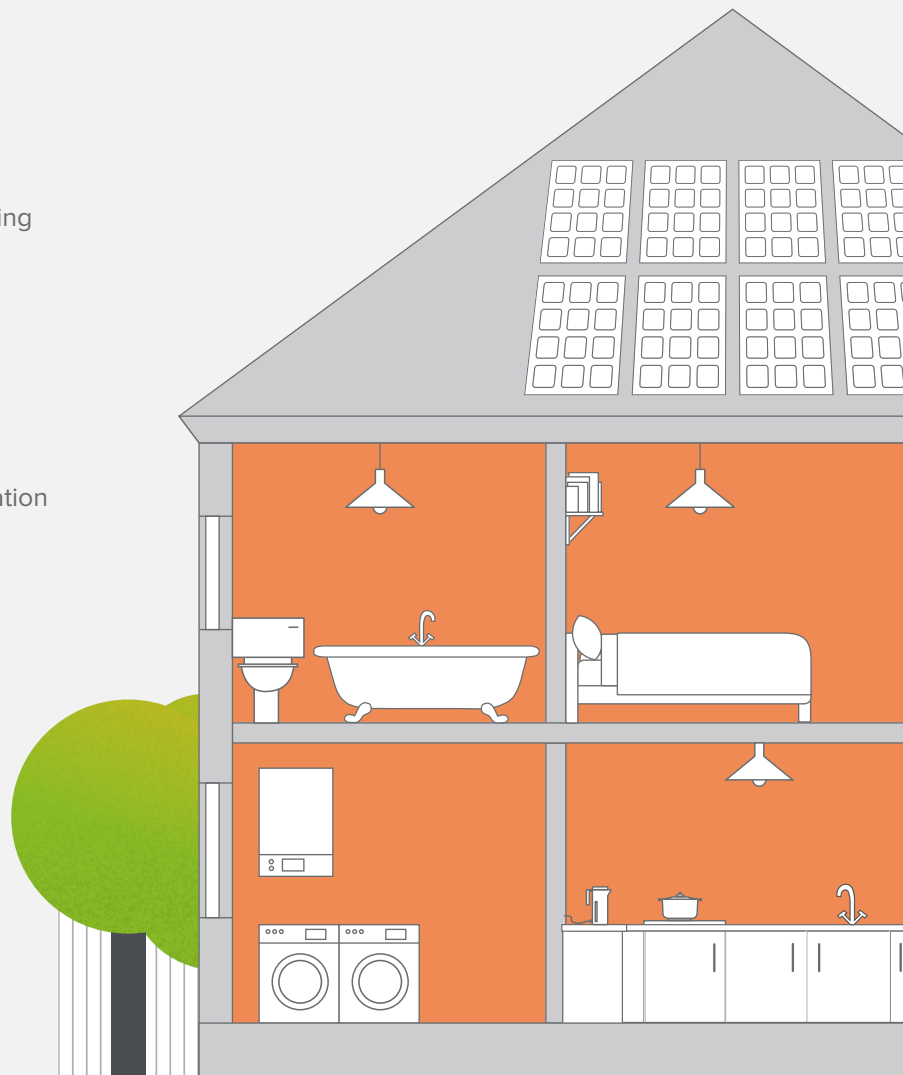
Low Energy Use

- The energy hierarchy (Be Lean, Be Clean, Be Green) is used to inform the design and building services strategy
- The building form and fabric is designed to have very low heating (& cooling) demands
- It uses efficient building services, appliances and smart controls
- It produces renewable energy using local generation
- It is designed to address Performance Gap risk

Microclimate

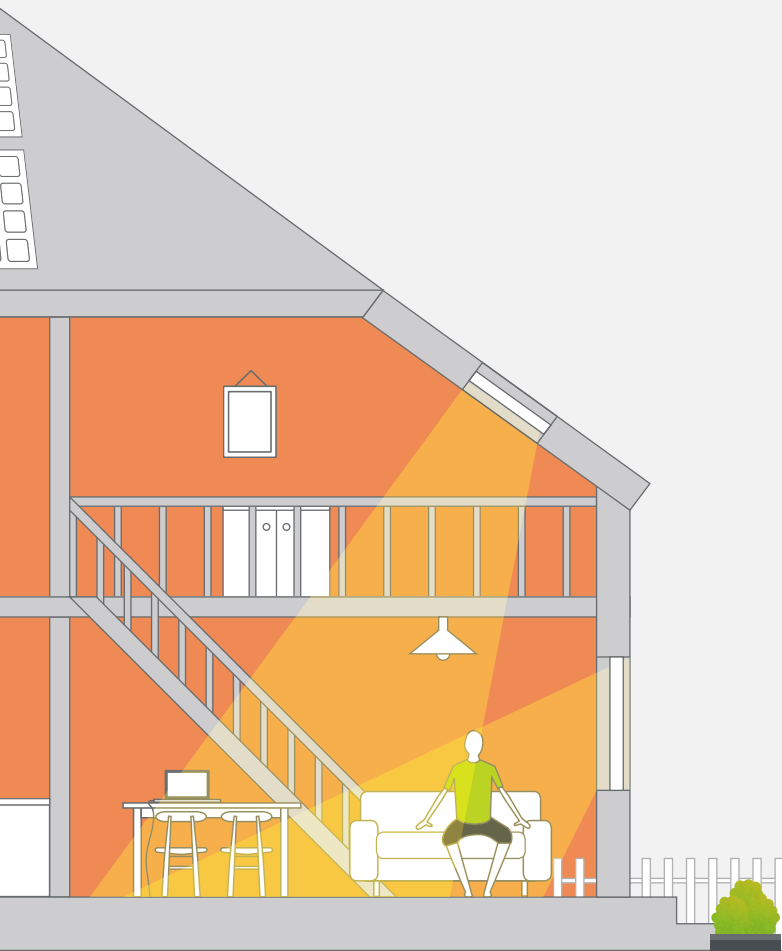
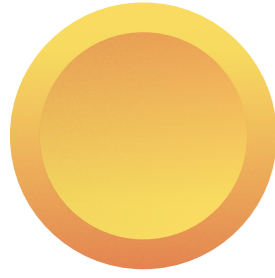
Green Infrastructure will improve the microclimate with these measures prioritised:

- Soft landscaping
- Biodiversity
- Vegetation and trees used to counter external pollution, noise and overheating
- Buildings orientated for wind buffering and ventilation
- SUDS to reduce surface water run off
- Local rainwater that irrigates green infrastructure



Thermal Comfort

- The building doesn't overheat and occupants are comfortable
- The design optimises solar gains within comfortable thermal limits
- The building is designed to adapt as the climate changes over its lifetime



Good Daylight

- The building is designed to deliver good levels of daylight and sunlight
- The health and well-being benefits of exposure to natural light are accounted for in the designs

Good Indoor Air Quality

- Design for appropriate ventilation as opposed to unintended infiltration
- The building envelope has low air permeability to reduce infiltration heat losses and minimise external pollutants
- Effective and efficient ventilation systems supply fresh air to meet indoor air quality requirements
- Internal fittings and finishes are specified to reduce internal pollution levels

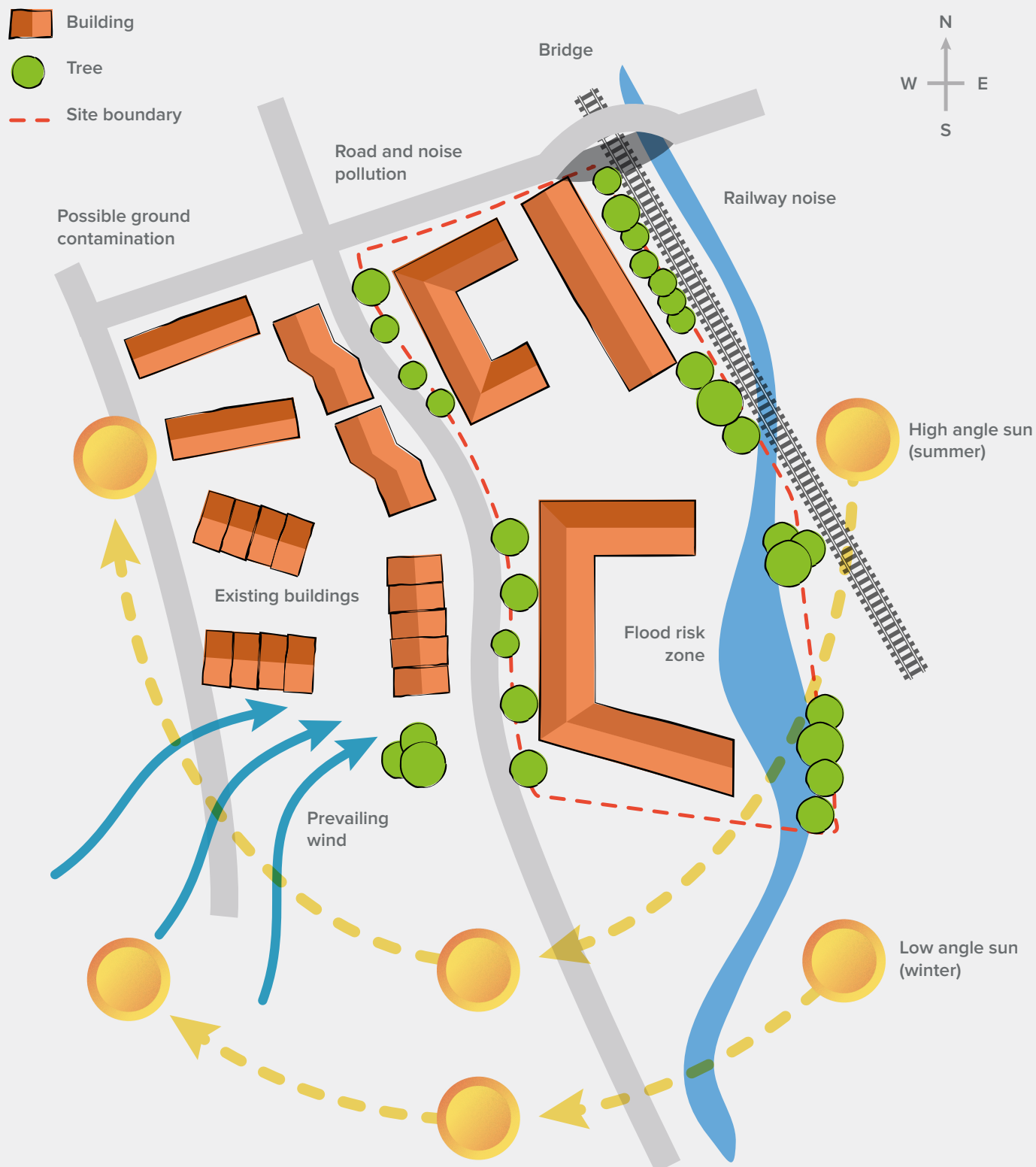
Adaptable to Climate Change

- Designs mitigate the risks of summer overheating and respond to anticipated future climatic conditions with scope for additional shading and increased ventilation
- Materials are selected for their durability as well as having lower embodied environmental impact
- Designs account for end-of-life to enable efficient deconstruction and reuse of valuable materials



1.0 SITE CONTEXT

Example opportunities and constraints plan





Opportunities and Constraints plan should include the following:

- Sun path for winter, summer and equinox (20 March) with overshadowing
- Prevailing wind to consider wind buffering and ventilation
- Microclimate features, e.g. lake, forest, city, mountain, park
- Existing landscaping, ecology and trees
- Existing amenity space and views
- Existing shelter and obstructions e.g. neighbouring buildings
- Local infrastructure, e.g. roads, railway, services, shops
- Transport routes, e.g. cycle or pedestrian paths, roads, train, bus
- Pollution and noise sources
- Flood risk areas
- Areas of contamination
- Underground and overground services
- Future development plans

Early designs should consider:

- Percentage glazing for each proposed elevation and potential shading options
- Roof orientation for solar access
- Green Infrastructure such as green roofs, SUDs and other microclimatic benefits
- Cycle and pedestrianised areas
- Space for communal plant
- Electric vehicle charging points

Key questions to ask

- Are there planning requirements that preclude efficient form or layout of the building(s)?
- Are adjacent buildings or trees overshadowing the site, or will they in the future?
- Have single aspect dwellings been minimised?
- Does the arrangement of windows and openings allow for good natural ventilation and daylight?
- Does the roof design maximise the opportunities for solar access?
- Have the building services been designed with future energy provision in mind?
- Are living rooms arranged in relation to sunlight, open space and views?
- Is there a risk of overheating?

Single Aspect Dwellings

- Avoid single aspect dwellings where possible.
- Where single aspect dwellings are unavoidable, model overheating and daylight. Improved fabric, windows, and enhanced purge ventilation will be necessary.
- Ensure designs can support external shading or shutters for south and west-facing single aspect apartments.
- Avoid west-facing bedrooms to prevent overheating.

Dense Developments

There is a higher risk of poor air quality, poor daylighting and overheating in dense developments. Environmental modelling (dynamic thermal simulation) should be carried out to check thermal comfort, with appropriate strategies implemented to mitigate this risk of uncomfortable temperatures. Daylight modelling will be needed to assess the daylight factor inside the dwellings, and design improvements made if necessary.



1.1 FORM FACTORS

The building form has a considerable influence on its energy demands. The form can be measured with the “Form Factor.” This is the relationship between the Heat Loss Surface Area and the Treated Floor Area (SA/TFA). This ratio can be useful when comparing the complexity of different building variants with the same total floor area. The general rule is that more compact buildings with lower Form Factors have less heat loss.

The more complex the form, the more insulation required and the better the building performance must become to achieve a notional standard (see table below).

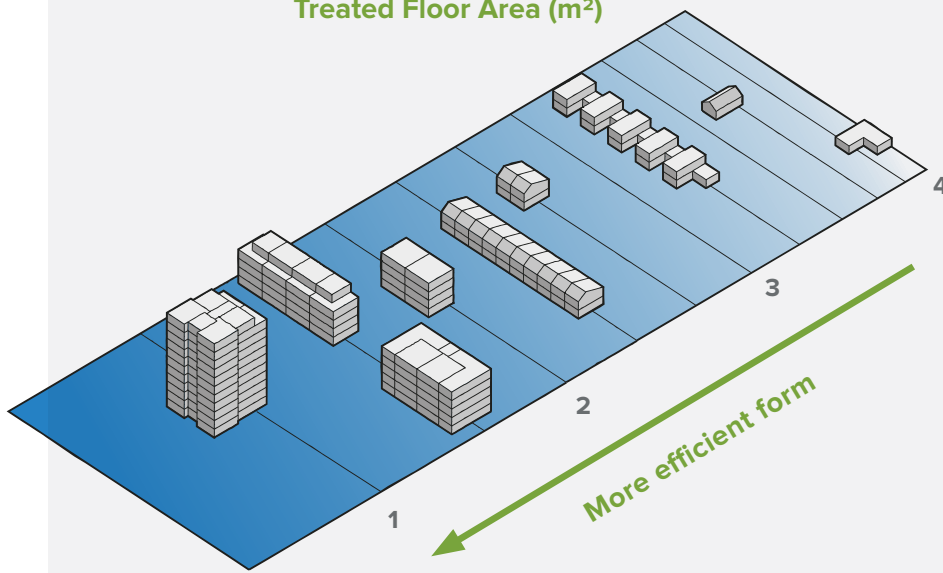
Key recommendations

- Use energy modelling early in the design process to test the impact of different forms and orientation on performance.
- Keep the building envelope as simple and compact as possible to improve thermal performance and reduce the complexity of joint detailing.

Form Factor (FF)	Typology	Approximate U-values required for low energy
<2	Apartment block or uniform terrace	0.20 to 0.15 W/m ² K
2-3	Semi-detached or compact detached houses	0.15 to 0.12 W/m ² K
3-4	Less compact detached houses or compact detached bungalows	0.12 to 0.10 W/m ² K
>4	Complex shape detached bungalows	<0.10 W/m ² K

More efficient form

$$\text{Form Factor} = \frac{\text{Heat Loss Surface Area (m}^2\text{)}}{\text{Treated Floor Area (m}^2\text{)}}$$



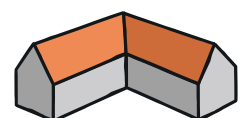
FORM FACTOR

2.9



FORM FACTOR

3.9



For example a detached 200m² property if configured as an L-shaped bungalow would be considerably less efficient (with higher Form Factor) than a 2-story rectangular plan house.

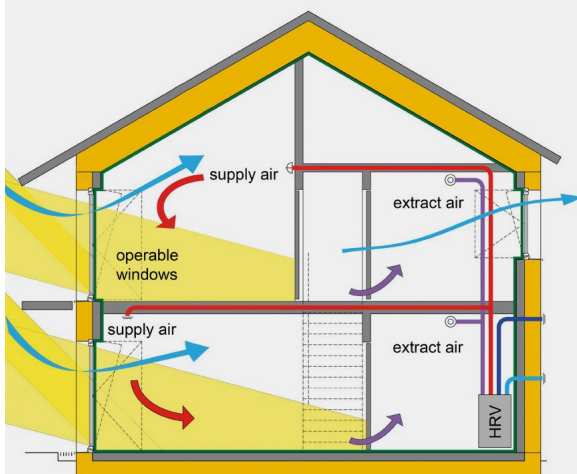


1.2 PASSIVE DESIGN

Passive design utilises energy from the outside environment (such as solar radiation) and available internal heat gains (such as people and appliances) to create a comfortable internal environment rather than relying on active equipment. Solar gain can contribute up to 25% of a new home's heating demand. Passive solar design must provide suitable measures to prevent overheating in summer.

The Passivhaus Standard

The passivhaus standard provides a framework and target for low energy comfortable homes that perform as intended. In practice, this means achieving a building with space heating and overall energy requirement close to the theoretical minimum. Passivhaus uses passive principles to their full extent before active systems are employed. Studies show that homes built to passivhaus certification perform better than other low energy homes. For more information see the Passivhaus Trust website, www.passivhaustrust.org.uk



© Passivhaus Trust

Key Recommendations

- **Orientate the long-axis of the building in an east-west direction**
This provides solar gain and allows more rooms to receive sunlight during the day. In cold or temperate climates like in the UK, winter sun is beneficial for the health and wellbeing of the occupants.
- **Locate living rooms on south side of the house**
The optimal area for good daylight should be the primary motive for the window designs, rather than maximising gains.
- **Large areas of south and west facing glazing should be avoided**
The area of glazing on a south or west façade should not be greater than 40% of the elevation unless suitable solar shading is provided.
- **North-facing windows don't need to be small, but should be high performing**
Ensure windows are high performance with low U-value, and high g-value to provide solar gains and minimise heat loss.
- **Use shading on south and west side of the house to prevent overheating**
Minimise reflective external hard surfaces adjacent to these areas. Consider overhangs, external shutters, louvres, low g-value windows (below $g=0.5$), vegetation and deciduous trees, and green roofs to keep the dwelling cool. Use environmental modelling to highlight risk of overheating.
- **Thermal mass where appropriate**
Thermal mass can help stabilise the internal temperature of dwellings in warmer climates, but should be used appropriately and with a suitable ventilation strategy.
- **Aim for the passivhaus standard**
The passivhaus design and construction process helps to reduce the Performance Gap, with careful detailing and rigorous construction management.



1.3 DAYLIGHT



Daylight or skylight is the diffuse light from the sky which improves visual and thermal comfort and has associated health and wellbeing benefits. It is different from sunlight which refers to the “direct sunlight” or solar gain which can heat a home but also produce glare and excessive heat gain.

Good practice daylight design has the following benefits:



Improved visual and thermal comfort



Improved health and wellbeing

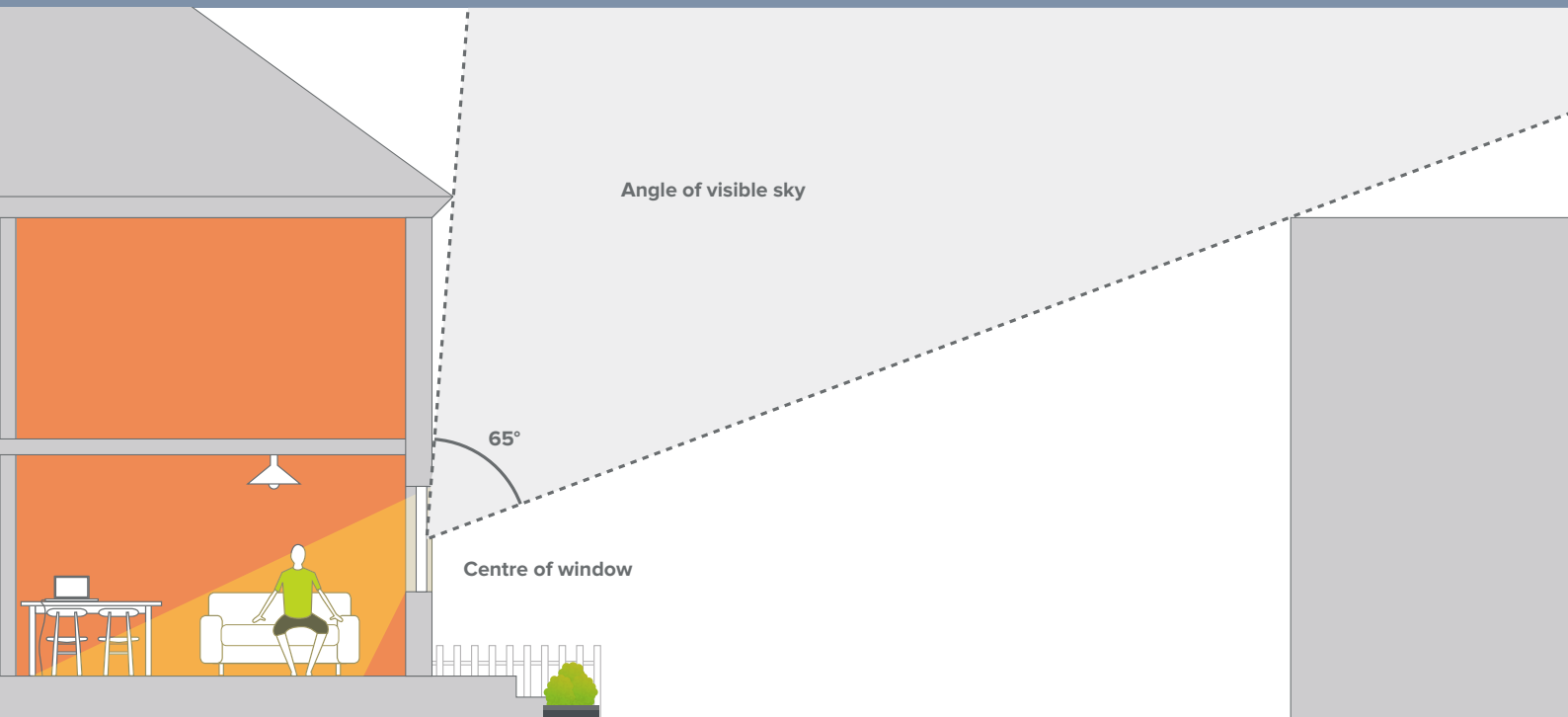


Reduced electric lighting costs

Daylight levels can be improved by: angling windows towards the sky; chamfering window reveals; increasing floor to ceiling heights; increasing the height of window heads; using light coloured internal finishes, increasing the percentage glazing of windows (increase Frame Factor); and specifying rooflights, lightwell and lightshelves. Note that triple glazing has a lower daylight and solar transmission (g-value). This is beneficial to help prevent overheating, but can slightly reduce daylight levels and useful winter solar gain.

Key recommendations

- Dwellings overshadowed by neighbouring units, like courtyard arrangements, should be modelled for daylight and sunlight at an early stage of the design process to ensure improvements to the design can be made.
- Window sizes should be appropriate to the size and use of the room. E.g. Living rooms will have larger windows than bedrooms. The total window area should be around 20% of the internal floor area.
- Aim for all habitable rooms to have daylight factors of 2 – 5%.



Angle of visible sky

If the angle of visible sky from the centre of the window is:

- greater than 65°, then good daylight can be provided using conventional windows
- between 45° and 65°, then larger windows or room layout changes are usually required
- between 25° and 45°, it can be very difficult to provide adequate daylight unless very large windows are used
- less than 25°, then it is generally impossible to achieve adequate daylight

i Average Daylight Factor (ADF)

The average daylight factor is a common measure for the amount of daylight in a room. It expresses the percentage of daylight available inside compared to the amount of daylight available outside the building. Rooms with an ADF of 2% or more are considered daylit. A room with an ADF above 5% has good daylight levels and reduced needs for electric lighting in overcast conditions. BS8206:2 has minimum ADF recommendations for dwellings of 2% for kitchens; 1.5% for living rooms; and 1% for bedrooms.

i The Vertical Sky Component (VSC)

The Vertical Sky Component (VSC) is a measure of daylighting potential. It is expressed as the percentage of daylight from an unobstructed sky falling on a vertical window compared to the percentage falling on a horizontal plane under the same sky conditions. The VSC test is the main test to assess the impact of a new development on neighbouring properties. The test should be applied to the main window of each habitable room.

2.0 MINIMISING HEAT LOSSES

Low energy homes that perform as intended have thermally efficient building envelopes, low air permeability and minimal thermal bridging.

The overall heat loss from a home includes transmission losses and ventilation losses. Transmission losses are the total heat loss by conduction through the heated building envelope. This can be calculated by adding together the element losses and the thermal bridge losses.

Ventilation losses include heat loss from infiltration, a result of the air permeability of the building fabric.

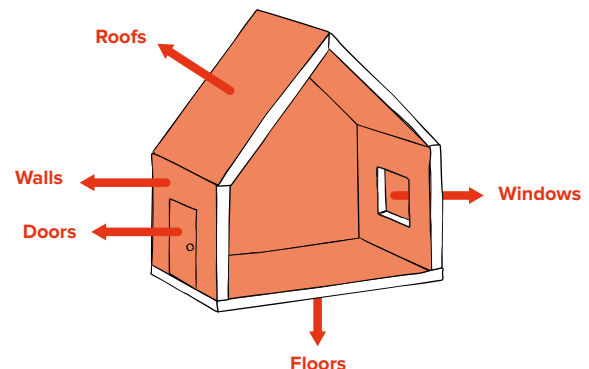
In construction terms, the overall heat loss from a home is the total heat loss through all building elements such as wall, roof, floor, and junctions, plus heat loss through infiltration and ventilation.

A good building fabric consists of three key elements:

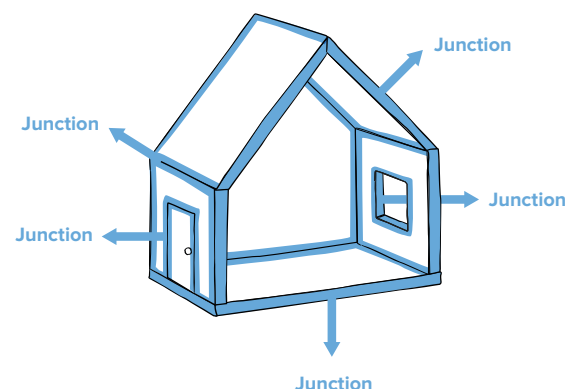
- Continuous insulation (low U-values)
- Minimal thermal bridging (low PSI-values)
- Continuous air barrier (low air permeability).

This section will deal with each of these in more detail.

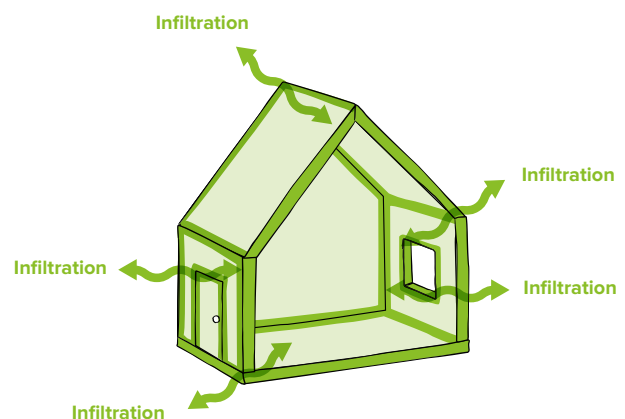
TOTAL HEAT LOSS



ELEMENT LOSSES (U-VALUE, W/m²K)



THERMAL BRIDGE LOSSES (PSI-VALUES, W/m.K)



INFILTRATION HEAT LOSS

Continuous Insulation

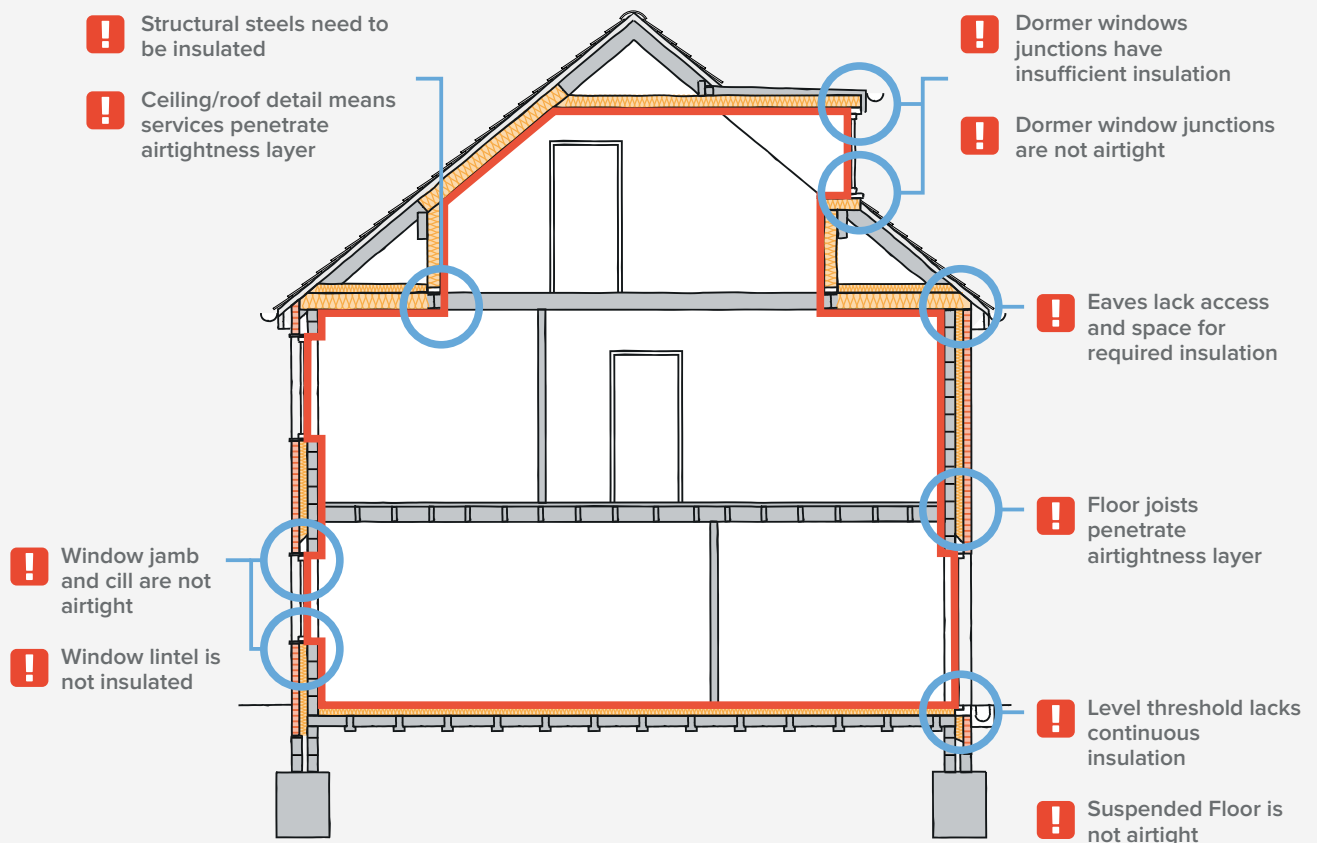
The building envelope needs a continuous layer of insulation in order to successfully reduce fabric heat losses. Ideally this should be continuous around all junctions, with no gaps.

Key building elements such as soffits, eaves, roof terraces, dormers, bay windows and undercrofts should also be insulated to the same standard as the main envelope to avoid cold-spots. These areas are often neglected and are key areas of performance failure because of buildability issues around fitting insulation in awkward locations or tight spaces.

Key recommendations

- Choose a construction method that readily allows continuous insulation.
- Consider specifying high performance insulation at key junctions.
- Consider the construction sequencing and installation methods.
- Insulate party walls/floors and sheltered walls to the same standard as external walls and floors.

Care needs to be taken in detailing at junctions to minimise thermal bridging and enable continuous insulation and airtightness barrier whilst ensuring buildability. Some issues are shown here:



Minimising Thermal Bridging

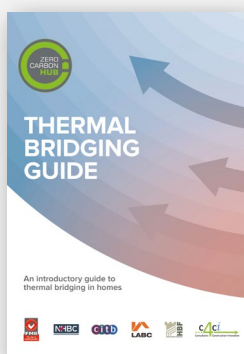
A thermal bridge (sometimes called a cold bridge) is a localised weakness or discontinuity in the thermal envelope of a building leading to increased heat loss, condensation and surface mould. They generally occur when the insulation layer is interrupted by a more conductive material.

The two types are repeating or non-repeating thermal bridges. Non-repeating (or linear) thermal bridges are dealt with by calculating “PSI-values”. PSI-values are a measure of heat loss through a junction in W/m.K. These can be combined to produce a dwelling Y-value which expresses the overall heat loss arising from all of the building junctions.

Although there are many junctions within a dwelling, some have low PSI-values because of the materials used and others occur over short lengths (e.g. cills). It is important to address junctions with the highest PSI-values (e.g. steel lintels) and those occurring over the longest lengths (e.g. wall-to-floor junction). For more detail, refer to the Zero Carbon Hub’s *Thermal Bridging Guide*.

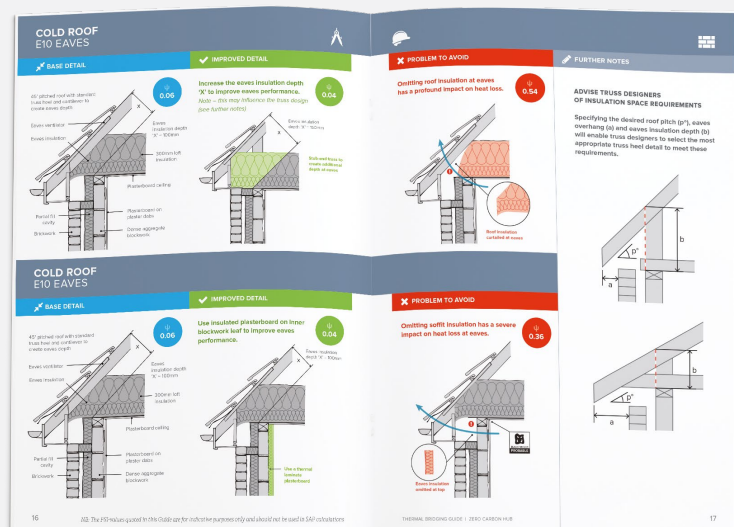
Key recommendations

- Significant thermal bridges should be designed out.
- Consider the use of standard details e.g. from LABC
- Where standard details are not available, e.g. concrete frame structure, then bespoke PSI-value calculations should be undertaken.
- Modelling key details for thermal bridging will highlight easy wins to reduce fabric heat loss.
- Check the buildability of the joint details.
- Mechanical fixings through the insulation create point thermal bridges and should be minimised or avoided where possible. If fixings are unavoidable, where possible use non-conductive fixings; e.g. plastic or hybrid fixings.



Thermal Bridging Guide

This is an introductory guide to thermal bridging in homes. It demonstrates key construction details in new build housing and gives examples of ways to reduce heat loss through the design of construction details.



Continuous Airtightness Barrier

The structure should have a designated air barrier which blocks air movement, which should be noted on relevant construction drawings.

- Masonry construction requires gap free blockwork and mortar with an airtightness layer of plaster. Plasterboard is not airtight so requires a continuous parge coat or alternatively a vapour control layer behind a service zone
- Concrete construction – concrete is airtight, but light steel infill will require an airtight layer of ply, OSB or polythene sheet, taped at joints and corners
- Timber frame construction will need an internal OSB board or polythene membrane

Reducing the air permeability of the fabric requires controlled ventilation to minimise build-up of moisture, CO₂ and other internal pollutants.

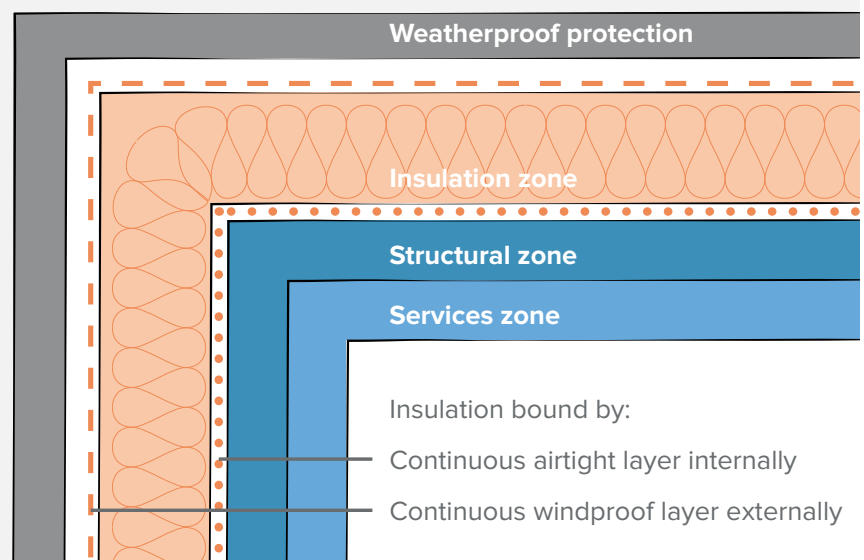
For low energy homes an air permeability of 3m³/h.m² @50Pa or below should be targeted to enable efficient heat recovery ventilation.

Key recommendations

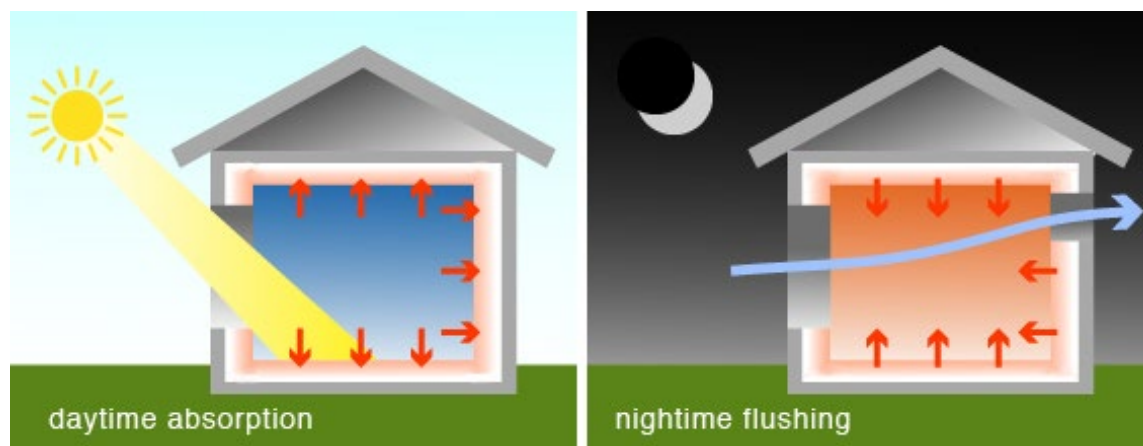
- The air barrier must be continuous over the entire thermal envelope, and sealed with special airtight tapes.
- It is good practice to allow for a service zone that is inside of the airtight layer.
- Services penetrations and window and door openings must be carefully sealed.
- Airtightness testing should be carried out before finishes are applied to provide a more robust, long lasting air barrier and to enable these internal layers to be changed or adapted without compromising the airtightness of the fabric.

Ideal Thermal Performance

To achieve a thermally efficient building envelope, the ideal position of each layer is shown in this notional plan of a external corner junction. Alternatively the airtightness layer can be on the inside of the structure, which allows easier testing, but is harder to keep continuous.



2.1 THERMAL MASS IN PRACTICE



Summer cooling by Thermal Mass illustrated

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Thermal Mass

Construction types can be broadly categorised as lightweight, medium weight or heavyweight according to the level of thermal mass. Thermal mass is the ability of a material to absorb and store heat energy. More heat energy is required to change the temperature of high density materials like concrete, bricks and tiles, than of a lightweight material such as timber, which has lower thermal mass. Thermal mass affects the internal temperature of dwellings, providing “inertia” against temperature fluctuations. It should be specified with regards to context, especially external environmental conditions and building occupancy.

- Thermal mass helps to make internal temperatures more consistent, but does not provide free heating or cooling.
- Thermal mass can potentially increase winter heating requirements and increase risk of overheating at night.
- A masonry cavity wall will provide high thermal mass if using wet plaster on the internal blockwork. Plasterboard on dabs will isolate the thermal mass from the internal space and so is not as effective.

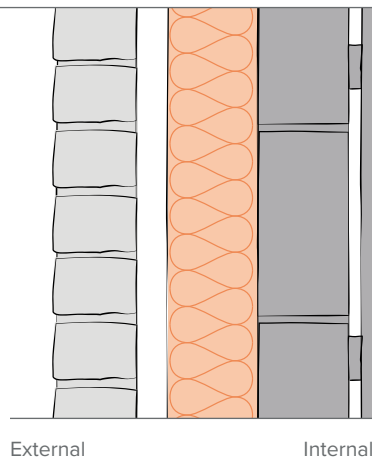
Key recommendations

- Effective thermal mass needs to be on the inside of the insulated building envelope, and in direct contact with internal air volume, to dampen the extremes of daily internal temperature cycles.
- When specifying thermal mass, ensure it is compatible with external climate and building occupancy patterns. For example, thermal mass is useful in climates with large temperature swings or homes with high internal gains and purge ventilation. Lightweight structures are preferable where homes are not occupied during the day as they are quicker to heat up.
- Thermal mass must be used with adequate ventilation to keep the building cool and release unwanted stored heat in summer.

Different forms of construction and their inherent levels of thermal mass

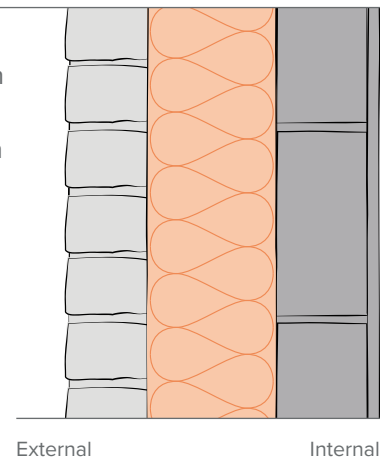
MEDIUM / LIGHTWEIGHT

Cavity wall construction using brick and block with partial fill insulation and dot/dab plasterboard internal face.



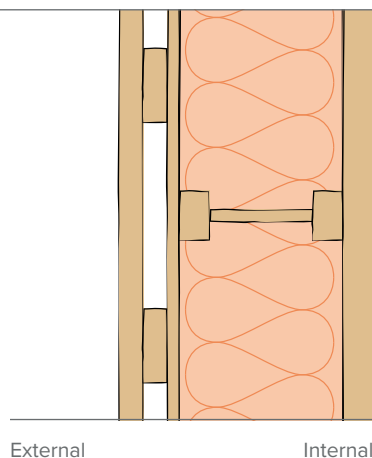
HEAVYWEIGHT

Cavity wall construction with plaster internal finish. The plaster finish provides thermal mass and good airtightness. Thermal mass varies depending on internal block specification.



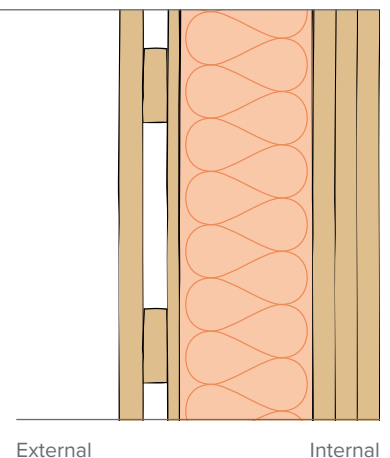
LIGHTWEIGHT

Timber I-joist panel, fully filled with insulation and rainscreen cladding. Internal claddings can vary to change thermal mass.



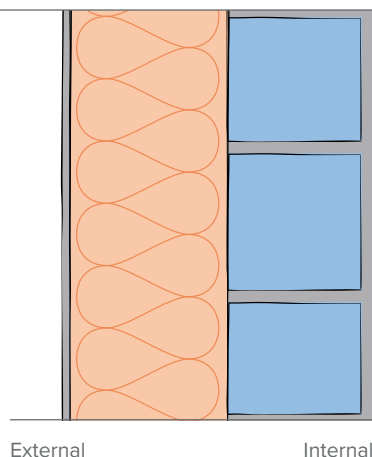
MEDIUMWEIGHT

Cross Laminated Timber (CLT) panels with external insulation and rainscreen cladding. CLT left exposed on internal face.



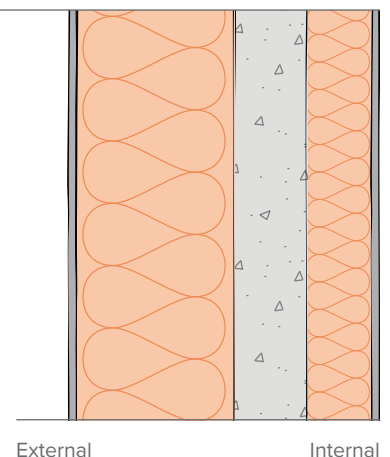
MEDIUM/ HEAVYWEIGHT

Load bearing block construction with external insulation composite system. Plaster internal finish will expose thermal mass and provide good airtightness.



MEDIUM/ HEAVYWEIGHT

Insulated Concrete Formwork (ICF) with plaster internal finish to expose concrete thermal mass.



2.2 RECOMMENDED PERFORMANCE SPECIFICATIONS

Specify detailed performance criteria and minimum requirements for all elements of the building envelope and services. This will help to ensure the same performance standards can be met by any future substitution of materials.

An example of an enhanced performance specification for a low energy home is shown in the table below, alongside the Notional values as set out in Building Regulations Part L1A (2013), for England (as a comparison).

Key recommendations

- Ensure the specification and drawings are clear and comprehensive and that the importance of installing the right products is communicated to the procurement and site teams.

Element	Enhanced specification	Notional Values (ADL1A Table 4)	Notes on enhanced specification
External Walls	0.15 – 0.12 W/m ² K	0.18 W/m ² K	100 – 300mm of insulation depending on thermal resistance (W/m.K). E.g. mineral wool versus PIR insulation. Required U-value varies depending on Form Factor.
Sheltered walls (wall to unheated space)	0.18 – 0.15 W/m ² K	n/a	Treat as external walls.
Party walls (between dwellings)	0.0 W/m ² K	0.0 W/m ² K	Fully filled with mineral wool insulation and edge sealed.
External doors (opaque)	Below 1.0 W/m ² K	1.0 W/m ² K	U-values <1.0 W/m ² K can carry a cost premium. External doors form a small percentage of treated envelope.
External doors (semi-glazed)	Below 1.0 W/m ² K	1.2 W/m ² K	U-values <1.0 W/m ² K can carry a cost premium. External doors form a small percentage of treated envelope.
Windows	Triple glazed 0.85 W/m ² K (whole window value) 0.5 g-value 0.8 Frame Factor	Double glazed 1.4 W/m ² K (whole window value) 0.63 g-value	Check and specify whole window U-value and g-value. Passivhaus certified or triple glazed windows recommended. Slight cost uplift for triple glazing, with potential additional installation cost due to extra weight.
Roof-lights	Below 1.0 W/m ² K	1.4 W/m ² K	Aim to match performance of vertical windows.
Ground floors	0.12 – 0.10 W/m ² K	0.13 W/m ² K	Approx 200mm insulation depending on thermal resistance and floor build-ups.

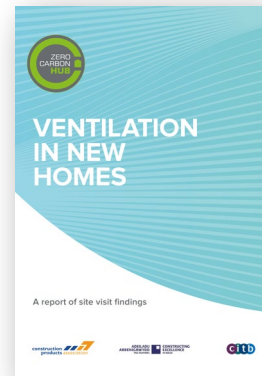


Element	 Enhanced specification	Notional Values (ADL1A Table 4)	Notes on enhanced specification
Intermediate floors	0.15 – 0.13 W/m ² K	n/a	Treat as ground floors.
Terrace and balconies above flats	0.15 W/m ² K	n/a	Ensure sufficient depth to achieve required U-values & level thresholds (see Building Regulations Part M).
Roof – flat roof	0.15 – 0.10 W/m ² K	0.13 W/m ² K	150 – 300mm of insulation depending on thermal resistance and roof build-ups.
Roof – pitched	0.12 – 0.10 W/m ² K	0.13 W/m ² K	More than 300mm loft quilt in cold roof.
Exposed soffit	0.15 – 0.13 W/m ² K	n/a	Ensure insulation is continuous; cold bridges avoided; ventilation included.
Linear Thermal Transmittance	Below 0.05 W/m.K	0.05 – 0.15 W/m.K	Appoint a specialist to model key details for thermal bridge PSI-values.
Design Air Permeability	<3.0 m ³ /h.m ² @50 Pa	5.0 m ³ /h.m ² @50 Pa	Use proprietary tapes, seals, grommets etc. <1.0 m ³ /h.m ² may be favourable solution.
Ventilation	System 4 – MVHR SFP <0.5 l/s Efficiency >85%	System 1	Use heat recovery ventilation to maximise benefits of super-insulated building envelope. Specify demand control MEV in warmer climates.
Air conditioning	None	None	Use dynamic thermal simulation to test for overheating and prevent with passive design measures such as external shading.

Note that calculated U-values generally indicate the best case scenario in ideal conditions, with worse as-built performance a common occurrence.

3.0 INDOOR AIR QUALITY

If ventilation is inadequate due to poor installation, poor controls or poor maintenance then there is a higher risk of poor indoor air quality (IAQ) in new build homes due to their low air permeability. Lack of ventilation leads to increased humidity and condensation levels, which can cause mould. It also contributes towards a build up of chemical pollutants, particulates, pathogens and other unwanted substances that can have a major impact on the health of occupants. For more information, please refer to the Zero Carbon Hub's *Ventilation in New Homes* study and *Services Guide*.



Key recommendations

- Consider the ventilation strategy with specialist input at pre-planning stage to ensure entire systems are correctly designed, co-ordinated and integrated. Plan how the homes will remove contaminant sources, dilution and control, and procedures for the pre-occupancy flush out of any contaminants.
- Ductwork is particularly vulnerable to poor installation and should be kept large, short, rigid and straight.
- Design for simple controls and easy maintenance of units e.g. filter change.
- Design, install and commission systems to meet the recommendations in the Domestic Ventilation Compliance Guide (DVCG).
- Specify a dedicated “indoor drying area” – a ventilated cupboard or utility room which will deter drying of clothes on radiators and in bedrooms.
- Specify non-toxic materials for indoor finishes to control the source of pollutants such as VOCs, formaldehyde and other particulate matter.
- Specify fully openable windows to provide a minimum of 1/20th area of internal floor area.
- Consider specifying sensors in all bedrooms and living areas to alert occupants to the levels of CO₂ and humidity.

Ventilation in New Homes

The findings from an investigation into how effectively mechanical ventilation systems are designed, installed, commissioned and handed over to occupants. It is intended for organisations with an interest in quality assuring the delivery of ventilation systems.



Testing ventilation flow rates is a requirement for Building Regulations that is often ignored.

Ventilation systems for new homes

This table shows the key aspects of the different ventilation system choices for new homes, using Building Regulations Part F (2010) England as an example.

Ventilation system	Description	Details	Background ventilation requirement (Part F: England)	Advantages	Disadvantages
System 1	Intermittent fan	Individual fan per wet room + kitchen	25000mm ² – >65000mm ² depending on TFA and no. bedrooms	Simple and low cost	Can lead to poor ventilation, can be noisy, reliant on high levels of background ventilation
System 2	Passive stack		25000mm ² – >65000mm ² depending on TFA and no. bedrooms	Zero energy use	Spatial impacts, reliant on high levels of background ventilation, may require mechanical support
System 3 C-MEV or D-MEV	Centralised or Decentralised Mechanical Extract Ventilation	Rigid duct work or decentralised units in each wet room; SFPs 0.25 to 0.17 W/l	2500mm ² in each room (except wet rooms) for design air permeability ≤5 m ³ /h.m ² @50Pa	Low background ventilation levels, decentralised versions are simpler to install, cost-effective, demand control possible	Reliant on background ventilation, adequate commissioning required
System 4 MVHR	Mechanical Ventilation with Heat Recovery	Rigid duct work for exhaust & inlets SFPs 0.8 to 0.5 W/l; efficiencies 80% to 90%	None	No background ventilation, supports areas with high ambient noise, reduced CO ₂ emissions from dwelling	Complex installation and commissioning, regular maintenance required, units and ductwork require significant space
System 4a PVHR	Passive Ventilation with Heat Recovery	SFP 0.01W/l; 30% efficient	None	No background ventilation, supports areas with high ambient noise, minimal maintenance, reduced CO ₂ emissions from dwelling	High cost, installation and commissioning can be complex, best suited to houses

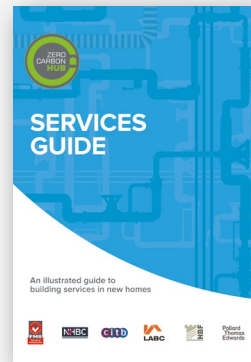
3.1 BUILDING SERVICES

Building services in new homes can represent a significant part of the performance gap. Well designed, installed and commissioned services can ensure the home performs as designed. Well thought out controls can provide the user with a high level of comfort in their homes and reduce unnecessary energy use.

Key Recommendations

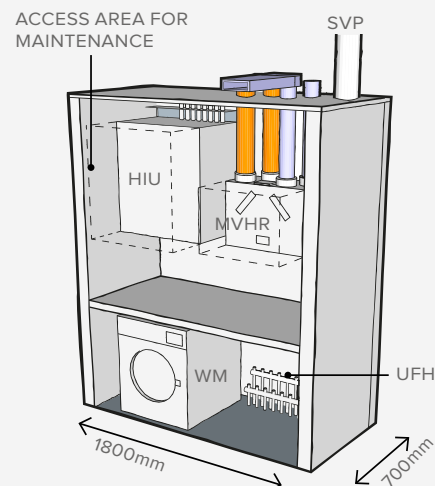
- Ensure integration of services in design to avoid unintended thermal bridging, compromised airtightness strategies and reduced system efficiencies.
- Simple services design will help installation, use and maintenance.
- Ensure enough space for access and maintenance of services.
- Be wary of complicated new technology and ask for experienced installers and as-built performance guarantee.
- Controls should be simple, easy to understand and accessible by all.
- Ensure that specification and drawings are clear and show performance requirements and that the importance of installing the right products is communicated to the procurement and site teams.
- Ensure SAP calculation matches design drawings, specification and site installation.
- Specify thorough commissioning of all services and provide training to occupants, particularly for ventilation and any unusual or new technologies.
- Refer to other guidance and checklists from BSRIA, CIBSE, NHBC, Passivhaus Trust and RIBA plan of work.

The following pages include a short description of common building services options along with their spatial impacts and installation requirements. For further guidance, please refer to the *Services Guide* by the Zero Carbon Hub.



Services Guide

Offers good practice guidance aimed at improving the standard of building services in new homes. Focused on the major problems around design and installation of services that affect comfort, indoor air quality and energy performance.



Well designed heating/ventilation cupboard in an apartment.



VENTILATION – SYSTEM 3

Continuous mechanical extract ventilation (with demand control)

Description

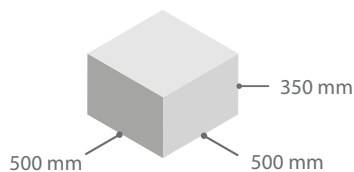
Continuous extract fan, with centralised or decentralised units

Trickle vents required for supply air

Sensors contained in habitable / wet rooms (humidity, CO₂, presence detectors)

Spatial requirement

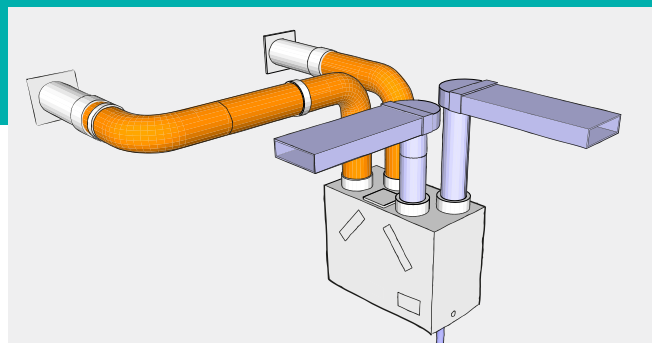
Allow for cupboard space of at least:
350mm (h) x 500mm (w)
x 500mm (d)



Background ventilation/air inlets (trickle vents in window frames) located in non-wet rooms designed to provide 2500mm² to 4000mm² per inlet

Key Recommendations

- Typically located in ceilings of wet rooms connected via ductwork (preferably rigid) to central fan; or can be decentralised with fans situated on external walls in wet rooms.



VENTILATION – SYSTEM 4

Mechanical ventilation with heat recovery (MVHR)

Description

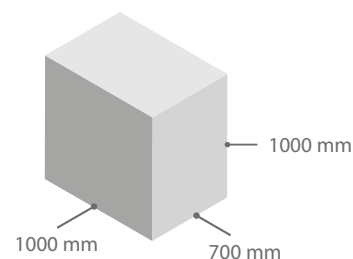
Heat exchanger combined with supply and extract fan

Summer bypass function

No trickle vents required

Spatial requirement

Allow for cupboard space within the thermal envelope of at least 1000mm (h) x 1000mm (w) x 700mm (d)

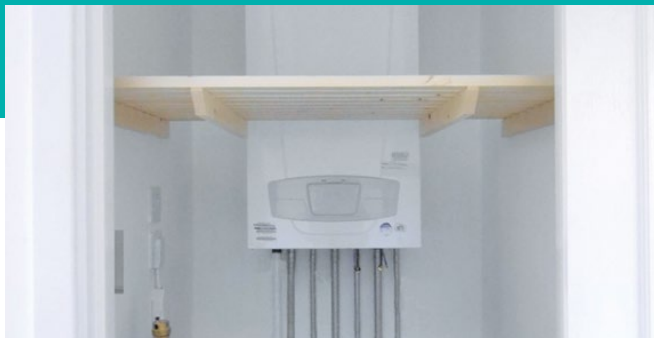


Supply ducts to all living rooms; exhaust ducts from all wet rooms

Condensate drain required near to MVHR unit

Key Recommendations

- Locate device adjacent to external wall/roof to minimise lengths of cold ducts.
- Specify rigid ductwork (circular profile performs better than flat).
- Ensure device is accessible for filter changing and is away from noise sensitive rooms.
- Specify central control panel with usage pattern adjustment and filter change notification.
- Specify robust summer bypass function.



COMBINATION BOILERS

Description

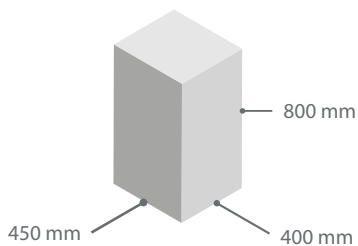
Heat produced on demand, with no hot water cylinder

Typical efficiency is 85%-90%

Can include Flue Gas Heat Recovery (FGHR) to increase efficiency

Spatial requirement

Boiler typically:
800mm (h) x 450mm (w)
x 400mm (d) excluding
clearances and flue



Horizontal flue lengths can be up to 10m but require inspection hatches every 1.5m

FGHR systems will require an additional head height of 300mm above the boiler

Key Recommendations

- Good for smaller homes with low hot water demand.
- Locate boiler next to external wall to minimise flue length.
- Correctly specify boiler for best efficiency in use e.g. not oversized.
- Consider Flue Gas Heat Recovery.



SYSTEM BOILERS

Description

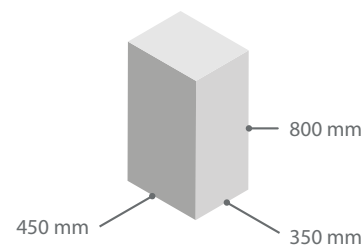
Boiler with an Unvented Hot Water Cylinder

Modern equivalent to regular boiler or conventional vented system but without need for expansion tanks.

Typical efficiency is 85%-90%

Spatial requirement

Boiler typically:
800mm (h) x 450mm (w)
x 350mm (d) excluding
clearances and flue



Unvented cylinder: 90 – 300 litres capacity; insulation thickness 65-80mm (pre-fitted)

Cylinder size: 835 – 2155mm (h) x 570 – 600mm diameter, depending on capacity

Key Recommendations

- Good for larger homes with multiple water outlets or high simultaneous demand or low mains pressure areas.
- Locate boiler next to external wall to minimise flue length.
- Compatible with solar thermal systems (twin coil cylinders).



BIOMASS PELLET BOILERS

Description

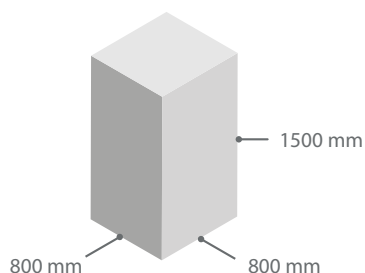
Automatic feed pellet boilers supplying heating and hot water

Capacity range from 10kW to 35kW for domestic use

Typical efficiency is 80-90%

Spatial requirement

Boiler: 1500mm (h) x
750mm (w) x 800mm (d)



Typical dry storage space for domestic use is 5-10 m³ but depends on boiler capacity, space, use and delivery frequency

Automated auger to deliver wood fuel to boiler



COMMUNAL HEAT NETWORK

Description

Larger developments connected to communal energy systems, typically heat networks fired using gas CHP (Combined Heat and Power)

Heat Interface Units (HIUs) located within dwellings

Spatial requirement

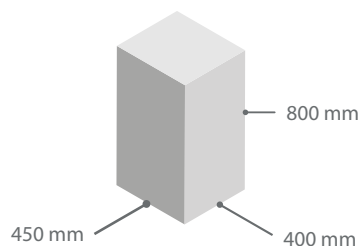
Heat Interface Unit:
800mm (h) x 450mm (w)
x 400mm (d)

Riser cupboards: 1500 –
2500mm (w) x 500mm (d)

Ceiling voids (horizontal pipework): 300mm (d)

Central plant rooms: dependent on scale of development; min 4.5m tall for large generating plant and thermal stores

Flue outlet must be 3m above accessible roof areas or openable windows (see CIBSE Guide B)

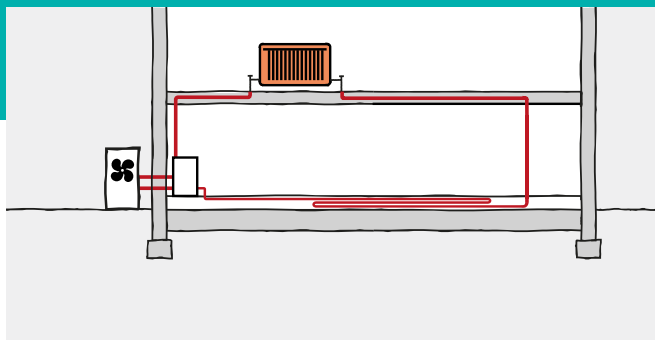


Key Recommendations

- Consult a specialist for system design.
- Look for condensing and modulating boilers and stainless steel combustion chambers.
- Compact prefabricated fabric fuel storage solutions are available.
- Check for local wood fuel suppliers and ensure they are within a 25 mile radius of your site to minimise transport cost and carbon emissions.
- Check planning constraints of air pollution and height of flues.

Key Recommendations

- Minimise lateral pipe-runs.
- Include space for hot and cold water pipework in all vertical risers.
- Specify enhanced insulation standards for all heat pipework, valves, flanges, HIUs etc.
- Consult a specialist for system design.
- Refer to Heat networks: Code of practice by CIBSE/ADE.



AIR SOURCE HEAT PUMPS (ASHP)

Description

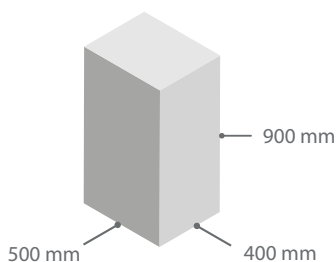
An ASHP absorbs heat from outside air which can then be used to provide space heating and hot water

Requires a hot water cylinder

Well designed and installed systems can be 300-350% efficient

Spatial requirement

Indoor unit typically
900mm (h) x 500mm (w)
x 400mm (d)



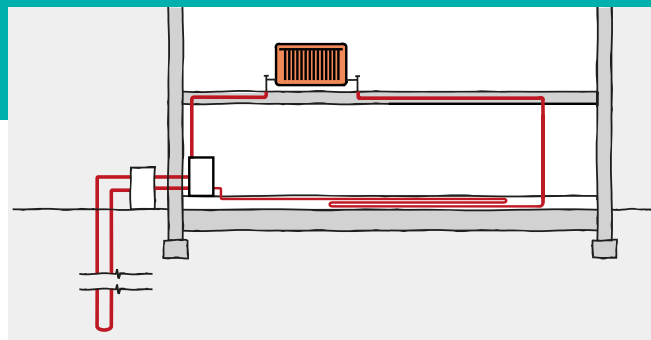
Plus hot water cylinder

Outdoor unit (fan coil) typically 750mm (h) x 950mm (w) x 450mm (d)

Hybrid systems are available that combine a small gas boiler with an ASHP which can run in combination or isolation to maximise efficiency

Key Recommendations

- Locate outdoor unit away from windows, and ensure it is protected from damage.
- To maximise efficiencies, keep heat flow temperature as low as possible and install low temperature heat emitters like underfloor heating.
- Consult a specialist for system design.



GROUND SOURCE HEAT PUMPS (GSHP)

Description

A GSHP extracts heat from the ground which can then be used to provide space heating and hot water

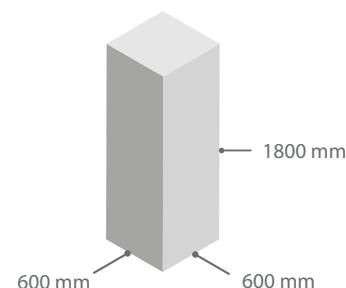
There are two main types: borehole and 'slinkies'

Requires a hot water cylinder

Well designed and installed systems can be 400% efficient

Spatial requirement

Indoor heat pump unit
varies with capacity, but
typically 1800mm (h) x
600mm (w) x 600mm (d)



Plus hot water cylinder

Outdoor: sized to the needs of the dwelling, with either closed loop boreholes (typically 30-100m deep) or closed loop 'slinkies' (pipework array typically 1-2m below the surface)

Key Recommendations

- To maximise efficiencies, keep heat flow temperature as low as possible and install low temperature heat emitters like underfloor heating.
- Consult a specialist for system design.
- Set up costs are higher than for ASHP, but the difference can be justified if the system design is good and achieves high efficiencies.



SOLAR THERMAL PANELS

Description

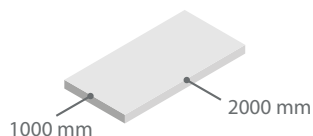
Solar Thermal Panels capture heat from the sun which is then used to provide domestic hot water

Requires twin coil hot water cylinder or second cylinder

Two types of panel: flat plate or evacuated tube

Spatial requirement

Flat plate panels are typically 2m² per panel



Panels should be south facing for maximum efficiency, east or west facing is also OK

Evacuated tubes are typically 2m long, with the number of tubes used dependent on dwelling size

Typically 1m² of panel is required for each 50l of hot water cylinder, for example, a 3 bed house with 200l cylinder = 4m² of collector

Typical twin coil cylinder size is 1500mm (h) x 600mm diameter

Key Recommendations

- Ensure panels are suitably sized for dwelling and system configuration.
- Specify pre-insulated flexible solar thermal pipework.
- Ensure panels are not overshadowed.
- Ensure controls are easily accessible.
- Consult a specialist for system design.
- Require that installers are experienced and have MCS certification.



PHOTOVOLTAIC PANELS

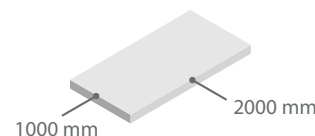
Description

Photovoltaic (PV) panels convert solar radiation to electricity

An inverter is required to convert the DC electricity generated into AC electricity to use in the home

Spatial requirement

PVs are typically 1.5m – 2m² per panel



Panels should be south facing for maximum efficiency, east or west facing is also OK

The inverter should be sited near the panels, preferably on the top floor landing for easy accessibility

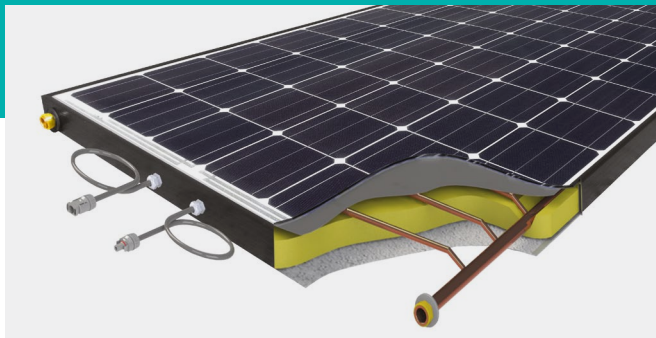
Consider building integrated PVs for better aesthetics and cost saving on roof tiles

Key Recommendations

- Specify minimum of 2 kWp (approx 8 panels) for a significant renewable energy contribution.
- Consider combining with battery storage to improve on-site usage of generated electricity.
- Ensure panels are not overshadowed.
- Specify an energy feedback display for occupants.
- Consult a specialist for system design.
- Require that installers are experienced and have MCS certification.



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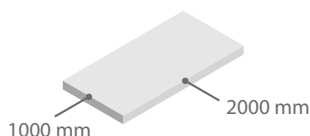
PV-T HYBRID SOLAR TECHNOLOGY

Description

PV-T solar panels convert solar radiation into thermal and electrical energy. These panels combine a solar cell, which converts sunlight into electricity, with a solar thermal collector, which heats water and removes waste heat from the PV module.

Spatial requirement

PV-T panels are a similar size to PV panels, at around 2m² each



Requires a large hot water cylinder to store the heat created



BATTERY STORAGE

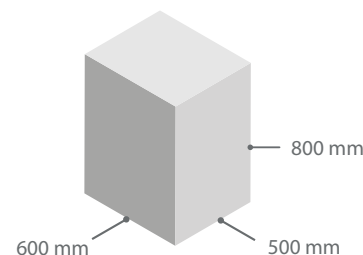
Description

Batteries can store surplus electricity generated by photovoltaic panels to be used later in the day

Lithium-ion batteries are the most common type for use in homes and can be installed as an encased wall-mounted unit

Spatial requirement

800mm (h) x 600mm (w) x 500mm (d) and 125kg would be a typical domestic unit to take a capacity up to 6kWh



Wall mounted units 1300mm (h) x 900mm (w) x 200mm (d) are also available

Key Recommendations

- Heat output can be three times the electricity output with a large array, so should be combined with large thermal store.
- It may be simpler to consider solar PV with a separate solar thermal system. This has the advantage of being able to specify the correct size of each panel type.
- Consult a specialist for system design.

Key Recommendations

- Battery storage is effective when the PV panels generate an excess of electricity during the day.
- Specify lithium-ion batteries which are lighter, longer lasting, more efficient (but more expensive) than lead acid batteries.
- Consult a specialist for system design.



4.0 OVERHEATING IN HOMES

Heat will accumulate in a building if external and internal heat gains (from the sun, people, lighting and equipment, for example) exceed the heat being lost (through the walls, floor, roof, windows and ventilation system).

If the design of the building then makes it challenging for the occupants to easily or effectively remove this excess heat, the living environment may become uncomfortably warm or excessively hot.

Overheating, in this context, describes scenarios where the temperature inside a building reaches an unacceptably high level for a given period of time.

People living in homes that overheat report experiencing discomfort, sleep deprivation, and dissatisfaction with the property. If the occupants are particularly susceptible to the effects of heat, such as the elderly or people with chronic health conditions, the situation can be life threatening.

Overheating is becoming increasingly common in certain types of new and refurbished homes, and our changing climate is likely to further increase the likelihood of it occurring. It is therefore essential for building designers to address the issue.

Skilful design, using passive strategies, can significantly reduce or avoid the risk of overheating in summer (or

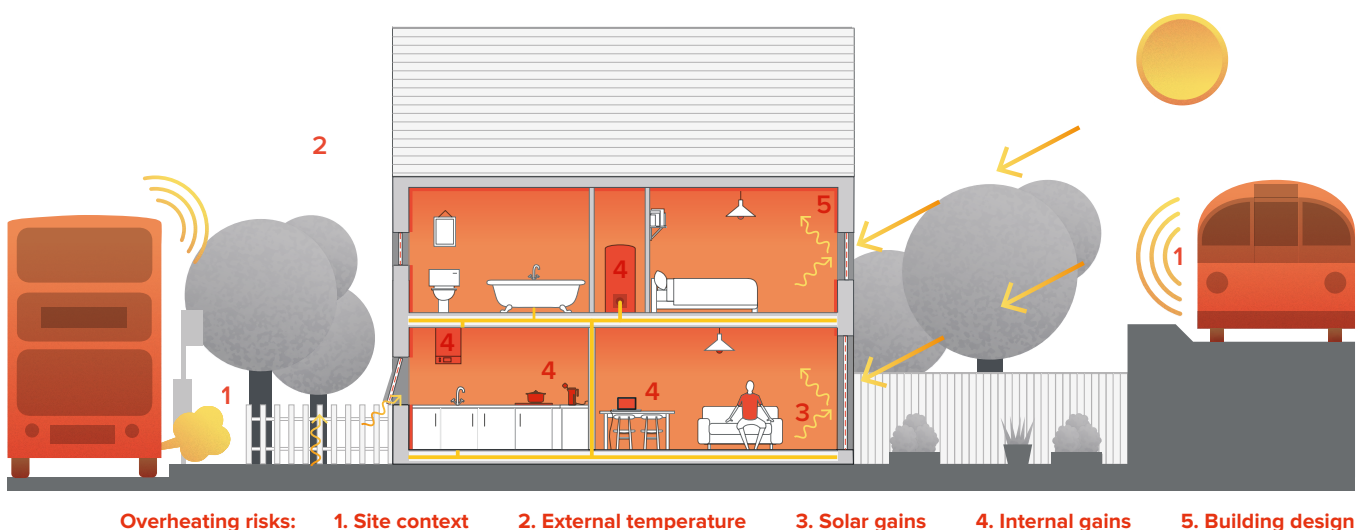
even during the winter) by carefully balancing the retention of useful heat when it is needed, minimising the amount of unwanted heat when it is not, and providing secure and controllable ways of purging excess heat. In the UK passive strategies can produce buildings that will maintain comfortable conditions well into the century. Mechanical cooling should only be used to augment rather than as a substitute for good passive design.

Key recommendations

1. Limit external heat gains.
2. Minimise internal heat gains.
3. Provide adequate and controllable ventilation.
4. Use thermal mass effectively.
5. Use the building layout effectively.
6. Use external space effectively.
7. Strengthen processes and risk assessments.

Refer to further guidance by the Zero Carbon Hub and others.

Examples of design strategies to fulfil these recommendations follow. Note that these suggestions are not exhaustive.





1. Limit external heat gains

- Consider the size and position of windows, as well as the type of glazing. Large areas of glass, facing any direction other than north, are highly likely to lead to excessive heat gain unless purposely shaded (preferably externally) or solar control glass is used. A balance will need to be struck with the need to provide views and good levels of daylight.
- With skilful design, windows can be shaded by the building itself, for example by balconies above, overhanging eaves or deep window reveals without the need to add external shutters, binds and awnings. It is relatively simple to shade south-facing windows from high angle summer sun – more care needs to be taken with those facing east or west.
- Wall and roof insulation, green roofs/walls, and the choice of colour of the façade all alter the amount of heat absorbed by and transferred through the building fabric.
- Consider the potential for adjacent external surfaces to absorb and reflect additional heat into the building.

Insulation

Insulation keeps homes cool as well as warm. It is important to stress that the trend towards warmer summers does not mean that insulation standards should be reduced. In addition to reducing the need for heating (and consequent CO₂ emissions) in winter, dark external materials can become extremely hot in direct sun and high levels of insulation help prevent this heat from moving into the home.

2. Minimise internal heat gains

In modern airtight buildings, heat from sources inside the building have the potential to significantly increase the risk of overheating. Whilst it is not possible to eliminate these completely, they can be reduced.

- Specify low energy lighting and energy efficient electrical appliances, and provide intuitive and understandable heating and hot water controls.
- Insulate hot water storage and distribution systems (particularly for communal areas in flatted developments) according to the guidance provided in the Domestic Building Services Compliance Guide. Ensure corridors with heat sources such as hot pipes can be ventilated.
- Specify appropriate flow rates and temperature levels for communal hot water distribution systems operating throughout the summer. See the Heat Networks Code of Practice for the UK (2015) produced by CIBSE and the Association for Decentralised Energy.



Ensure there is adequate insulation around pipes and valves



3. Provide adequate and controllable ventilation

Heat will inevitably build up inside a property, even if steps have been taken to minimise the external and internal gains. It is vital to provide a means of achieving a high number of air changes over a short period of time to “purge” hot air and replace it with cooler air from outside. Although simple in theory, it can be difficult to achieve in practice, for example, in buildings in noisy or polluted areas where people may avoid opening windows.

- Aim to design “dual-aspect” dwellings with windows on opposite sides of the unit to ensure a good through-flow of air.
- Specify an appropriate window opening area and number of ventilators. If windows have restrictors fitted for safety reasons, consider what additional means of ventilation needs to be provided to remove large volumes of hot air quickly.

- Ensure mechanical ventilation with heat recovery (MVHR) systems have a summer by-pass mode to avoid ventilation air being pre-heated in summer.
- If specifying mechanical ventilation systems, check whether an additional means of natural ventilation will be required to effectively purge hot air (Approved Document Part F does not cover this at present).
- Avoid locating ventilation inlets or window openings directly above air conditioning units (or other heat sources) to avoid pre-heated air being drawn into homes.

4. Use thermal mass effectively

- Thermal mass is effective in reducing daytime internal temperatures only if it is coupled with effective night-time ventilation when the air is cool to remove the heat that has been stored up during the day.

Illustration of some of the considerations necessary to reduce the risk of overheating

- 1 Reduce external heat gains.
- 2 Provide adequate purge ventilation.
- 3 Use the building's fabric to slow heat transfer.
- 4 Consider how to use the external space.





5. Use the building layout effectively

- Locate boiler cupboards and other similar heat sources away from living spaces, and particularly bedrooms.
- Consider locating bedrooms in cooler areas of the building where possible - for example on the north side. Consider how to make best use of cooler spaces or floors in the building.
- Aim for 2.5m or more ceiling heights where possible to give additional volume for stratification and the potential for ceiling fan retrofit.

6. Use external space effectively

- Make use of trees and plants to provide attractive, low-cost shade and to provide a cooling effect through transpiration.
- Water features can also provide a cooling effect.



Overheating leaflet series

The Zero Carbon Hub has produced a series of six leaflets on various themes related to the management of overheating risk in homes.

7. Strengthen processes and risk assessments

- Factor in the building's location and site context when assessing the potential for overheating. For example, is the building located within an urban heat island or next to a noisy road, limiting the potential for window opening?
- When assessing risk, make realistic assumptions about occupancy patterns and internal gains - "standard" assumptions frequently underestimate occupancy.
- For blocks of flats or large schemes, consider whether any individual units are especially likely to overheat and strengthen the design for those as necessary.
- Agree with clients what future climate assumptions will be used in building modelling. Using current or historical weather data will not be representative of the conditions the building will need to withstand during its lifetime.
- Consider what additional protection is needed if a property is intended for use by people who are particularly susceptible to the effects of high temperatures, such as care homes.
- Consider future adaptation strategies and ensure these are practicable as a future step (e.g. additional shading).

Assessing risk

Designers should consult CIBSE's Guide A: Environmental Design (2015) for current best practice on assessing overheating risk. Building owners and landlords should also familiarise themselves with the Housing Health and Safety Rating System guidance, which sets out a procedure for Environmental Health Officers to assess whether an existing building is hazardous to health due to excess heat (as well as other hazards).

USEFUL DOCUMENTS

Author	Resource	Link
Zero Carbon Hub	<ul style="list-style-type: none"> ○ Services Guide ○ Thermal Bridging Guide ○ SAP Untangled ○ Ventilation in New Homes ○ Overheating in Homes - The Big Picture ○ Overheating in Homes - Introductory leaflets (x6) ○ Solutions to Overheating In Homes - Evidence Review 	www.zerocarbonhub.org/guidance www.thebuildingshub.co.uk
Greenspec		www.greenspec.co.uk
Passivhaus Trust		www.passivhaustrust.org.uk
NHBC Foundation	<ul style="list-style-type: none"> ○ NF44: Understanding Overheating - Where to Start (2012) ○ NF72: The Challenge of Shape and Form (2016) 	www.nhbcfoundation.org/publications
CIBSE	<ul style="list-style-type: none"> ○ CIBSE Guide A: Environmental Design (2015) 	
Alan Lewis & Thomas Pocklington Trust	<ul style="list-style-type: none"> ○ Daylight in Older People's Housing (2016) 	www.pocklington-trust.org.uk/wp-content/uploads/2016/05/Daylighting-Guide.pdf
Franca Trubiano	<ul style="list-style-type: none"> ○ Design and Construction of High Performance Homes – Building Envelopes, Renewable Energies and Integrated Practice (2012) 	
Bill Gething & Katie Puckett	<ul style="list-style-type: none"> ○ Design for Climate Change (2013) 	
Sofie Pelsmakers	<ul style="list-style-type: none"> ○ Environmental Design Pocket Book 2nd Edition (2015) 	
CIBSE/ADE	<ul style="list-style-type: none"> ○ Heat Networks Code of Practice for the UK (2015) 	
The Passivhaus Trust	<ul style="list-style-type: none"> ○ How to Build a Passivhaus: Rules of Thumb (2015) 	www.passivhaustrust.org.uk/guidance.php
Tom Woolley	<ul style="list-style-type: none"> ○ Low Impact Building: Housing Using Renewable Materials (2013) 	
Bruno Gaiddon, Henk Kaan & Donna Munro	<ul style="list-style-type: none"> ○ Photovoltaics in the Urban Environment: Lessons Learnt from Large Scale Projects (2009) 	
Sarah Lewis	<ul style="list-style-type: none"> ○ PHPP Illustrated: A Designer's Companion to the Passive House Planning Package (2014) 	
BRE & Paul Littlefair	<ul style="list-style-type: none"> ○ Site layout planning for daylight and sunlight: A guide to good practice (2011) 	
Keith Hall	<ul style="list-style-type: none"> ○ The Green Building Bible - Volumes 1&2, Fourth Edition (2008) 	
Christina Hopfe & Robert McLeod	<ul style="list-style-type: none"> ○ The PassivHaus Designer's Manual: A technical guide to low and zero energy buildings (2015) 	
Janet Cotterell & Adam Dadeby	<ul style="list-style-type: none"> ○ The Passivhaus Handbook: A practical guide to constructing and retrofitting buildings for ultra-low energy performance (2012) 	
Emma Walshaw	<ul style="list-style-type: none"> ○ Understanding Architectural Details 	www.understandingarchitecturaldetails.co.uk
Masa Noguchi	<ul style="list-style-type: none"> ○ ZEMCH – toward the delivery of zero energy mass custom homes (2016) 	

NOTES

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