Programme Area: Smart Systems and Heat

Project: Enabling Technologies

Title: System Analysis of Concept Design

Abstract:

Whilst space heat and hot water can be provided to customers in a variety of ways, different methods are more appropriate for some locations than others, depending on local factors such as housing density. This paper considers the energy system design options for the Smart Systems and Heat programme and identifies twenty end-to-end energy system configurations. Eleven of these have been taken into a detailed gap analysis of their characteristics against emerging consumer equirements. As part of the work a preliminary energy system transition plan was developed for Loughborough, which identified a number of practical findings such as data access, and the challenges of developing confidence in transition pathways given the uncertainty over future investment support mechanisms and the immaturity of the supply chain. The report was initially prepared in November 2013. Some details and analysis may be out of date with current thinking.

Context:

This project identified gaps in the range of potential smart systems technologies to accelerate the development of component technologies which are required for any successful deployment and operation of a future smart energy system. This £500k project was announced in February 2013 and was delivered by a consortium of partners that includes Hitachi Europe, EDF Energy, Element Energy, David Vincent & Associates and Imperial Consultants.

SYSTEM ANALYSIS of CONCEPT DESIGN

John Batterbee
November 2013

Introduction

This paper:

- Defines the system design options for the SSH programme;
- Short-lists those system design options for further analysis;
- Analyses the short-list against insights emerging from the consumer research and other relevant design requirements, to identify ‘gaps’ in the SSH space; and
- Identifies ‘products’ to be developed in the SSH programme to address the ‘gaps’.

A supplementary paper, being developed elsewhere in the SSH team, documents the development and exploitation strategy for those products and the plan for implementing it.

The focus for the SSH programme, and this paper, is on solutions for existing buildings. For new buildings the design space has more degrees of freedom, unlike existing properties, as a result of constraints inherent in their design and ongoing occupation.

A design case study has been undertaken (for Loughborough) to ground the analysis in practical reality and help inform the identification of ‘gaps’ in the SSH space. This is presented at Appendix A. The principal findings were:

- Difficulty in accessing sufficient data to have confidence in the selection of which design configuration(s) to build for where, at both the network and building levels;
- The likelihood that the preferences of building owners will be at least as significant in choices as pure cost competition between different system design configurations;
- The challenge of developing sufficient confidence in the pathways for the town and individual buildings within it, given the uncertainty of future capital and operating cost support mechanisms, the low state of development of the various supply chains required to deliver a set of integrated solutions and the unfamiliarity of many of the key technologies to almost all of the key decision makers.

The chart overleaf summarises the ‘gaps’ in the SSH space that emerge from the analysis and the ‘products’ to be developed in the SSH programme to address them.

The systems design analysis reported in this paper is the first version; it will continue to be updated through the life of the SSH programme. The SSH programme needs to retain significant flexibility to adapt as knowledge increases. Specific updates for the next version (completion anticipated for the end of 2013) include:

- Extension of the 'gap' analysis to building fabric components;
- Refinement of the evaluation parameters with future insight from the CRaB project;
- Further detailing of the 'gap' analysis using a full QFD process, including to add market segmentation and parameter weighting to the analysis.

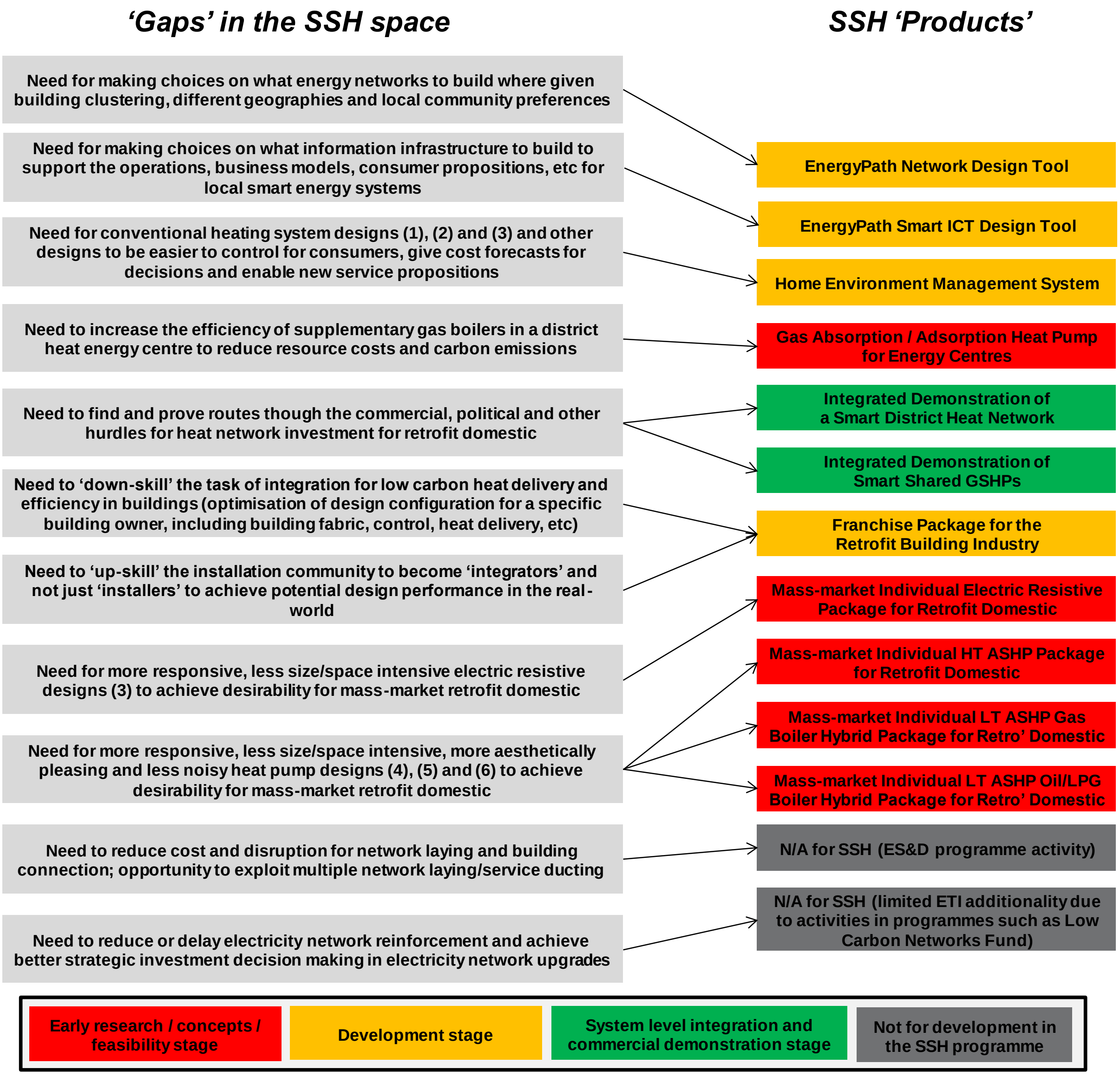


Figure 1: Summary of 'gaps' in the SSH space and 'products' to be developed in the SSH programme

The Candidate System Design Options for the SSH Programme

There are eleven primary system design options to be analysed further in the SSH programme. The detail of each of these system designs is configurable, depending on location specific needs at both the network and the building levels. This reflects a key theme across all of the system designs; the need for effective design tools to select, configure and optimise solutions for specific locations and to communicate the expected performance and cost of the system to consumers at both the network and building levels in meaningful terms. A related theme consistent across all system designs is the need for up-skilling of the retrofit building contractor/heating installer industry, to enable them to effectively become 'system integrators' for a given building (supported by design tools embedded in the workflow).

(1) Individual High Efficiency Gas Boilers

Individual gas boilers are not expected to have a significant place in an energy system compatible with the UK's 2050 energy and climate change goals (even with the highest efficiency level and considerable building insulation and air tightness measures). However, individual gas boilers currently dominate the UK market (>80% of buildings) and will continue to do so for many years to come while the UK's local energy infrastructure is transformed one location at a time. Low carbon solutions will need to compete against this incumbent system design.

With the advent of instant hot water via combi- boilers, in-building heat storage has been gradually declining (currently less than 60% of properties have a hot water tank). The typical gas connection to a domestic property of 64kW is more than adequate for this purpose. The space freed up by removal of the hot water tank has then been used for other purposes perceived to be of more value. This trend is expected to continue and make it increasingly difficult to implement alternative system designs with a greater footprint in and around the building, especially where they occupy 'premium' space (kitchen vs. loft space, for example).

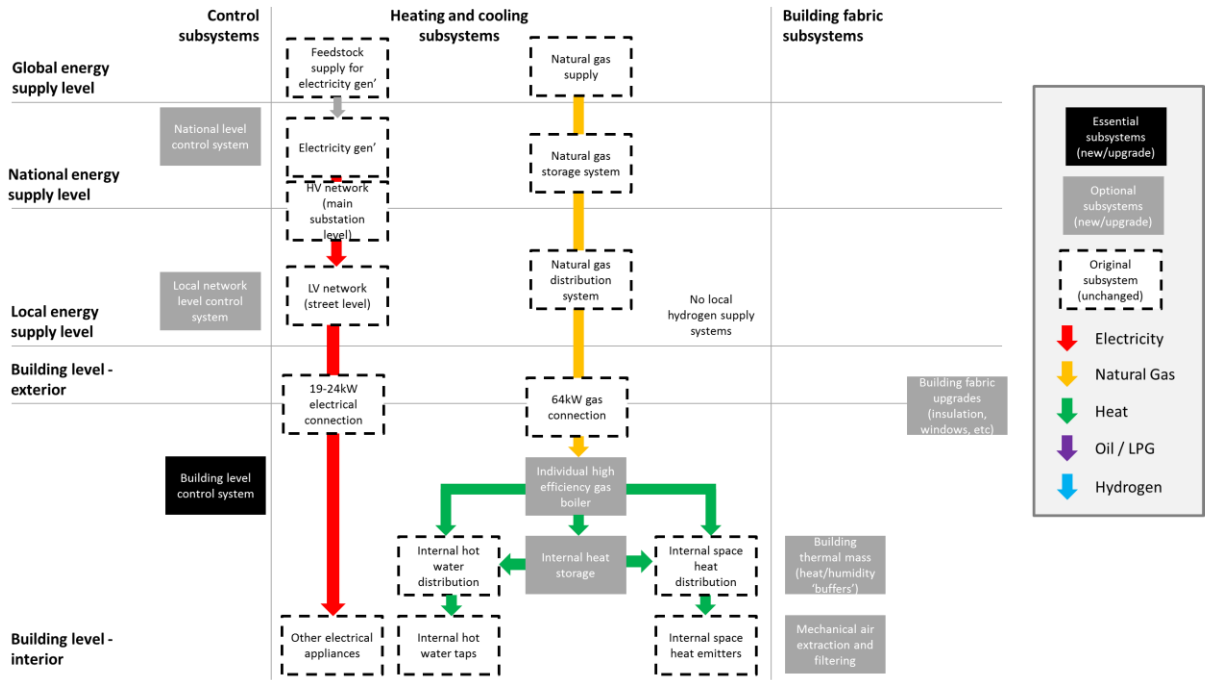


Figure 2: System Designs – (1) Individual Gas Boilers

(2) Individual Oil or LPG Boiler

This system design is very similar to an individual gas boiler, but with an energy delivery system via road based oil or LPG tankers. Storage at the building level is incorporated in both the raw fuel storage tank and in a heat tank (a larger proportion of oil or LPG heated properties have retained their hot water tank). This is the dominant system design in rural areas off the gas grid. As for individual gas boilers, this system design is unlikely to play a part in meeting the UK's 2050 energy and climate change goals, but it is nonetheless the incumbent against which low carbon solutions will need to compete in rural areas off the gas grid. Given the high cost of road delivered fuels, the costs for alternative low carbon system designs are likely to compare more favourably in these areas.

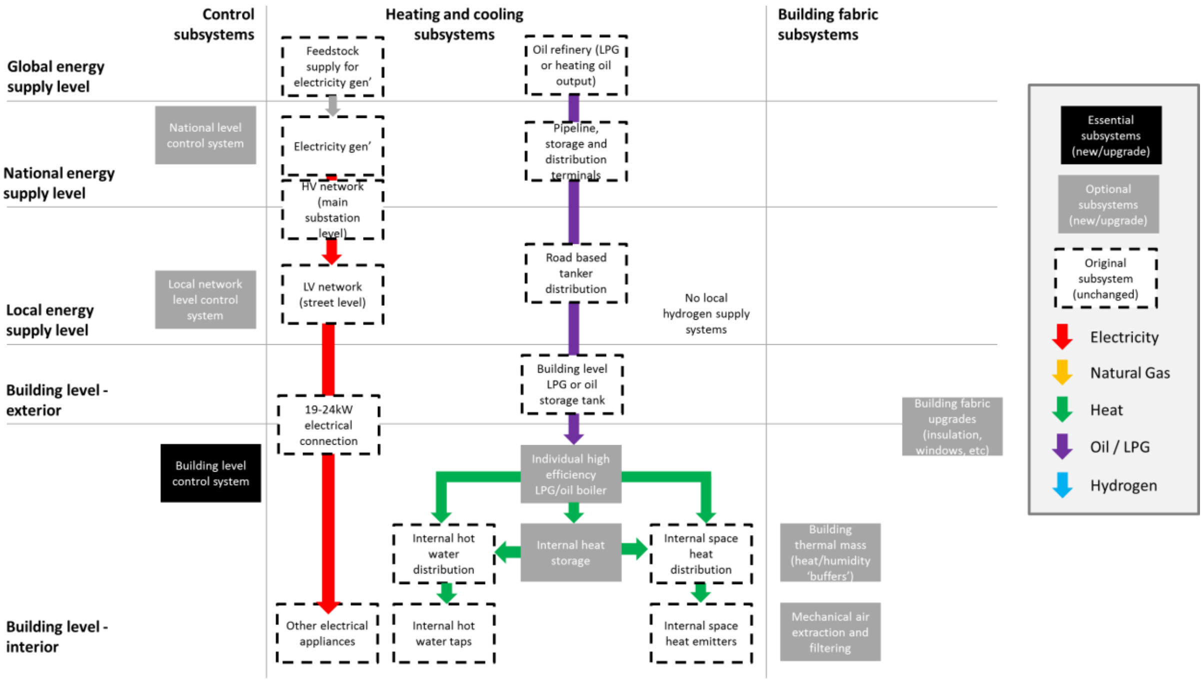


Figure 3: System Designs – (2) Individual Oil or LPG Boilers

(3) Individual Electric Resistive Systems

Individual electric resistive heat systems are the dominant solution for properties where gas is available but prohibited on safety grounds, such as large blocks of flats. This system design is also used in some rural areas off the gas grid instead of road tanker delivered oil or LPG boilers. Due to the supply capacity constraints at the individual building level (typically 24kW), these systems almost always include hot water storage and some form of heat storage for space heating, which is typically integrated into the heat emitter and heated directly via a resistive coil. Instant hot water can be provided for showers or taps, but the flow rate is significantly reduced compared to that available from an instant gas hot water system. This system design is directly compatible with the UK's long-term energy and climate change goals without modification; the upstream electricity generating sector can gradually decarbonise without any involvement from the consumer.

For this system design to be suitable for more extensive areas of the UK, significant upgrades to the Low Voltage (LV) and High Voltage (HV) distribution networks will be essential. It is unlikely this can be achieved without large scale laying of new supply cables.

- In many cases, to deliver adequate system responsiveness and to provide sufficient heating for older, less thermally efficient buildings, it will be necessary to upgrade the incoming electricity supply capacity from the existing 19-24kW level.
- The LV network was constructed assuming a high diversity of demand between dwellings. Diversity is likely to drastically reduce, due to the need to heat all properties simultaneously on peak winter days. The capacity of the LV network in an area with minimal electric heating has a typical capacity of 1-3kW per dwelling. This will require significant upgrading, to give sufficient capacity for peak winter heating demand; over five times more capacity is likely to be needed (area dependent).

- The HV network was also constructed assuming a high diversity of demand and will also require significant upgrading. However, there may be routes to increasing capacity in some areas without new supply cables (voltage increase, for example).

Decarbonisation of the electricity generation sector is a prerequisite for larger scale use of this system design to contribute to the UK’s 2050 energy and climate change goals. Furthermore, a significant increase in national electricity generation capacity would be required; with customer satisfaction being dependent on having a significant capacity of very low utilisation peak generation plant to meet the occasional very cold day heating demand.

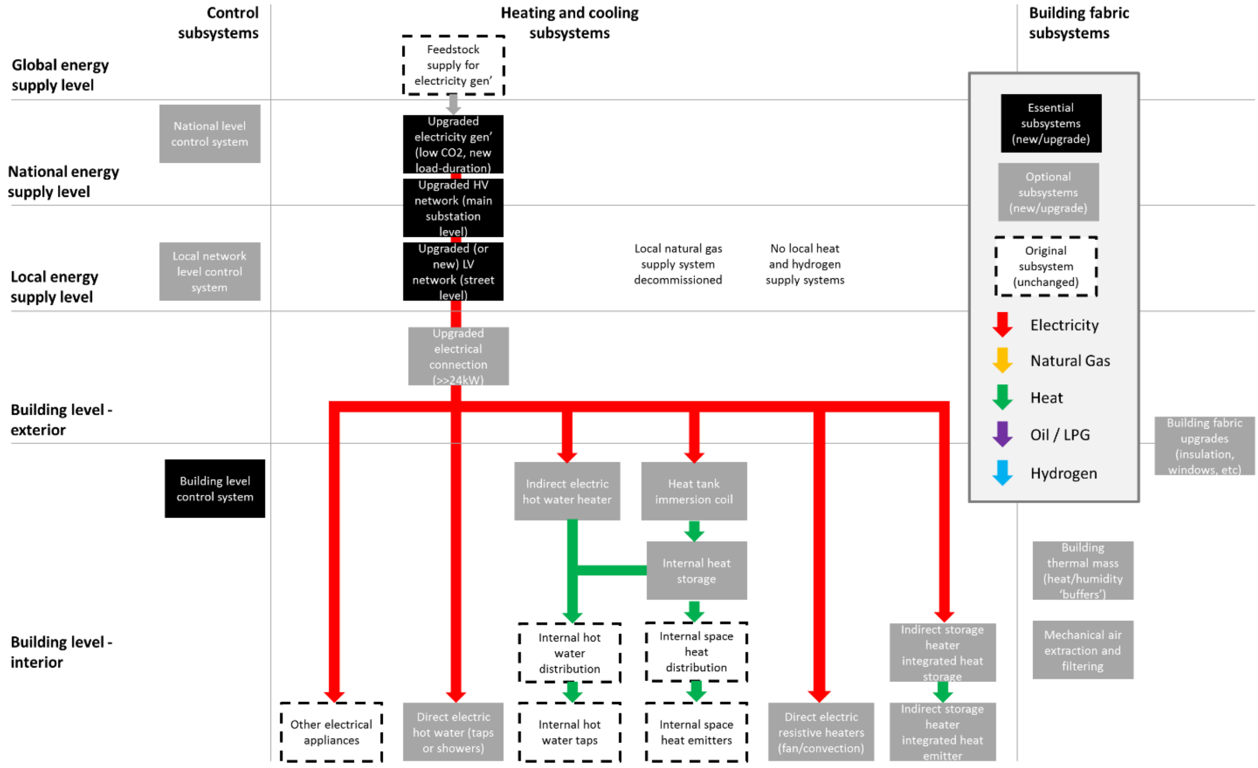


Figure 4: System Designs – (3) Individual Electric Resistive

(4) Individual High Temperature (HT) Air Source Heat Pumps (ASHPs).

Existing domestic properties with a wet radiator system are typically designed with a high water temperature requirement for sufficient heating on peak cold days (70ºC is typical, but there is a lot of variability). Heat pump efficiency drops as the spread between inlet and outlet temperature increases. To minimise demand for costly peak electricity, the ASHP would need to operate efficiently with a high outlet temperature (say, 70ºC) and low inlet temperature (say, -7ºC); a Coefficient of Performance (COP) of at least 2.5 at this temperature spread is desirable.

The space heat distribution within the building could be via integration with an existing wet radiator system, installation of a new low temperature under floor radiator system or installation of a new forced air ventilation system. The hot water distribution would be via the existing system in the building. A hot water tank within the individual building is essential to the design, to ensure efficient operation of the ASHP (efficiency drops when the heat pump is operated on short cycles) and a sufficient flow rate for hot water supply. Space will be required inside the building for this hot water tank and the internal compressor unit. Space will be required outside for a heat exchanger to provide the heat source.

This system design could offer the addition of cooling, but that is likely to require a new forced air ventilation system to be installed. For retrofit buildings, the choice will largely depend on the cost of making the transition from an existing wet radiator system to a forced air ventilation system and the building owner's perceived value of the extra functionality of cooling. Given the high cost, disruption and the relatively low importance of air conditioning in the UK, it is unlikely to be valued sufficiently highly by most retrofit consumers.

As for the electric resistive system design, major upgrade to the electricity network at street level and above will be essential. With smart appliances, to manage the heat pump demand and other high power devices such as vehicle recharging, cookers, dishwasher heating elements, etc, it may be possible to avoid the need for an upgraded electricity connection for the building. However, in many cases, a new connection to the electricity grid may well be required as well.

It is unlikely to be affordable to maintain the gas network in areas where 'Individual HT ASHPs' are expected to be the predominant solution; the local gas network would eventually require decommissioning. A major decarbonisation of electricity generation is a prerequisite for 'Individual HT ASHPs' to deliver a material reduction in CO_2 emissions.

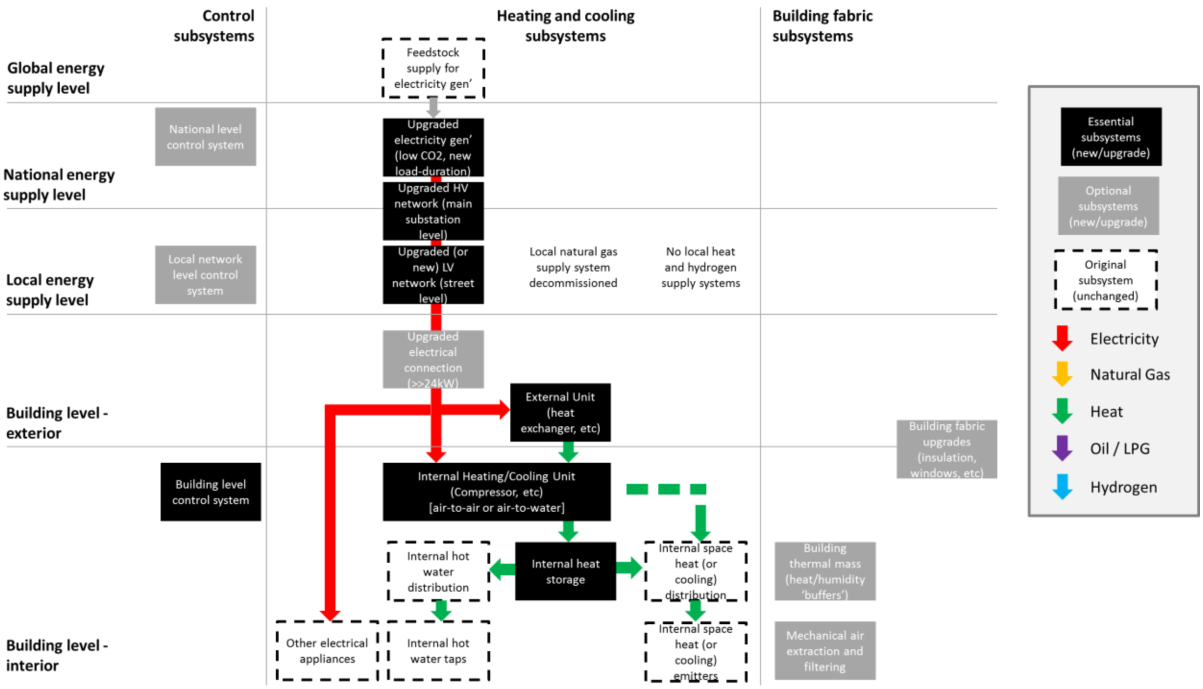


Figure 5: System Designs – (4) Individual HT ASHP

(5) Individual Low Temperature (LT) ASHP / Gas Boiler Hybrid

This system concept design is very similar to the 'Individual HT ASHP', but with a lower cost heat pump with poor peak winter weather performance. The gas boiler provides for the peak heating demand instead.

As for system design (4), this system design could offer cooling as well as heating. However, for this system design to be integrated with the required forced air ventilation system, an alternative boiler configuration would be needed; one designed to heat air directly.

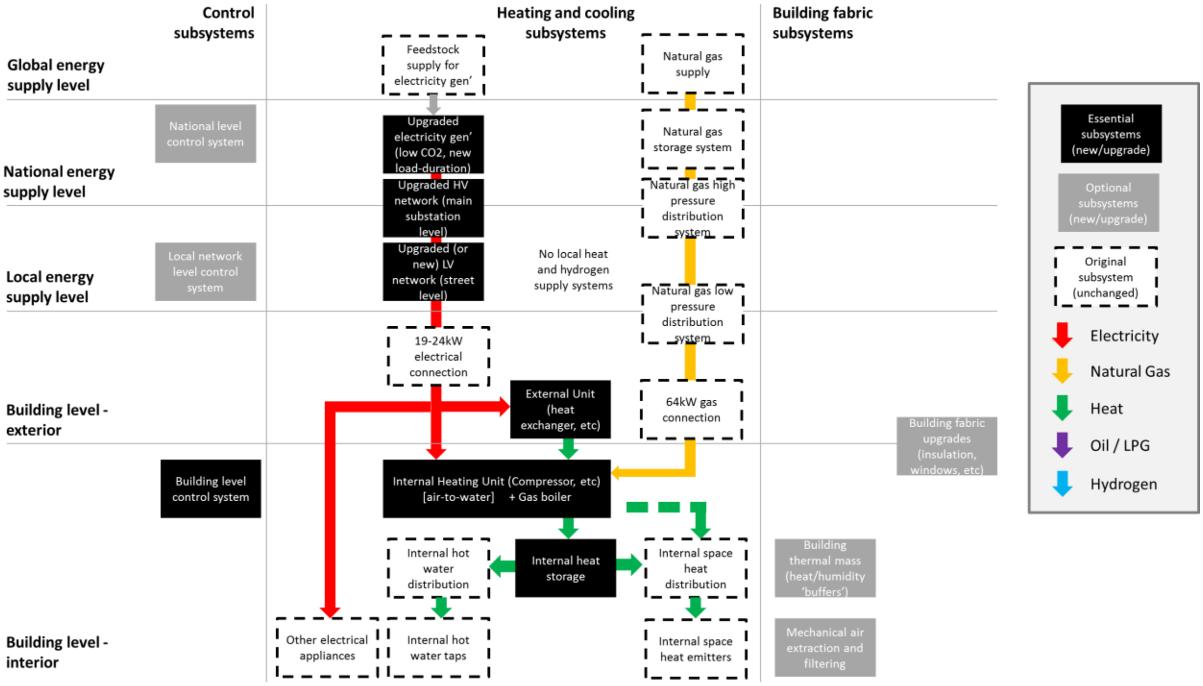


Figure 6: System Designs – (5) Individual LT ASHP / Gas Boiler Hybrid

(6) Individual Low Temperature (LT) ASHP / Oil or LPG Boiler Hybrid

This system concept design is the same as the Individual LT ASHP / Gas Boiler Hybrid, but with a road tanker delivered supply system for oil or LPG as the feedstock for the boiler. It is possible this system might return to areas which cannot support continued use of the gas grid; bottled LPG could be an economic solution to cover rare periods of very cold weather.

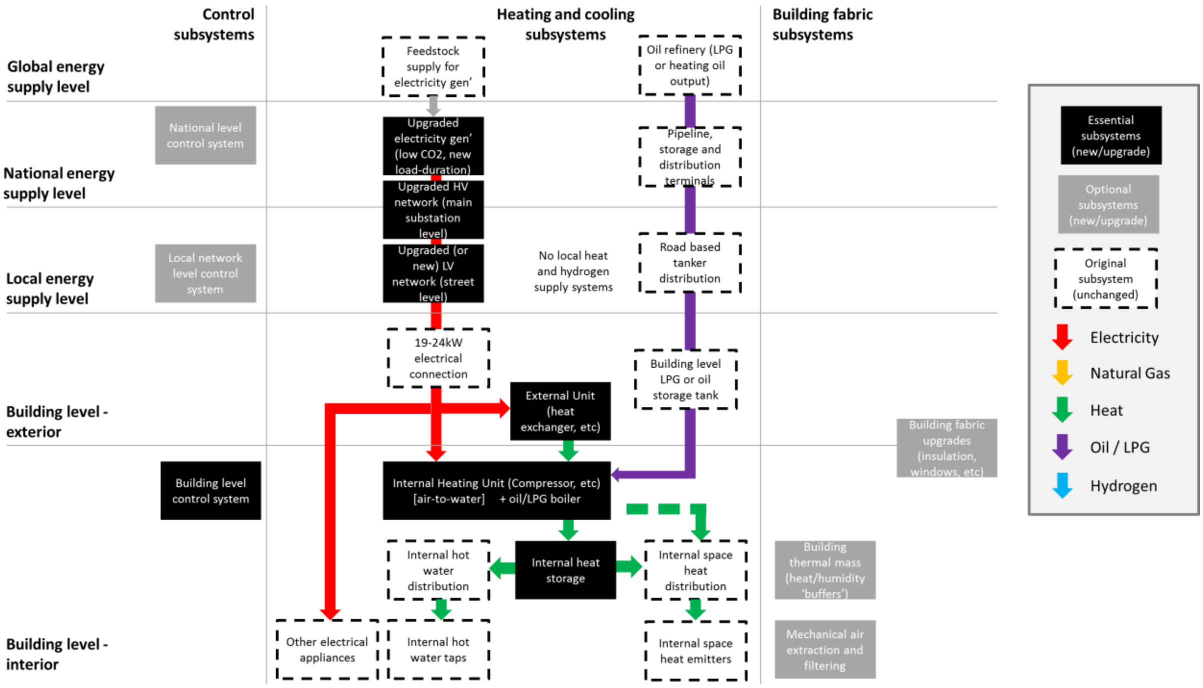


Figure 7: System Designs – (6) Individual LT ASHP / Oil or LPG Boiler Hybrid

(7) Shared ASHP / GSHP

This system concept design addresses the space and aesthetic issues for individual ASHPs and the cost issues for individual ground bores/loops for GSHPs by providing a small energy centre for 10's of dwellings and a shared heat distribution network between them. This is likely to be appropriate in more rural or suburban places where a large scale district heat network may be inappropriate. It could be particularly applicable to blocks of flats or small rural communities (blocks of cottages in a small hamlet, for example).

Rather than a single stage heat pump, a two stage design may be installed with a shared heat pump elevating the temperature of the transfer fluid to each building (to, say, 40ºC) and then individual heat pumps in each building to further elevate the temperature (to, say, 70ºC). The details will need to be configured for each installation.

As for other electric based designs, decarbonisation of the national electricity grid is a prerequisite for this system design to meet the UK's 2050 energy and climate change goals. Upgrade to the electricity network is likely to be needed to provide sufficient capacity for connection of the shared heat pump, but the potential to integrate significant heat storage capacity at the shared heat pump level may mitigate that to some extent.

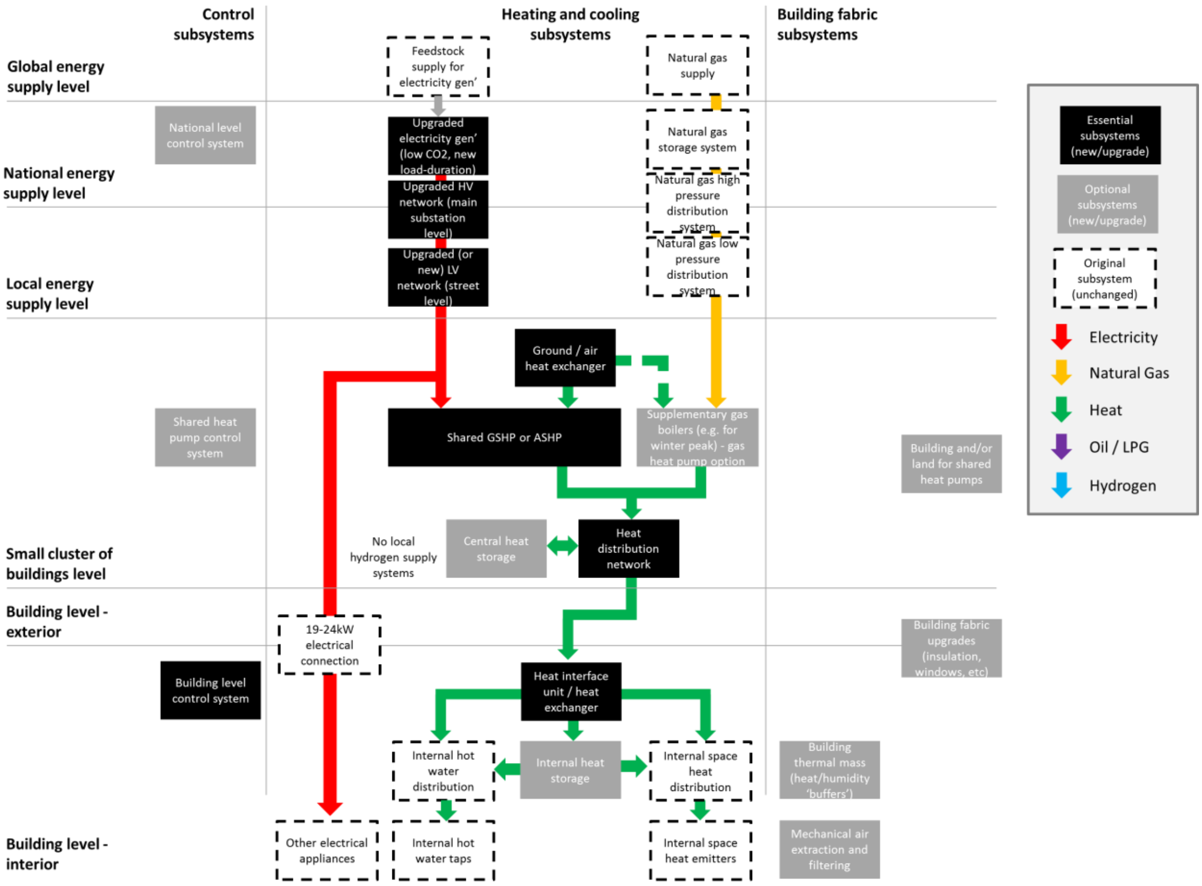


Figure 8: System Designs – (7) Shared ASHP / GSHP

(8) Large Scale GSHP/WSHP DHN

This system concept design is based on an ‘energy centre’ populated with ground source or water source heat pumps powered by national electricity generation. Heat distribution is via a large scale heat network providing high temperature heat directly to individual buildings.

Careful location and configuration of the ground bores or water sources will be critical to performance; to avoid ‘freezing’ the ground or water source when extracting heat over consecutive periods of cold weather in deep winter. It is unlikely to be desirable to construct a single large energy centre for this system design; rather, a number of heat pumps distributed around the network area is likely to be best. Surface area clearances will be required to avoid adverse effects. The scale and nature of these installations will be very dependent on the built environment, land usage and the local geology. In some areas, the bores could be very deep, similar to the existing geothermal scheme in Southampton.

Decarbonisation of the national electricity grid is a prerequisite to meeting the UK’s 2050 energy and climate change goals.

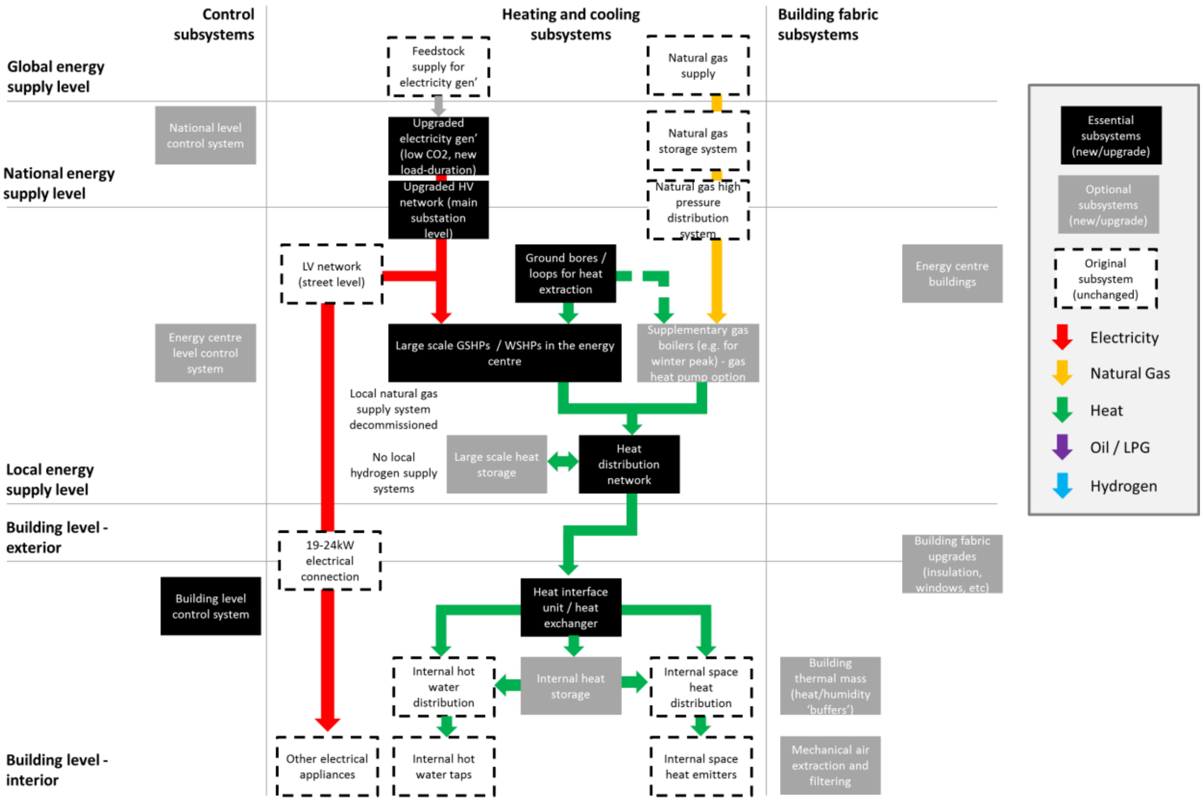


Figure 9: System Designs – (8) Large Scale GSHP / WSHP DHN

(9) Large Scale NG CHP DHN

Similar to the GSHP DHN, but the energy centre is populated with a combination of natural gas Combined Heat and Power (CHP) generation (most likely as gas engines or gas turbines) together with supplementary gas boilers to meet winter peak heating demand.

There is the option to increase the efficiency of the gas boilers for winter peak heating demand by using gas absorption/adsorption heat pumps instead of conventional gas boilers; the boiler efficiency would rise from ~90% to ~130-150%.

This system configuration would only make a limited contribution to the UK's 2050 energy and climate change goals, but opens up significant strategic flexibility to transition the energy centre at a later date to one of the other DHN based configurations without any consumer involvement. Careful design will need to plan for this transition; to ensure sufficient space for further development and to ensure assets can be reused in a future upgrade of the energy centre (the energy centre land use requirements for this system design and the GSHP based design are very different). Over time, the gas-engines may transition from high-utilisation assets producing heat and electricity to peaking assets to provide for occasional deep winter demand. It is very likely that heat pumps will form a major or even dominant part of future heat supply (at energy centre or individual building scales). In that case, the national demand for electricity will peak at a similar time to the local demand for heat, enabling these assets to compete strongly in the national electricity capacity market.

The investment return for this configuration may be significantly helped by exports of electricity, in particular at peak times, if it can be sold into the national grid at a true value reflective price for marginal electricity production (which is not the case in the current electricity market).

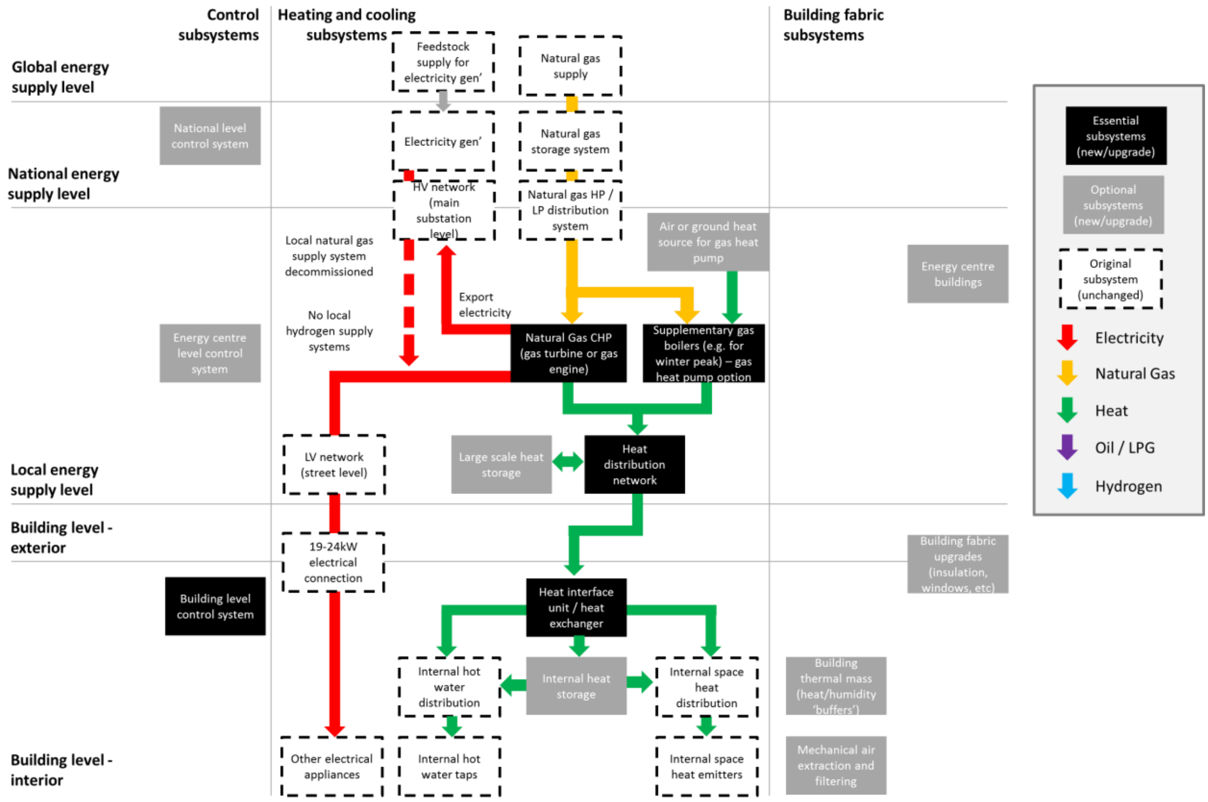


Figure 10: System Designs – (9) Large Scale Natural Gas CHP DHN

(10) Large Scale H2 DHN

This configuration is similar to that above, but with a hydrogen energy centre. The hydrogen energy centre could be comprised of gas engines, gas turbines, fuel cells, gas boilers or gas absorption/adsorption heat pumps; or any combination as required by the needs of the specific location.

The energy centre could be connected to a high pressure hydrogen pipeline, depending on the size of the connected heat network; a low pressure hydrogen pipeline may be needed for smaller scale designs. There is an implied need for upstream conversion and storage capacity.

A low carbon supply of hydrogen is a prerequisite for this system concept design, which is likely to be dependent on the availability of low cost coal or natural gas in combination with Carbon Capture and Storage (CCS). Although electrolysis from renewable electricity generation is an option, it is unlikely to be cost effective for mass-scale heat delivery on the basis that it would be much more cost effective to use electricity directly to provide heat (and then store energy as heat). There is potentially value in the use of electrolysis to produce hydrogen from intermittent renewable assets with a very low marginal cost (such as wind) to help balance the electricity system. However, the volume of hydrogen affordably produced by this, given that heat demand far exceeds general electricity demand, is unlikely to be sufficient to justify the cost of investment in a hydrogen distribution network. Instead, it would be more cost effective to use it in a hydrogen turbine located close to the electrolysis plant.

Peak winter heating demand could be met by heat storage at the energy centre or hydrogen storage upstream (for safety reasons, large scale storage of hydrogen at the energy centre may be unattractive and, for cost reasons, large scale geological storage of hydrogen is likely to be more attractive). Heat storage at the individual building is unlikely to be necessary, but is an option; specific consumers may want a higher hot water flow than standard, for example.

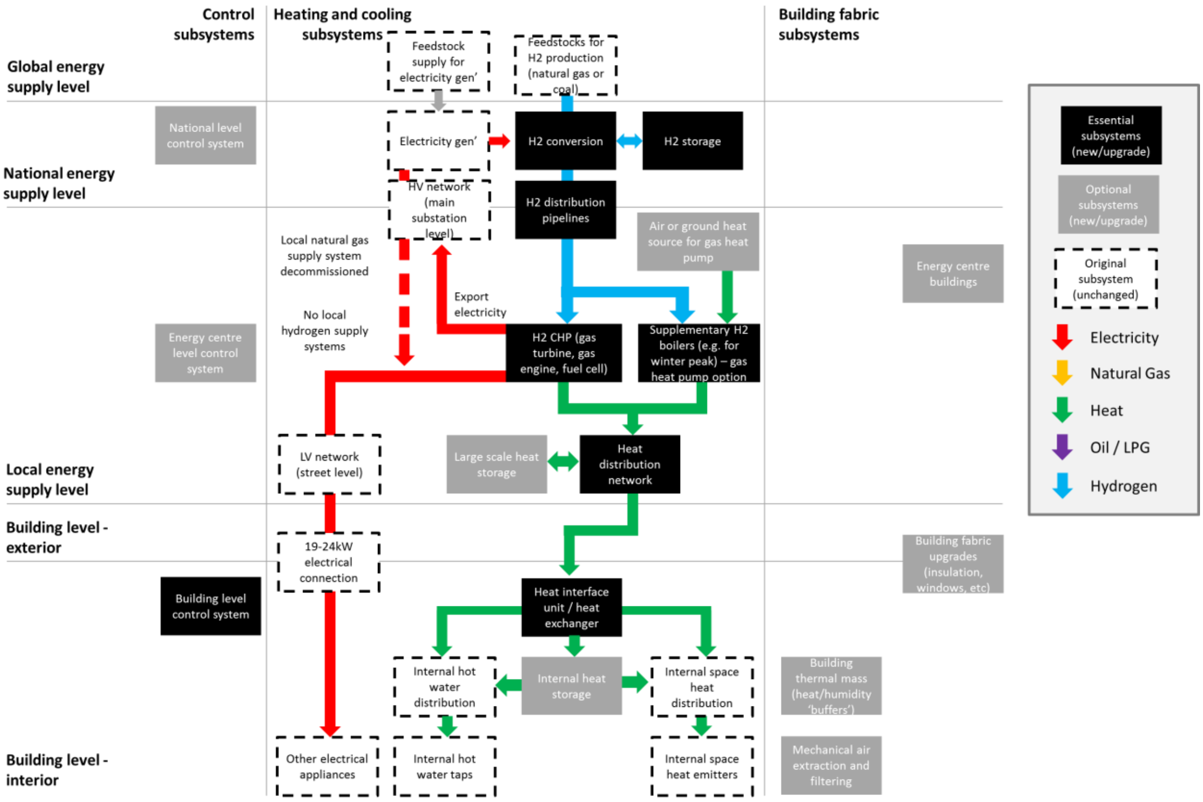


Figure 11: System Designs – (10) Large Scale Hydrogen DHN

(11) Waste Heat Exploitation DHN

This system concept design is similar to the 'Large Scale GSHP/WSHP DHN', but with the energy centre predominantly fed by waste heat (e.g. from thermal electricity generation or industrial processes). Typically, this requires reasonably high waste heat temperatures but, in combination with a heat pump to elevate the temperature to a useful level, lower waste heat flows could be exploited.

Once large scale district heating networks are established they create a market for heat which can either be accessed by existing industrial processes of various scales or they provide an incentive to locate new facilities, such as thermal power stations, waste to energy plants, etc so they can gain significant additional revenues. It is economic to move heat comparatively long distances (for example, over 50km for a thermal power station).

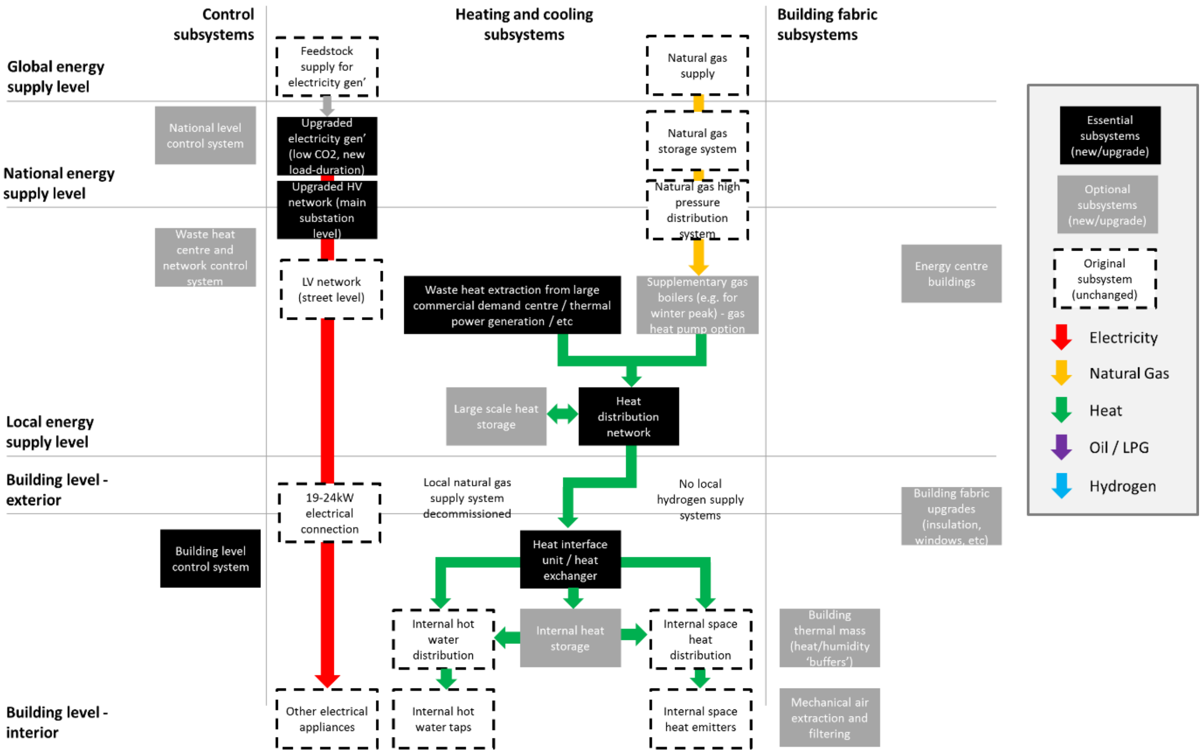


Figure 12: System Designs – (11) Waste Heat Exploitation DHN

Summary, Applicability and Excluded Design Options

These eleven system concept design are expected to have different applicability depending on the type of location. This is summarised below.

System Design Option	Applicability to Location Types			
	Dense Urban	Suburban	Market Towns	Rural
(1) Individual Gas Boiler	√	√	√	?
(2) Individual Oil or LPG Boiler	X	X	X	√
(3) Individual Electric Resistive	√	√	√	√
(4) Individual HT ASHP	X	?	?	√
(5) Individual LT ASHP / Gas Boiler Hybrid	X	?	?	?
(6) Individual LT ASHP / Oil or LPG Boiler	X	?	?	√
(7) Shared ASHP / GSHP	X	?	?	√
(8) Large Scale GSHP/WSHP DHN	√	?	?	X
(9) Large Scale NG CHP DHN	√	?	?	X
(10) Large Scale H2 DHN	√	?	?	X
(11) Waste Heat Exploitation DHN	√	?	?	?

In addition, there are nine concept design options not being taken forward in the SSH programme at the current time. They should nonetheless remain on an ongoing horizon scanning exercise to inform regular technology strategy reviews.

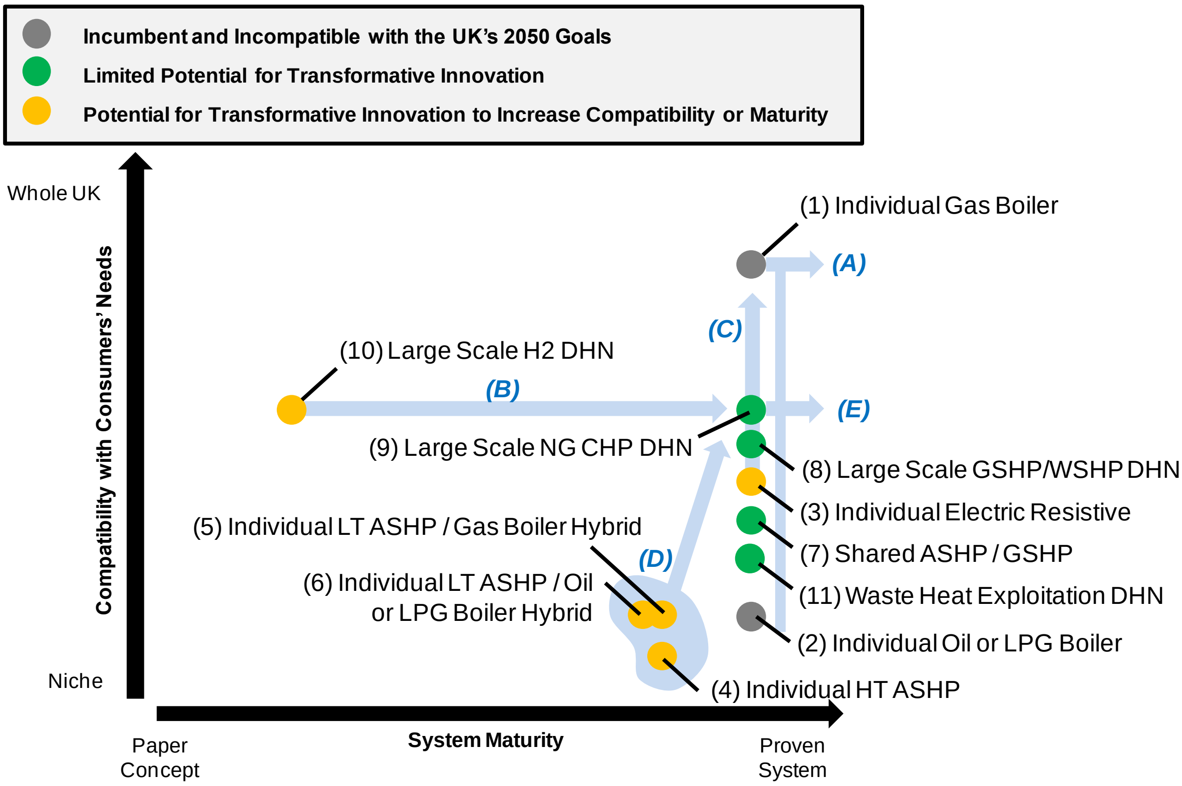
- **(12) Individual H2 Fuel Cell CHP** and **(13) Individual H2 Boilers** due to the major infrastructure investment, significant technology maturity gaps and a lack of evident advantages over alternative system design options such as shared heat schemes.
- **(14) Individual gas absorption or adsorption heat pumps** on the basis that the carbon reduction is insufficient to achieve the UK's 2050 energy and climate change goals and it is not evident that they would help to manage the transition to that goal either.
- **(15) Individual High Temperature ASHP / Gas Boiler hybrid** because it does not appear to be financially attractive to combine an expensive high performance heat pump with good peak winter performance with a gas boiler (a cheaper, lower performance heat pump hybridised with a gas boiler is still an attractive option).
- **(16) Individual GSHPs** due to the high cost for the individual ground bores.
- **(17) Individual Low Temperature ASHPs** due to inadequate winter performance leading to poor consumer satisfaction and a need for a significant excess of low utilisation peak electricity generation and distribution capacity.
- **(18) Low Temperature DHNs** on the basis that the temperature is unlikely to be sufficient for most retrofit buildings and the efficiency benefits are not expected to be sufficiently compelling to drive additional investment in the building stock or in-building heat delivery systems to enable low temperature DHNs to be attractive.
- **(19) Biomass Boiler DHNs** on the basis that ETI's current analysis in the Bioenergy Programme suggests the UK's limited biomass resource would be better used in locations where it can be combined with Carbon Capture and Storage (CCS) such as central electricity generation. If our understanding of the viability of CCS changes, this should be reviewed, but for the time being it is not being taken forward in SSH. However, some niche uses of biomass may still be integrated into the designs above; for example, as part of the heat supply in a district heat energy centre using locally produced low density biomass that would be unaffordable to transport long distances.
- **(20) Individual Biomass Boilers** for the same reasons as 'Biomass Boiler DHNs'. However, this may still be applicable in some niche locations; for example, the Highlands of Scotland where significant biomass resource is available but is unlikely to be affordably transported elsewhere for uses where it can be combined with CCS.

Maturity of the Design Options and Compatibility with Consumer Needs

The focus of this maturity analysis is on solutions for existing buildings. For new buildings, the degrees of freedom of the design space are largely unconstrained and any 'gaps' that exist for existing properties can largely be overcome at the building design stage.

The focus for the analysis below is on the heating, ventilation and cooling systems in a building. There may be additional innovation needs with building fabric improvements, beyond the need for design tools and up-skilling the supply chain as previously noted, which are still under consideration for a future update of this paper.

The current maturity and compatibility with consumer needs of the above system concept designs is summarised at a high level in the illustrative chart below. The later parts of this section present a more detailed analysis of each system design. The *'Limited Potential for Transformative Innovation'* system designs are unlikely to be moveable in terms of maturity or compatibility with consumer needs, but there are nonetheless potential incremental innovation opportunities discussed later in this paper. The *'Potential for Transformative Innovation'* system designs are those where more radical innovation could fundamentally transform the maturity and/or compatibility with consumer needs.



Key System Design Issues / Opportunities:
(A) Controllability / consumer interfaces (common issue to all system designs)
(B) Lack of real-world experience
(C) Size/space, responsiveness, installer capability
(D) Size/space, noise, aesthetics, responsiveness, installer capability
(E) Supplementary boiler efficiency opportunity

Figure 13: High-level Overview of System Design Options – Maturity and Compatibility with Consumer Needs

Emerging from the SSH consumer research in Work Area (WA) 5 are some key themes against which the system concept designs in the SSH programme should be developed. These are combined with insights from the wider SSH programme. This is a very early stage list of parameters, which will be refined as the SSH programme progresses.

- **End-to-end System Efficiency (Average)**
  This parameter describes the efficiency through the entire energy chain of converting raw feedstock into useful heat at the building.

- **End-to-end System Asset Utilisation**
  This parameter describes how effectively the system design is able to utilise the asset base, for example the level of demand for peak low usage electricity generation.
- **Total Cost of Ownership (Excluding Carbon Price)**
  This parameter includes the annualised capital cost for the individual building assets, network asset and upstream energy conversion and storage assets, as well as operating and resource costs throughout the energy chain.
- **Responsiveness to Consumer Control**
  This parameter describes the inherent physical characteristics of the design, such as the maximum heat output from a heat pump constraining the minimum warm-up time for the building. It is the physical constraints, rather than the human interfaces covered by the next parameter. However, there is interdependency; an easy to control remote access to the heating system, for example, may mitigate some of this issues of a system design with poor physical response characteristics.
- **Ease of Controllability for Consumers**
  This parameter describes how easy it is for a consumer to set their system appropriately, get what they want out of it, know the cost implications of their decisions, etc. This is about the human interaction with the system rather than its physical constraints (covered by the previous parameter). It includes the ability to implement predictive control (‘self learning’ control).
- **Form Factor, Size and Fit into Buildings**
  This parameter relates to the space required for the various components, their form factor, the type of space they take up in the building (e.g. low value vs. high value space, integrated into the building fabric vs. occupying otherwise useful space, etc).
- **Aesthetics for Consumer and Community**
  For the consumer, this relates to things inside the building, such as internal components like boilers, storage tanks, compressors, etc. It also covers things outside the building, which also affect the wider community when installed at scale; such as heat exchangers for ASHPs, energy centres, etc.
- **Noise for Consumer and Community**
  This parameter covers things like noise from heat exchangers outside buildings. It also covers noise inside the building by things like compressors in heat pumps, etc.
- **Installation Disruption for Consumer**
  This parameter refers to the disruption the consumer will experience when making the decision to install a new system. It includes the complexity of configuring the system to have installed, time for installation, need to move furniture/fixtures/fittings, dirt and dust during installation, need for trenching in the drive/garden, etc.
- **Installation Disruption for Community**
  This refers to disruption imposed on the wider community (many of which may not be wanting to change to a new system yet); for example laying a heat network.

- **Compatible with Carbon Reduction Trajectory**
  This parameter is not a measure of whether the design meets an 80% reduction in GHG emissions as yet, but whether it puts the local area on to a trajectory to meeting it. For example, a natural gas energy centre may not significantly reduce carbon emissions, but it does open the option to transition the energy centre to something else later with low cost and disruption; e.g. when electricity carbon emissions fall and gas/carbon costs rise, the energy centre could be transitioned to large scale GSHPs.
- **Potential for Incidental Benefits**
  Things like the ability to add new services as marginal cost additions to the concept design are covered by this parameter. For example: the opportunity to install gigabit fibre optic network connections at the individual building level at the same time as laying a heat network, the opportunity to incorporate air conditioning/filtration, etc. It also includes co-benefits, such as increased market value of the building, health improvement, etc.
- **Resilience to Energy Price Volatility**
  This refers to the inherent flexibility in the design to changing energy prices; for example, how sensitive the design is to uncertain resource costs vs. certain sunk capital costs, how flexible the design is to change to an alternative feedstock if prices change, etc.

The current ETI appraisal of the eleven system concept designs against the above parameters is outlined below, together with an indication of the innovation needs. Each concept is appraised relative to the incumbent (Individual Gas / Oil / LPG boilers) and assuming upgraded Home Energy Management Systems (HEMS) can address the primary innovation ‘gap’ with that system design as it stands today (as highlighted below).

Further development of this analysis will extend it into a full Quality Function Deployment (QFD) process, which will include consumer segmentation and weighting of the parameters.

Where the innovation needs are similar between the system designs listed above, they have been grouped into one section.

(1) and (2): Individual Gas, Oil or LPG Boilers

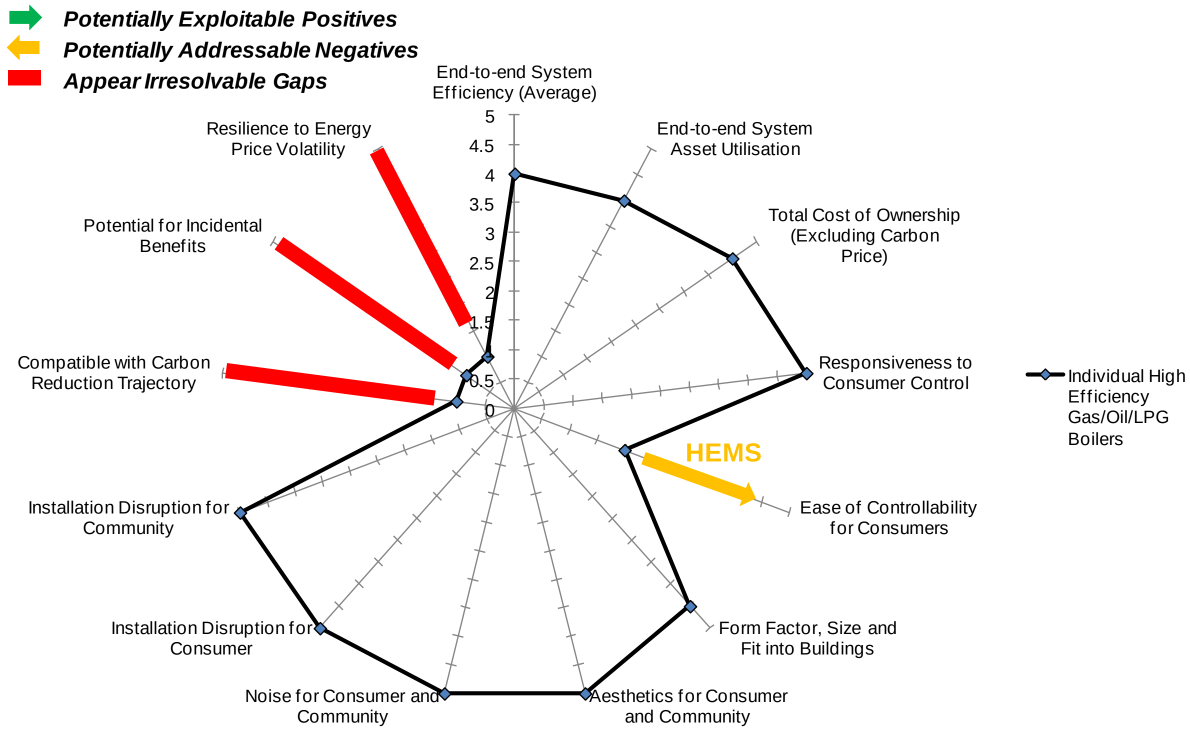


Figure 14: System Design 'Gaps' - (1) and (2): Individual Gas, Oil or LPG Boilers

The primary innovation 'gap' with conventional systems is in terms of controllability for consumers. The current control systems have a number of significant issues:

- Poor usability and lack of intuitive design.
- Lack of information in a form meaningful to consumers; for example, controls are based on boiler on/off times rather than desired temperature times.
- Lack of information on the cost of adopting particular controller settings ('control strategies') and information on alternative control setting options and their costs.
- Lack of differential zone control, to enable different temperature settings in each room or area of the building. This is due to a lack of installed sensors and actuators.
- Lack of a 'plug-and-play' type interoperability framework, to enable different control units to optimally control boilers. This tends to lead to a need to procure the boiler manufacturer's control system or accept degraded control system performance. This is especially so for condensing boilers, where optimised control can significantly improve real-world performance by managing the return flow temperature.

The early market for Home Energy Management Systems (HEMS) is starting to address some of these issues, but ETI review of the products currently on the market or near to market suggests significant gaps. Current products for advanced HEMS include: ChopCloc, NEST, OWL, EWGECO, PassivSystems, etc.

(3): Individual Electric Resistive

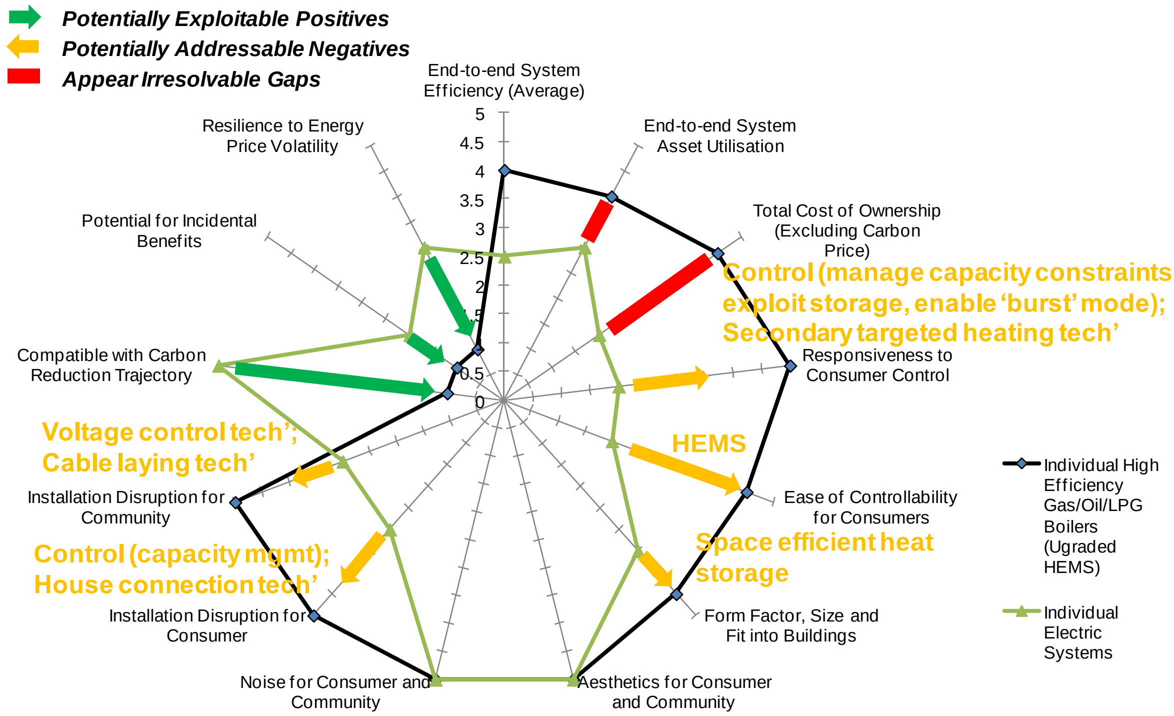


Figure 15: System Design 'Gaps' - (3) Individual Electric Resistive

For electric based systems, the high cost of upstream electricity generation (or storage) capacity leads to a high importance for 'smart' demand management. The nature of the expected load-duration curve drives the selection of generating plant, which in turn fixes the relationship between annual costs for capacity (capital depreciation, fixed maintenance) and usage costs (feedstock resources, additional maintenance). This is highlighted in the charts below (the expected costs in 2030). This highlights the extremely high cost of very low utilisation marginal electricity generating plant and the importance of demand management to minimise the investment in such low utilisation capital assets.

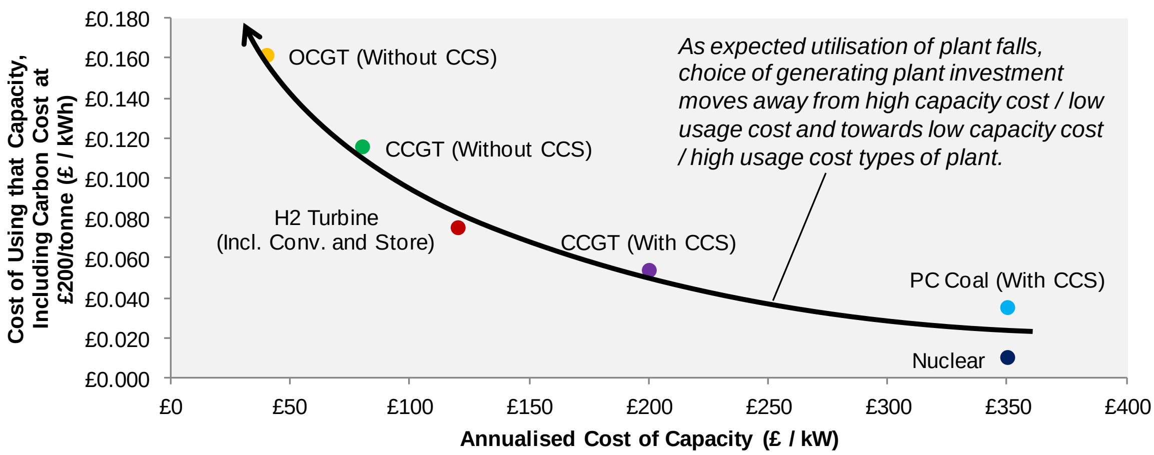


Figure 16: Cost of Capacity and Cost of Using Capacity for Electricity Generation Technologies in 2030

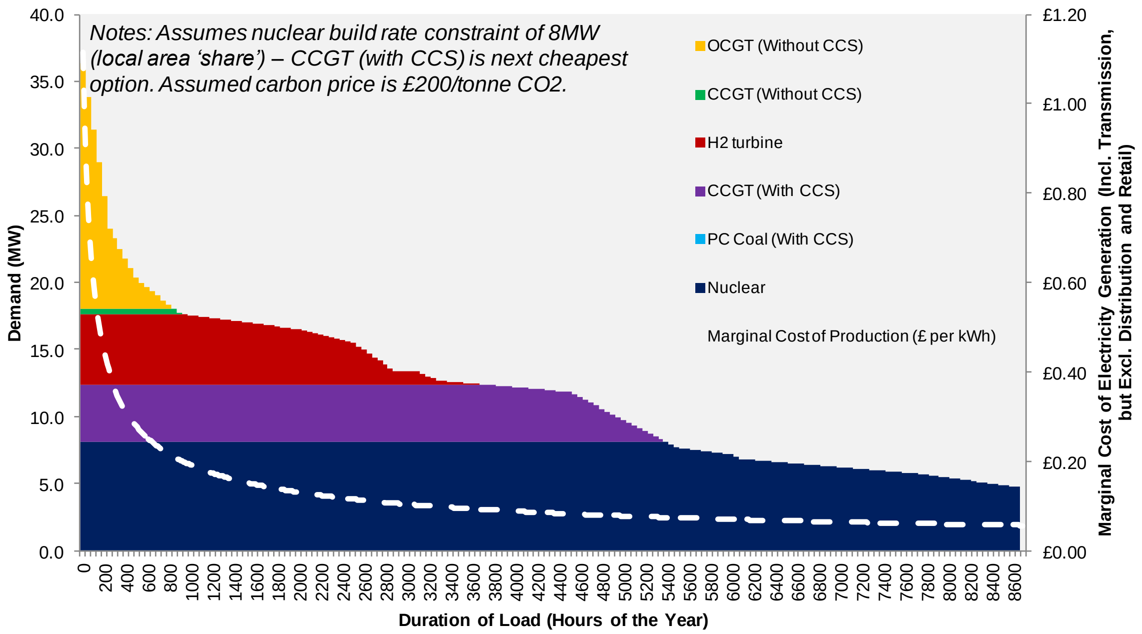


Figure 17: Generating Plant Configuration and Marginal Cost for a Typical Load-Duration Curve

Existing electric based heating systems tend to have a reasonable performance in well insulated dwellings with a high capacity of storage for both space heating (typically integrated into the heat emitter and heated directly by a resistive coil) and in a hot water tank (heated by an immersion coil). However, the responsiveness of the system to consumer control requests is extremely poor with existing designs and, where instant hot water is available for showers or taps, the flow rate tends to be extremely low.

In properties not designed for electric heating, the thermal efficiency tends to be much lower, space for heat storage is less available and the disruption for new electrical connections throughout the building is considerable.

Potential innovation opportunities to address these gaps are:

- Technologies to upgrade the electrical supply capacity to the building with less disruption and lower cost than the current invasive trench digging approach.
- Technologies to upgrade the capacity of the street level Low Voltage (LV) electrical network with reduced cost and disruption.
- 'Smart' in home control systems to actively manage the demand within the capacity headroom of the incoming supply connection. This could enable the system to be much more responsiveness to consumer control requests (for example by controlling the use of secondary targeted heating). It could also enable much higher flow rates from instant hot water elements such as electric showers.
- Controllable heat output adjustment from storage heaters to enable the consumer to avoid under/over heating due to poor weather prediction in overnight 'charging'.
- Secondary targeted heat delivery integrated with the primary heating control system, such as directional fan heaters to increase the responsiveness of the overall system.

- Novel approaches to thermal storage to minimise the amount of useful space consumed by a hot water tank and minimise the hassle for installation.

However, the annualised cost of electric based heating systems for existing properties not currently electrically heated is very large and it is not evident there are innovation opportunities to reduce cost to a price level comparable to systems with a similar level of disruption and much higher performance (DHNs or Shared ASHP/GSHP type solutions).

(4): Individual HT ASHP

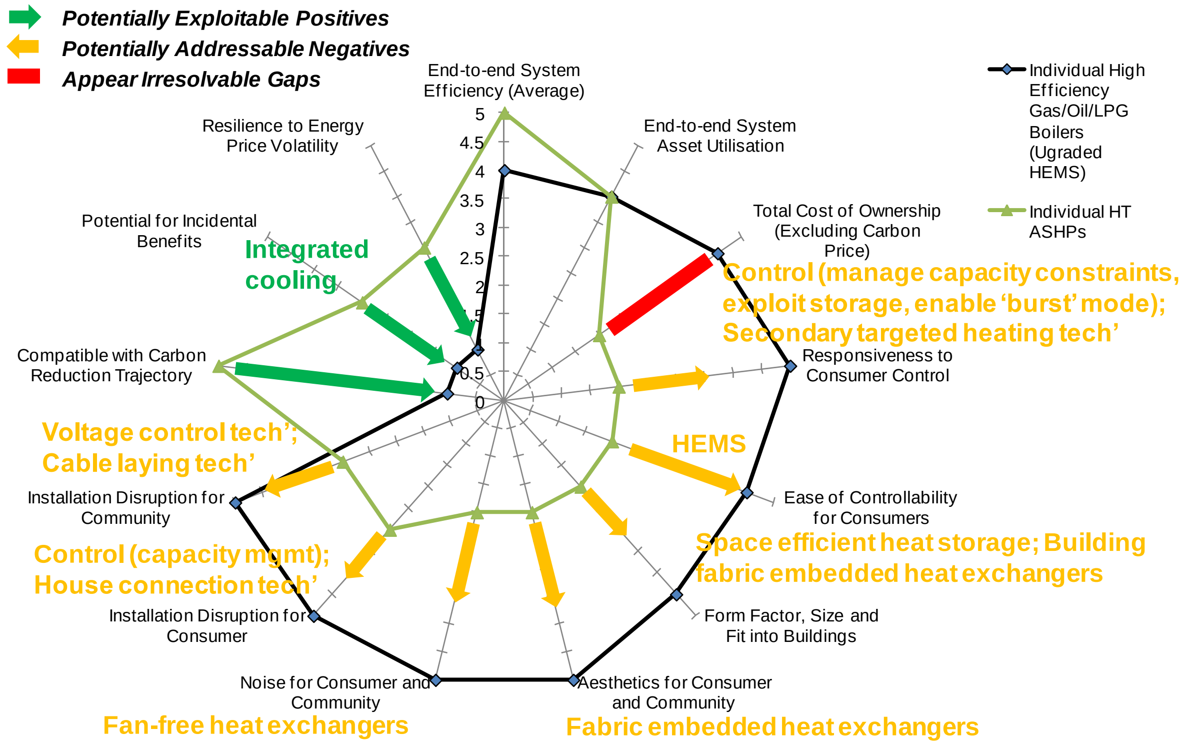


Figure 18: System Design 'Gaps' - (4) Individual HT ASHP

High Temperature (HT) ASHPs are a relatively new product in the UK for residential dwellings (for example, the Daikin Altherma HT). These products offer the potential to integrate with existing wet radiator systems (with an outlet temperature of 70-80ºC) and provide high efficiency at a low air source temperature (-7ºC or below).

However, while this recent product development has led to a high efficiency, there remain a number of significant issues that could be addressed through innovation:

- There are innovation opportunities to reduce the cost and disruption for the upgrade of the street level electricity network and individual building connections.
- As for electric resistive type systems, there are opportunities to improve the poor responsiveness of the system by 'smart' demand management within the capacity headroom of the building. This could include an ability to control the use of heat from a storage tank to rapidly heat the radiator system, use of targeted secondary electric resistive heating, over-sizing the heat pump and using variable compressor speeds to ensure the optimum balance of responsiveness and efficiency.

- Novel approaches to thermal storage to minimise the amount of useful space consumed by a hot water tank and minimise the hassle for installation.
- Novel designs for external heat exchangers to minimise noise and increase aesthetic appeal by reducing the need for fan driven forced convection (with enough surface area, natural convection may be sufficient). This implies a need for more complex design and control system configuration to ensure proper matching of the internal compressor unit and the external heat exchanger for each individual building.
- Noise suppression for internal compressor units to enable installation in 'living' areas of the building such as kitchens.
- Integration of cooling into the ASHP design configuration, to deliver additional consumer benefits.

While costs are more favourable than for electric resistive type systems, the annualised cost for these systems is still considerably higher than a conventional gas boiler based system. An indicative comparison of the Daikin Altherma HT (£1,266 per annum, all-in) against the top of the range Worcester-Bosch Greenstar 42CDi condensing gas boiler (£929 per annum, all-in) for an 'average' existing building indicates a significant cost gap. While there is some scope for cost reduction as production volumes scale-up, the majority of the underlying components are mature and are unlikely to see dramatic cost reductions. Assuming the marginal electricity generating plant used to supply the ASHP is an efficient natural gas Closed Cycle Gas Turbine (CCGT) without CCS, which reflects the current electricity grid mix, an effective carbon price of over £300/tonneCO_2 would be required to offset the cost difference.

(5) and (6): Individual LT ASHP / Gas or Oil or LPG Boiler Hybrid

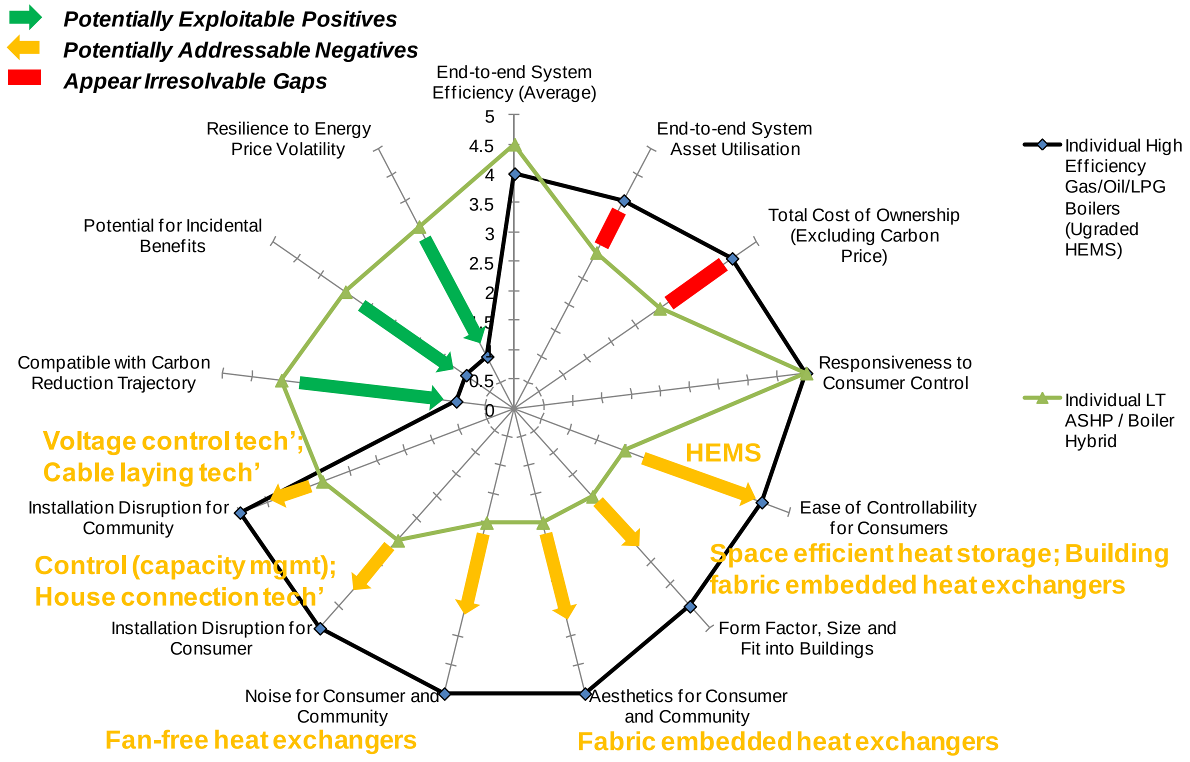


Figure 19: System Design 'Gaps' - (5) and (6): Individual LT ASHP / Gas or Oil or LPG Boiler Hybrid

Hybridisation with a gas boiler addresses the poor responsiveness of the Individual HT ASHP system design and partially addresses the cost issue. However, the other innovation gaps identified above remain.

(7): Shared ASHP / GSHP

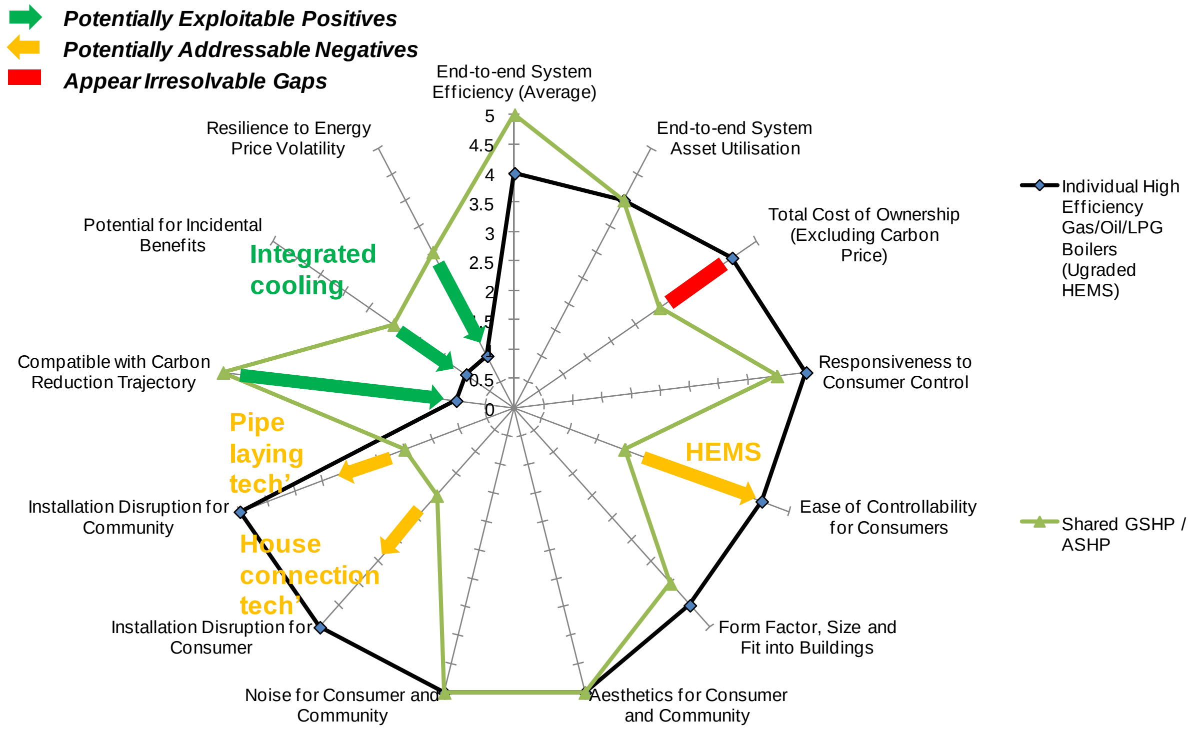


Figure 20: System Design 'Gaps' - (7) Shared ASHP / GSHP

This system concept design would offer performance to consumers very similar to a conventional combi- gas boiler. In addition, there is scope to offer additional functionality in terms of integrated cooling if consumer demand justifies the additional costs. While the costs are significantly higher than a conventional gas boiler, in off gas-grid areas the high cost of road tanker delivered fuel may make this system design attractive even without a carbon price. However, the costs are very much dependent on the very localised conditions and a general 'indicative' cost estimate has not been produced for this reason.

Daikin offers a shared ASHP solution which would be applicable to large blocks of flats, with costs and performance characteristics that could be very favourable compared to the current electric based systems installed in those locations (gas is often not permitted for safety reasons). However, considerable disruption to the fabric of existing blocks of flats will be incurred and some means is required to get the buy-in from all residents of the block for it to be viable.

The technical innovation opportunities are essentially modest refinements:

- Technologies for low cost, low disruption installation of pipe-work at the street level and building connection level.

- Products to integrate cooling into the heat delivery system within the building.

The more radical innovation opportunity is in the community engagement process to get sufficient buy-in to be able to install the system and make a successful return.

(8), (9), (10) and (11): Large Scale GSHP, NG CHP, H2 or Waste Heat DHN

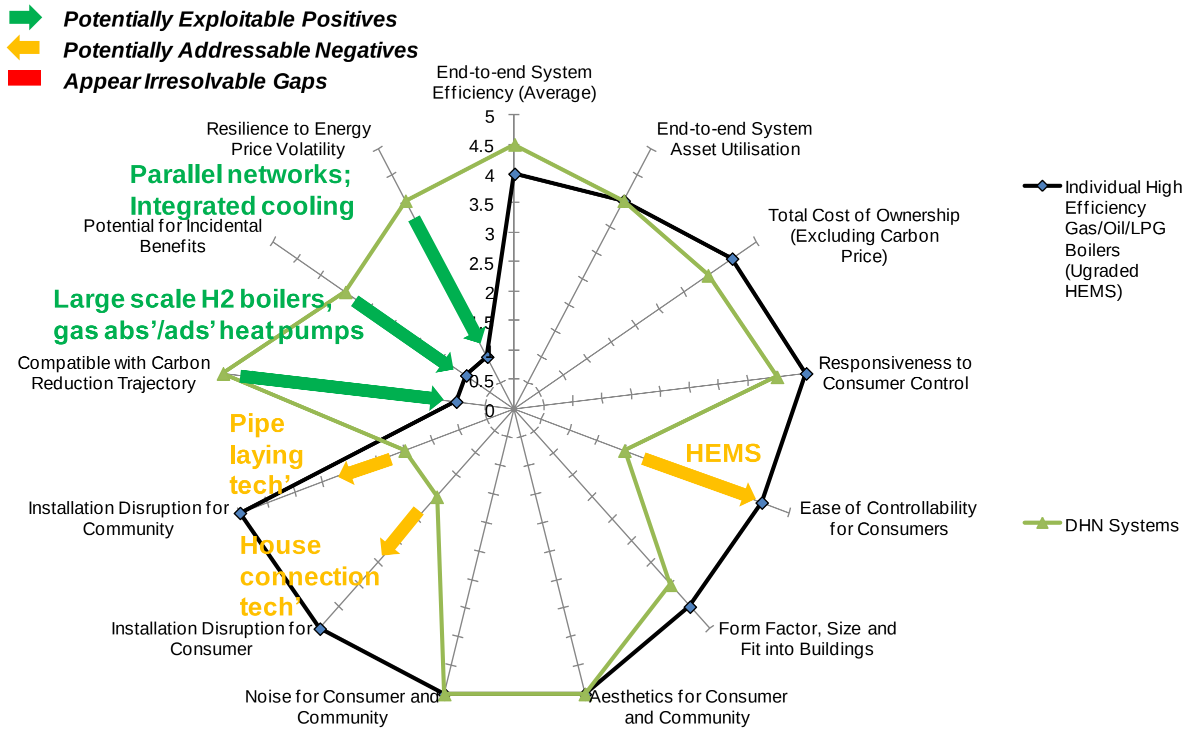


Figure 21: System Design 'Gaps' - (8), (9), (10) and (11): Large Scale GSHP, NG CHP, H2 or Waste Heat DHNs

The innovation needs are very similar to those for Shared ASHPs/GSHPs. The additional innovation opportunities are at the energy centre level:

- Gas absorption/adsorption heat pumps for the supplementary gas boilers. The efficiency increase from ~90% to ~130% is anticipated to more than pay for the addition capital outlay in the energy centre investment in many cases, even without a carbon price. There are some commercial scale gas absorption/adsorption heat pump products on the market (the products manufactured by Robur, for example), but the market is at a very early stage of development.
- Hydrogen turbines, engines and fuel cells, but these are likely to be very long-term opportunities given the need for a low carbon supply of hydrogen. The inherently high resource costs for hydrogen based systems are unlikely to make this an attractive option for the energy centre until the carbon price rises significantly (which is likely to be some years away).

The above system designs have been applied to a case study location (Loughborough), which highlights the importance of DHN type solutions. This is attached at the appendix.

Summary of ‘Gaps’ and Focus for the SSH Programme ‘Products’

The analysis has identified a number of ‘gaps’ in the SSH programme space, which naturally leads to a number of SSH ‘products’ the ETI could develop to address those ‘gaps’. The focus for the programme should be on retrofit buildings; there is unlikely to be significant ETI additionality in the new build space.

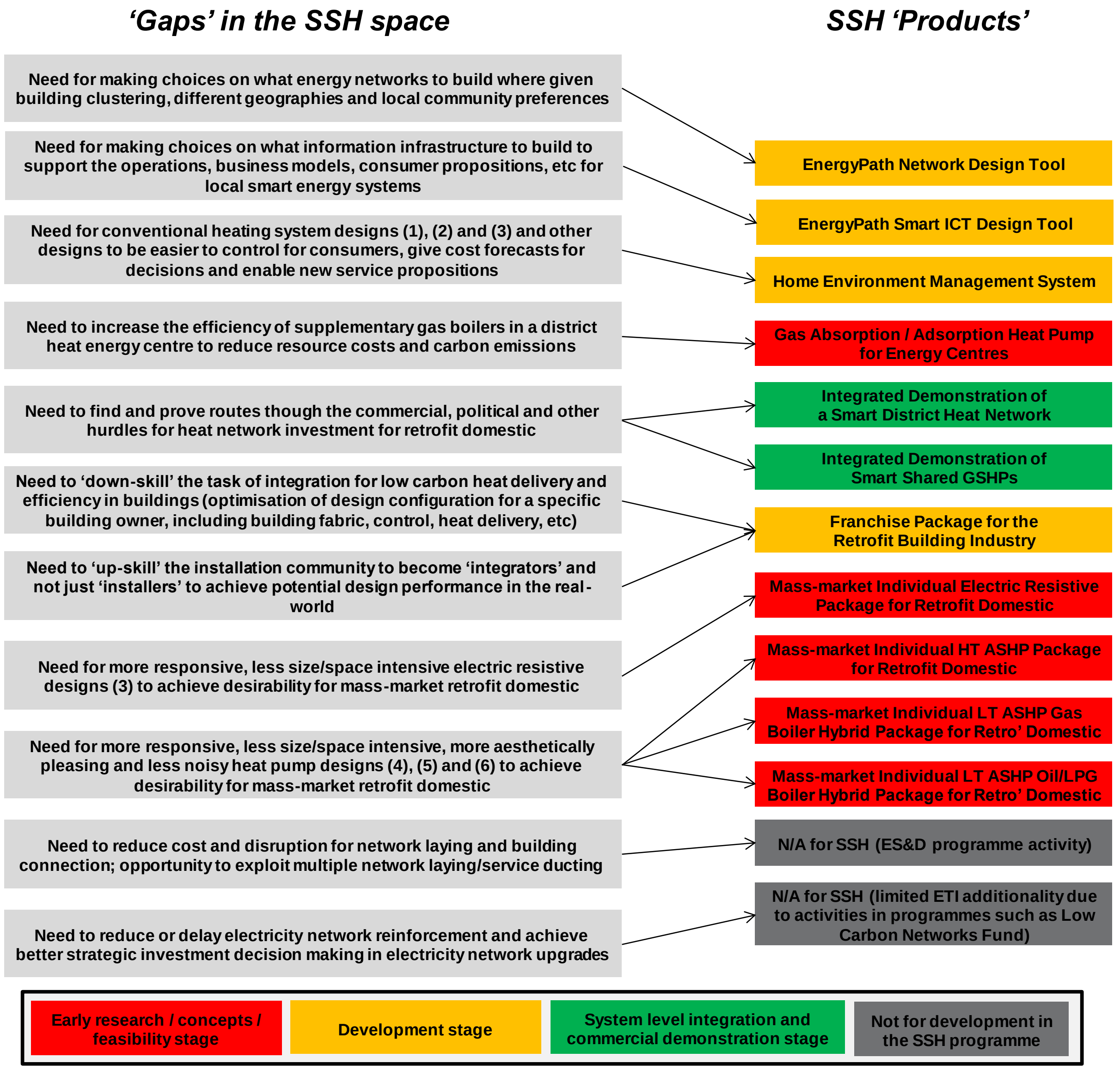


Figure 22: Summary of ‘gaps’ in the SSH space and ‘products’ to be developed in the SSH programme

SSH ‘Product’	High Level Description
EnergyPath Network Design Tool	A suite of software tools designed to enable an expert user to work with a local authority to help it develop an energy master plan (the physical heat assets ‘layer’). It will provide the objective and robust analysis to inform decision makers within the local authority.

SSH ‘Product’	High Level Description
EnergyPath Smart ICT Design Tool	A suite of software tools, including a business/market model simulator and test bench for real-world testing, to enable an expert user to design the appropriate ICT configuration for a ‘smart’ local energy system (the information assets ‘layer’).
Home Environment Management System	Consumer-centric design (simple control choices with cost forecasts); enables new service models (weather and energy price risk underwriting); key source of individual building data for input to design tools.
Gas Absorption/Adsorption Heat Pump for Energy Centres	The gas heat pump should deliver efficiency of ~130% for the supplementary gas boilers within the energy centre of a natural gas district heat scheme. This is against an efficiency of ~90% for conventional supplementary gas boilers.
Integrated Demonstration of a Smart District Heat Network	A real-world trial, at scale, including: • Construction and operation of networks; • Community engagement in collective decision making; • Validation of the district heat network elements of the EnergyPath tools; • Include multiple heat sources in the energy centre (natural gas turbine/engine CHP, boilers, gas absorption/adsorption heat pumps, ground source heat pumps, etc); • Prove the routes to transition a natural gas energy centre to zero carbon over time; • Develop and refine control algorithms for the energy centre with multiple heat sources and the integrated system; • Selling packages to building owners; • Validation of the building franchise package (design tools, training, shared logistics, etc); and • Different consumer propositions and business models (underpinned by HEMS).
Integrated Demonstration of Smart Shared GSHPs	A real-world trial, at scale, including: • Community engagement in collective decision making; • Validation of the shared heat pump elements of the EnergyPath tools; • Selling packages to building owners; • Validation of the building franchise package (design tools, training, shared logistics, etc); • Different consumer propositions and business models (underpinned by HEMS); and • Control algorithms for the integrated system.

<table>
<tr><th>SSH ‘Product’</th><th>High Level Description</th></tr>
<tr><td>Franchise Package for the Retrofit Building Industry</td><td>A package of design tools, training, brand/shared marketing/customer leads (and potentially expanding to shared logistics, buying power, etc) for a supply chain capable of being ‘integrators’ and not just ‘installers’. It should provide sufficient confidence for performance guarantees to be offered by installers.</td></tr>
<tr><td>Mass-market Individual Electric Resistive Package for Retrofit Domestic</td><td rowspan="4">A product or set of component products to address the ‘gaps’ identified in the performance of existing systems for retrofit domestic properties – size/space, noise, aesthetics, responsiveness, etc. A key underpinning is the Franchise Package for Installers, since installation of systems that address these issues is likely to require a high degree of configuration of the system for specific buildings.

It is not currently clear what the ETI ‘product(s)’ will be in this area; further concept and feasibility stage work is required. Key component products the ETI may develop are: space efficient thermal storage, better control algorithms, better integration with secondary heating to improve responsiveness, low noise heat exchangers, etc. A key first step is exploring the potential for space efficient thermal storage.</td></tr>
<tr><td>Mass-market Individual HT ASHP Package for Retrofit Domestic</td></tr>
<tr><td>Mass-market Individual LT ASHP Gas Boiler Hybrid Package for Retro’ Domestic</td></tr>
<tr><td>Mass-market Individual LT ASHP Oil/LPG Boiler Hybrid Package for Retro’ Domestic</td></tr>
</table>

The development and exploitation strategies for these ‘products’ are documented in an additional paper for the November 2013 SSH Programme Stage Gate Review.

The systems design analysis reported in this paper is the first version; it will continue to be updated through the life of the SSH programme. New ‘gaps’ may be identified, and early feasibility work and business case analysis for the ‘products’ identified above may change the case for their development. The SSH programme needs to retain significant flexibility to adapt as knowledge increases. Specific updates for the next version (completion anticipated for the end of 2013) include:

- Extension of the 'gap' analysis to building fabric components;
- Refinement of the evaluation parameters with future insight from the CRaB project;
- Further detailing of the 'gap' analysis using a full QFD process, including to add market segmentation and parameter weighting to the analysis.

Appendix A: Application of the System Designs to a Case Study

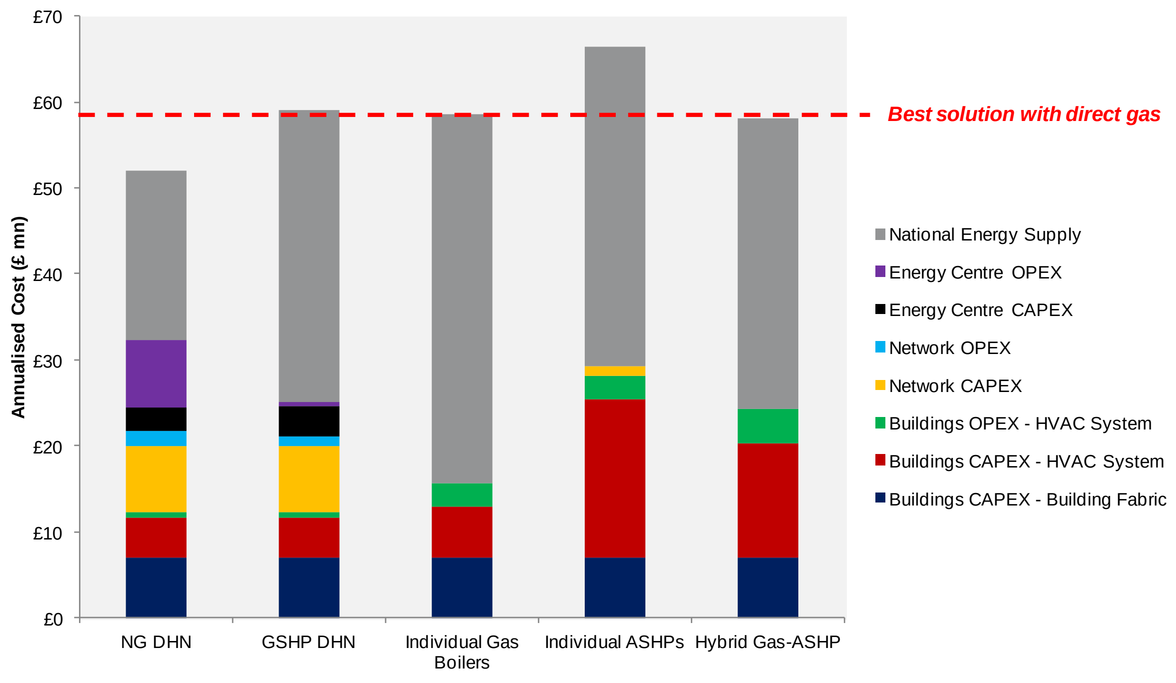
Five of the energy system design options described above have been evaluated for Loughborough, a small market town of 22,500 dwellings. These configurations reflect both the residential and commercial energy demand within the town. For Loughborough, the latter is very significant since commercial demand in the town consumes around the same amount of energy currently as residential demand (a total of 792 GWh). However, there are significant data gaps which severely limit the robustness of the findings presented here.

- A districting heat system with a natural gas fuelled combined heat and power energy centre (gas turbines and supplementary gas boilers) – system design (9) above.
- A districting heat system with a large scale GSHP based energy centre powered by national grid electricity – system design (8) above.
- A continuation of the current paradigm, individual gas boilers, but with a transition to the most efficient product – system design (1) above.
- Individual high temperature, high performance ASHPs in individual buildings – system design (4) above.
- Individual hybrid gas boilers and ASHPs – system design (5) above.

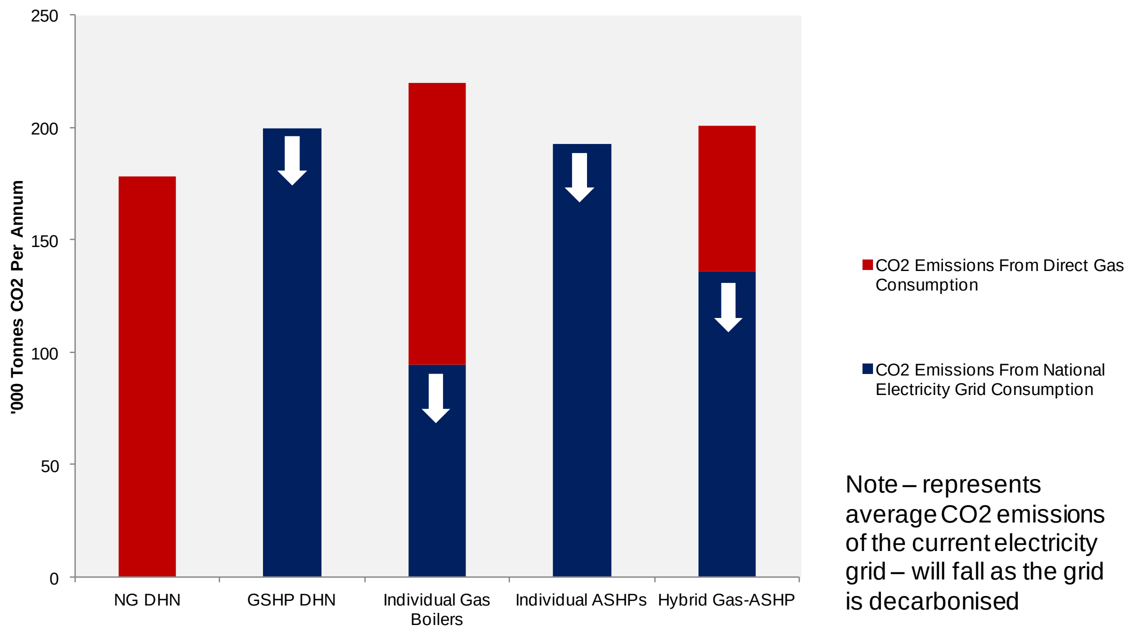
The other system design options were not considered for the Loughborough case study:

- Road delivered fuels are unlikely to be appropriate for an urban area like Loughborough – system design (2) and (6) above.
- Electric resistive heating is not as preferable as individual heat pumps (for those properties not already electrically heated) due to the high cost for electricity consumption – system design (3) above.
- There do not appear to be small clusters of buildings detached from the rest of the town where small scale shared heat would be preferable – system design (7) above.
- Hydrogen is currently unattractive due to a lack of hydrogen supply infrastructure into the town (now or in the foreseeable future) – system design (10) above.
- Waste heat is available (from the coal power station at Ratcliffe-on-Soar ~8km North), but it is not clear how long that source would be available for or on what commercial terms to calculate the cost of heat supply – system design (11) above.

Annualised Cost of Options for Loughborough



Annual Carbon Emissions of Options for Loughborough



Note – represents average CO_2 emissions of the current electricity grid – will fall as the grid is decarbonised

Preliminary Transition Plan Recommendation for Loughborough

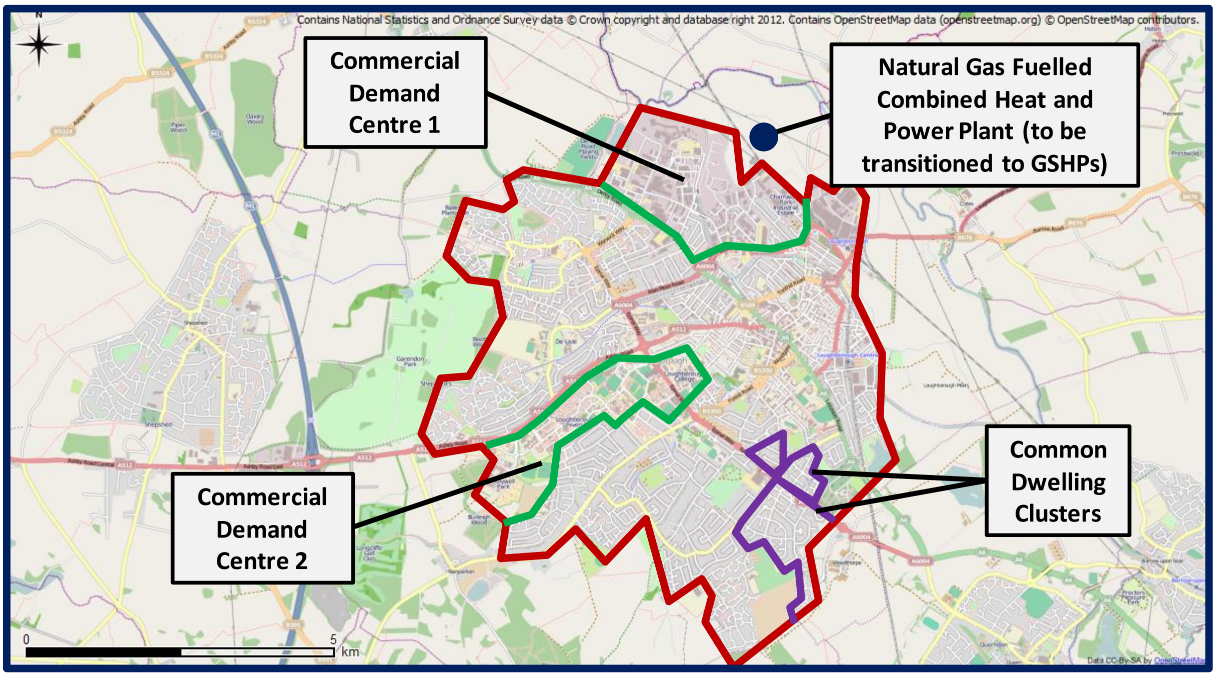
The broad characteristics of the preliminary transition plan for Loughborough and the rationale are:

- Strategic investment to deploy a heat network throughout the town, starting with the two large commercial demand centres in the North East and South West of the town. The reason for starting with these two centres is to create a nucleus of demand for the energy centre with limited network investment.
- Investment in a natural gas combined heat and power energy centre, with gas turbine electricity (and heat) production and supplementary gas boilers for peak winter heating demand. The energy centre should be sized and located to meet the long-term needs of the town, but of modular construction such that additional gas turbines and boilers are only added as and when demand rises. The initial capital outlay is anticipated to be around £10mn. The anticipated long-term annualised cost once the energy centre reaches full capacity is £10.6mn per annum (excluding fuel). Due to the efficient production of electricity and the exploitation of waste heat, significant cost savings for the town can be achieved even without a carbon price. These cost savings could be significantly larger than shown in the chart above if surplus electricity is exported at times of high local heat demand and national electricity demand (at its true value, which is not possible in the current market). Intelligent automated system management will be critical to maximise the value of export electricity. A large scale GSHP energy centre is unattractive due to both costs and CO_2 emissions being higher until low carbon electricity is available at scale from the national grid.
- Gradually extending the heat network to cover all residential areas. A large scale capital investment will be required, anticipated to be around £120mn. The anticipated annualised cost for the network when at full capacity is £9.4mn per annum.
- Adopting policy measures to incentivise building owners to move onto the district heat network as fast as reasonably practicable and decommissioning the gas network quickly to save on excess operating costs for duplicate networks. The cost saving from the district heat scheme is sufficient to offset the write-off of even a relatively newly installed gas boiler. However, policy will have to overcome the ‘emotional attachment’ of consumers to sunk capital. Consumer research on the best routes to achieve rapid adoption of district heat would be helpful, as would engagement of the community in the decision making process when commencing investment in the district heat scheme.
- As the cost of carbon rises and the CO_2 intensity of the national electricity grid falls, the energy centre should be gradually transitioned to a set of large scale GSHPs. Once the heat network is installed, this transition can be timed to suit circumstances as they emerge with no effect on end consumers. The energy centre should be designed with this transition in mind; it is unlikely to be appropriate to locate the GSHPs in a single energy centre due to the large subsurface area required to avoid ‘freezing’ the ground due to heat extraction. Rather, it is likely to be appropriate to have GSHPs in several locations around the town and connected into the heat network. Local geology will be important to the optimal configuration, which needs to be studied in detail to optimise the location and depth of ground bores. Heat storage

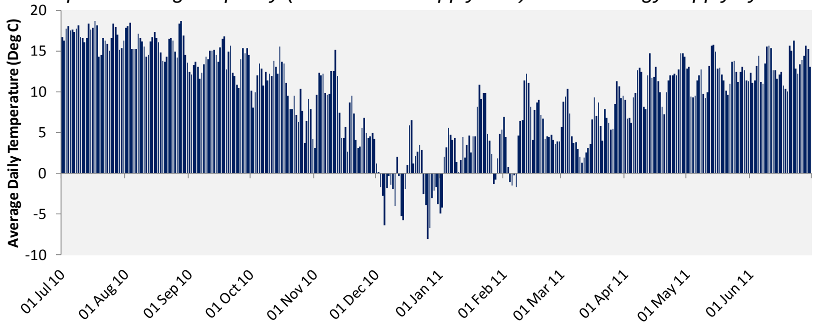
sized for consecutive days of peak cold weather[1]) is likely to become increasingly important to reduce the need for marginal use peak electricity generating assets.

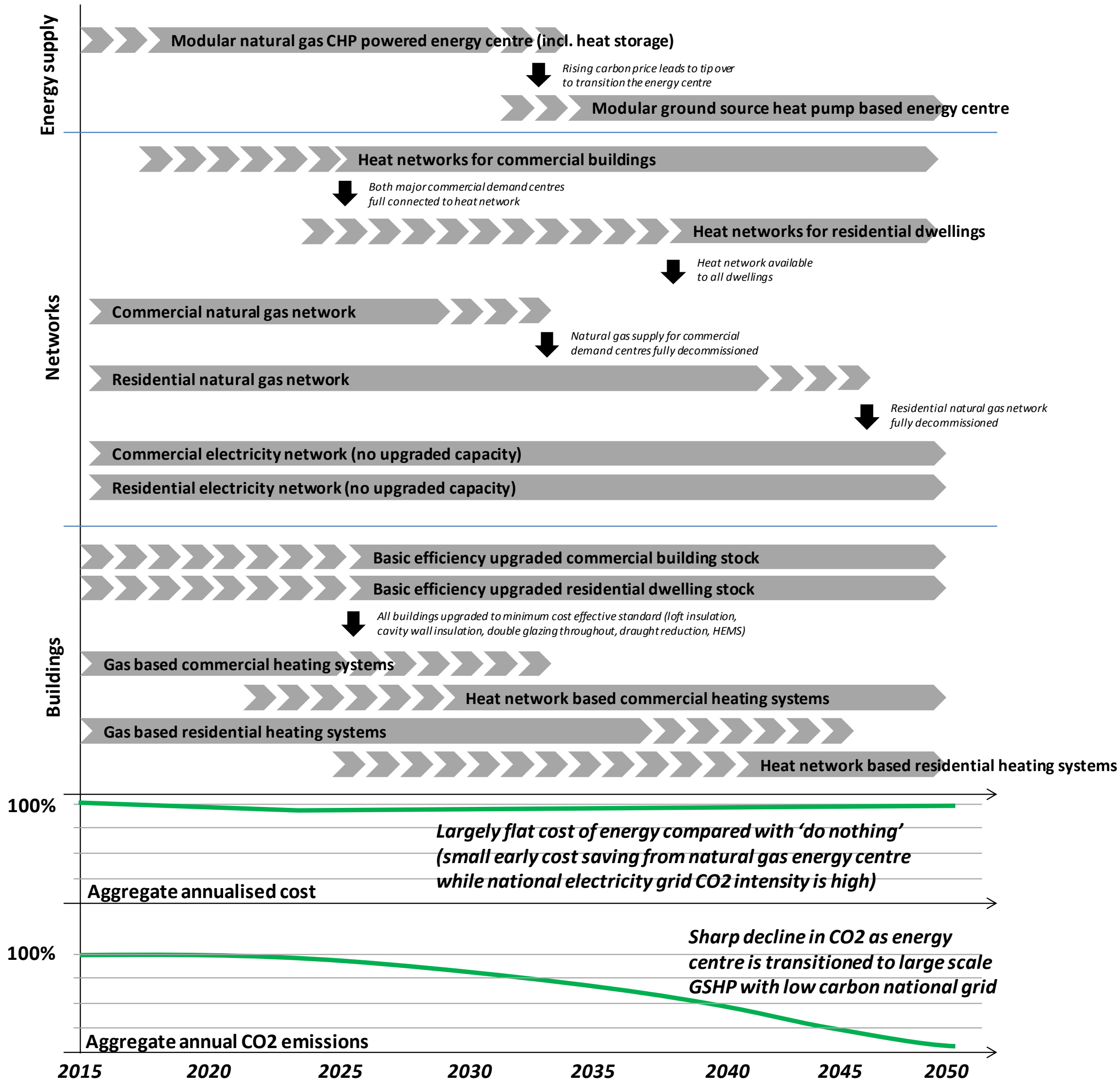
- Upgrades to the building stock are not a pre-requisite for this transition strategy and, furthermore, the modular nature of the energy centre and flexible use of flow rates and temperatures in the heat distribution network, means this can be left to individual consumers to decide on as and when they see fit. However, for consumers to get the greatest benefits in terms of comfort, factors such as window surface temperatures and draughts are important. It is advisable that policy works towards all dwellings being brought up to a minimum affordable ‘standard’ (loft insulation, cavity wall insulation, double glazing, draught proofing, etc); there appears to be a significant pool of dwellings in poor condition in Loughborough. More extensive measures such as solid wall insulation appear expensive and unnecessary when compared to the cost of gradually reducing carbon emissions by transitioning the energy centre to GSHPs.

- Overall, assuming a near zero CO_2 national electricity grid can be realised, the eventual CO_2 emissions from energy consumption in Loughborough can be reduced to almost zero at a broadly flat cost throughout the period of transition to 2050. Depending on the configuration of the national electricity system, increased resilience to uncertain long-term energy prices may also be achievable.



[1] *The required storage capacity (or feedstock supply rate) for the energy supply system is driven by clustering of cold days.*

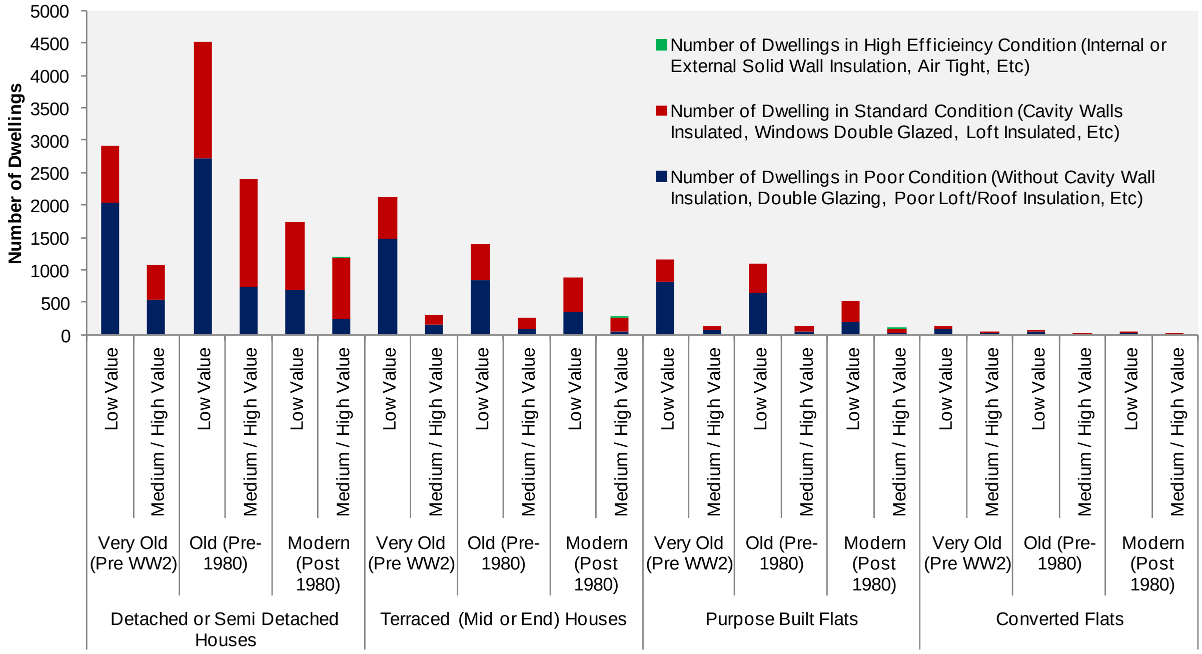




Details of the analysis:

Common theme to all design options – analysis of residential dwellings

Loughborough dwellings are primarily old and of fairly low value. There appears to be a significant pool of dwellings in poor condition in Loughborough. However, this is anecdotal evidence and more detailed data has not been found (the chart below reflects best guess estimates). Some data on dwelling condition is held by the Valuation Office Agency, but from the high level aggregate data available at the Borough level (Charnwood) this data appears to be missing for most dwellings in any case.



For Loughborough, the condition of dwellings does not appear to be material to the choice of which design and transition path to opt for. Nor does it appear to be significant to the detailed design due to the inherent flexibility of a modular energy centre configuration and variable control of the flow rate and temperature in the heat distribution system. For other locations, it may be more significant and new survey methods may be required to gather this data at a low cost. In summary, the options evaluated for the building stock in Loughborough are shown below. This analysis is based on National Statistics data at the LSOA level where available, the English Housing Survey and the ETI Buildings programme; in addition, many crude assumptions have been made due to large data gaps, especially on the correlation between available datasets, social and physical clustering of dwellings and their current condition.

- ‘Standard’ includes loft insulation, cavity wall insulation, double glazing, draught proofing, etc
- ‘High Efficiency’ includes more extensive intervention, including internal or external solid wall insulation

Leave Dwellings As-Is	Annual Heat Demand	264,143,508	kWh
	Peak Heat Demand (Before Diversity)	215,786	kW
Upgrade All Dwellings to 'Standard'	Annual Heat Demand	219,763,837	kWh
	Peak Heat Demand (Before Diversity)	179,531	kW
	Cost to Upgrade Dwellings	£86,723,000	£ CAPEX
Upgrade All Dwellings to 'High Efficieincy'	Annual Heat Demand	150,291,687	kWh
	Peak Heat Demand (Before Diversity)	122,778	kW
	Cost to Upgrade Dwellings	£349,804,000	£ CAPEX

Not all measures in the ‘standard’ level of improvement are cost effective on a pure heat loss basis, but there are additional benefits that are currently difficult to quantify such as improved comfort2 from warmer window surface temperatures, reduced draughts, reduced noise, etc and increased property value. An enhanced model of consumer comfort is required to extend the analysis beyond heat loss and into the true dimensions of comfort[2]. A model of property value would also be helpful to target dwelling improvements. However, the measures in the ‘High Efficiency’ level of improvement are unlikely to be cost effective for Loughborough even with a broader definition of comfort and taking property value into account.

The scope for exploiting the building thermal mass as heat ‘storage’ to reduce peak heat demand is presented in Appendix B.

Common theme to all design options – commercial buildings

For Loughborough, commercial energy demand is very significant (around the same consumption as for residential demand). However, almost no data has been found to enable a robust analysis of commercial heat demand and its transition, which requires detailed insight at the individual building level. For example, data on the number of buildings, their purpose, the type and size of their construction, etc has not been found. It is understood that the Valuation Office Agency holds some data on commercial buildings, but the usefulness of it is unknown as it has not been possible to obtain this data so far. Rapid survey techniques such as aerial LIDAR may be helpful to gather this data. The recommended design solution and transition plan for Loughborough appears to be resilient to this uncertainty, but this data will be important for detailed design and delivery.

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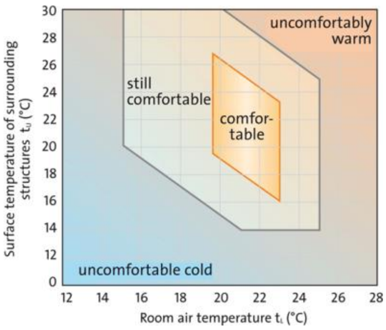
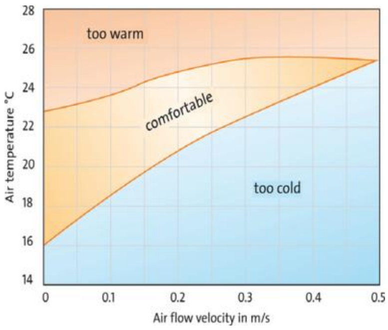
[2] *Considerable research has been undertaken over the last few decades on how people perceive thermal comfort. One of the leading quantitative models of thermal comfort was developed by P.O. Fanger in the 1970s. The key factors he identified are:*

Individual person factors:
- *Activity of the person,*
- *Clothing of the person.*

Environment factors:
- *Air temperature*
- *Heat of surrounding surfaces*
- *Air flow (draughts and convection)*
- *Air humidity*



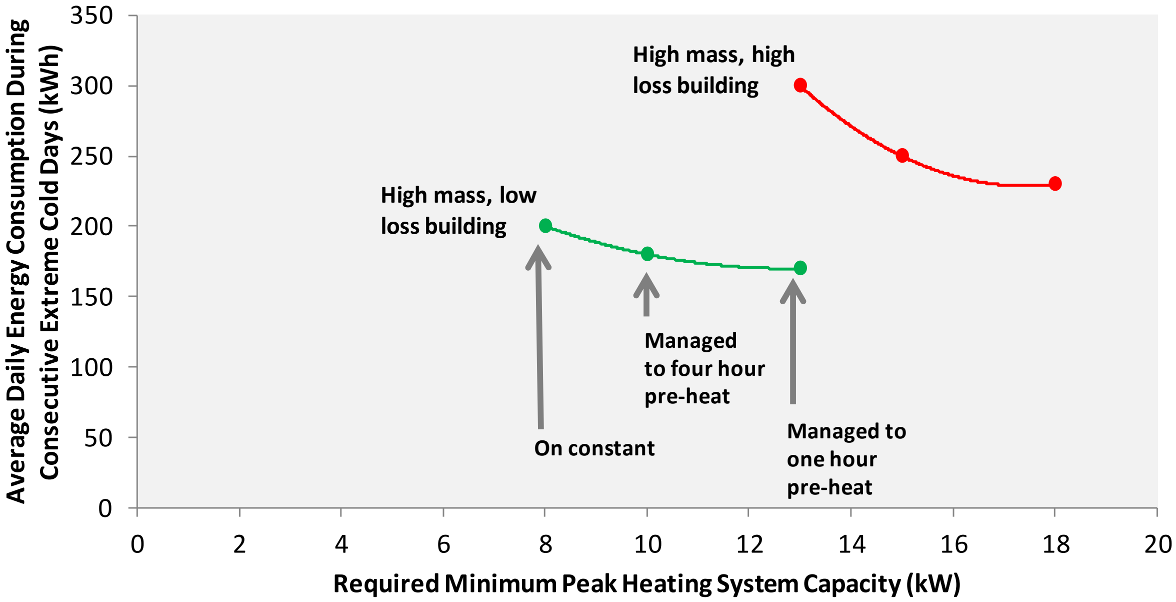


To achieve thermal comfort, there is a trade-off between these parameters. For example, if the walls or windows of a building are cold, air temperature needs to be elevated to compensate. Furthermore, cold surfaces create convection currents increasing air flow within the room and further increasing the need for a higher air temperature to compensate.

Appendix B – Cost / Benefit of Exploiting Building Thermal Mass

Overview of the analysis and conclusion:

An analysis of the cost/benefit of exploiting the thermal mass of buildings has been undertaken. Preliminary analysis of the dynamics of the heating system interaction with the building fabric indicates that the peak heat demand may be reduced by up to 30% by using very long pre-heat periods to store heat in the thermal mass. For a reasonably efficient dwelling, the analysis indicated a consequential increase in heat consumption of around 10% (more for less efficient dwellings).



However, further analysis of the rest of the energy chain suggests that building thermal mass 'storage' is unlikely to translate into an overall system cost saving for the following reasons:

- While it is true that many of the low carbon electricity generating sector technologies are capital intensive with relatively low usage costs, this is not true of the generating plant that is likely to be used for meeting the very low utilisation peak heating demand. Depending on the carbon price, that marginal generating plant is likely to be some combination of H_2 turbine, CCGT without CCS or OCGT without CCS.
- It is unlikely that exploitation of the thermal mass will be sufficient to drive the very low utilisation peak heating demand away from these types of marginal generating plant towards other generating plant with a more intensive capital vs. usage cost ratio.
- The cost saving from the reduction in peak electricity capacity is insufficient to offset the cost rise due to increasing usage of marginal generating plant required for the longer pre-heat duration.
- The maximum cost for this marginal electricity generation is capped by the most expensive low carbon marginal generating technology; a H_2 turbine (including associated costs for H_2 production and storage). Even with a carbon price sufficient to drive out all unabated CCGT and OCGT generating plant, an overall cost saving does not appear likely.

- While there is a small capital cost saving from the reduction in size of an ASHP, this is unlikely to be significant (the Daikin HT Altherma unit, for example, only costs around 10% more for the 16kW version vs. the 11kW version)[3].

However, there remains significant scope for cost benefits from exploiting the thermal mass of buildings. Analysis of these opportunities would require more complex dynamics modelling. For example:

- Occupant comfort by 'buffering' external temperature and solar gain changes.
- Reduced energy consumption by maximising the exploitation of solar gain.
- Dynamic supply and demand matching in the electricity system.
- Overcoming short-term bottlenecks in electricity distribution between buildings.
- Overcoming short-term bottlenecks in internal electricity supply capacity in buildings.

Details of the analysis:

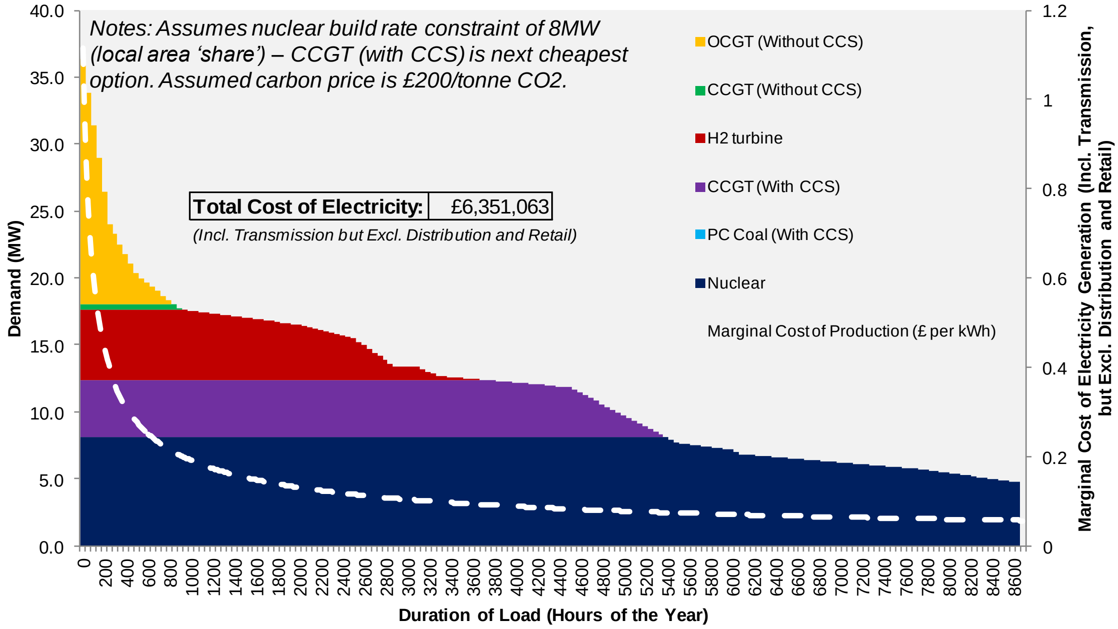
Two scenarios are presented. Both scenarios are for 2030, with the assumption that, by this point in time, the national energy system can be entirely reconfigured to optimally meet the aggregate of local energy demands.

- **The first scenario** assumes a demand profile for electricity and heat similar to today, with negligible exploitation of thermal mass to reduce peak heat demand. The demand profile is for Harrogate 015, which is the only data available at this level of detail from the Macro DE project.
- It was assumed that all heat is delivered via high temperature, high performance heat pumps with a COP of 3. Dynamic effects of variable heat pump efficiency with varying inlet and outlet temperature were neglected due to the complexity of such dynamic modelling and lack of sufficiently detailed data.
- The average cost of capacity (£/kW), cost of usage of that capacity (£/kWh) and carbon emissions for 2030 were used. This data was derived from ESME.
- A carbon price of £200 per tonne CO_2 was assumed.
- **The second scenario** assumes that the peak heating demand is reduced by 15% (reduced from 30% for an individual building to reflect the diversity of peak demand between buildings). The peak is flattened and extended as appropriate to give an increase in energy consumption of around 10%.

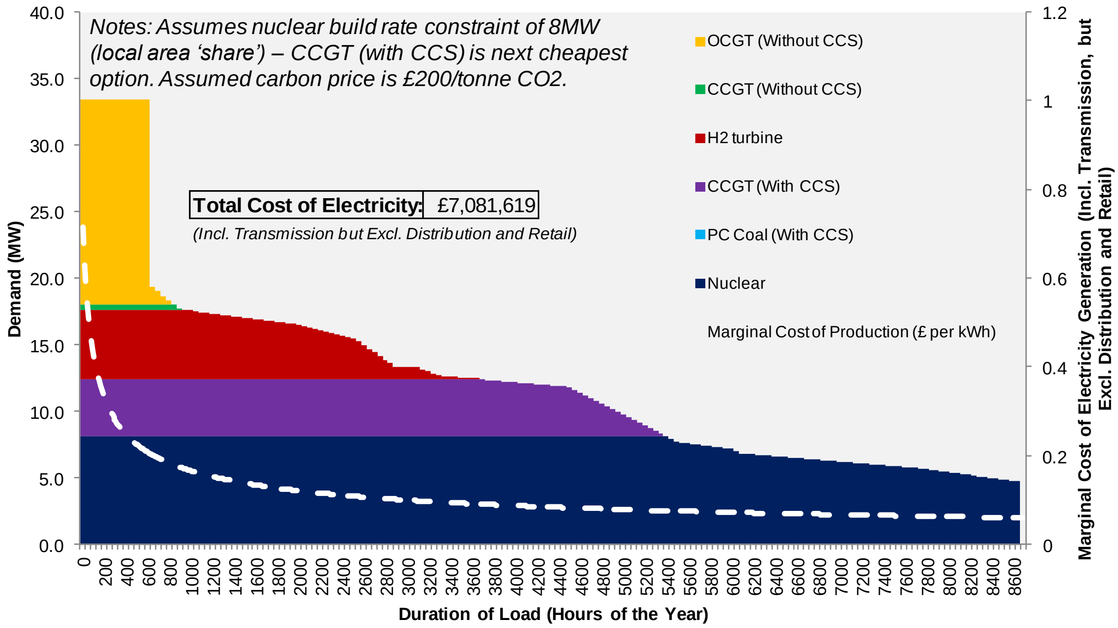
The implied grid configuration for each of these two demand profiles is shown below, together with the marginal costs of electricity.

[3] *This appears contrary to a lot of existing cost data for heat pumps which indicates a linear increase in cost as a function of capacity.*

Scenario 1 – Without Exploiting the Thermal Mass – Total Cost for Electricity (Excl. Distribution and Retail): £6.35mn



Scenario 2 – Fully Exploiting the Thermal Mass – Total Cost for Electricity (Excl. Distribution and Retail): £7.08mn



At an elevated carbon price, all unabated CCGT and OCGT generating plant would be pushed out of the grid configuration and replaced by additional H_2 turbine capacity (together with additional H_2 production and storage capacity). The costs between the two scenarios become much closer in this case, reflecting the higher capital intensity for hydrogen plant, but exploitation of the thermal mass in this case still appears insufficient to reduce overall energy costs – £7.31mn for Scenario 1 and £7.44mn for Scenario 2.

Appendix C – Current UK Domestic Energy System Configuration

This appendix is presented for information only. It shows the outline configuration of the current UK energy supply system for domestic dwellings, with the exception of a small proportion of dwellings supplied by road delivered fuels (oil, LPG, coal, biomass, etc), and the interface into the regional and national energy supply systems.