Programme Area: Smart Systems and Heat

Project: Enabling Technologies

Title: Identifying a short-list of technologies for potential engagement by the ETI

Abstract:

The key objective was to identify a short-list of technology development opportunities for specific technologies which are likely to have a role in smart heating systems that, under certain scenarios, have the potential to make a significant contribution to reducing national carbon emissions. To provide a comprehensive assessment of the issues associated with implementing new, low carbon heating systems, it is also necessary to consider the impact of technology selection on the wider energy system and the influence that the nature of the local area might have on technology choice. To provide a framework for this analysis, the Consortium has developed the concept of Host Space Environments (HSEs), which are archetypes of local areas, typical in terms of mix and density of buildings, to real towns, cities and rural settlements. The report was initially published in July 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 Some details and analysis may be out of date with current thinking.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.

Smart Systems and Heat – Work Area 1:

Enabling Technologies

Task 3, Step 1 – Identifying a short-list of technologies for potential engagement by the ETI

Final Report

19th July 2013

Contents

1 Executive Summary

The Task objective

Task 3 Step 1 of WA1 was set up following discussions with the ETI to address the revised objective set by the ETI: *"to identify (through the identification of "gaps") a small number of short term involvement / engagement opportunities for the ETI – these relate to technologies / systems that are likely to be included in a smart energy and heat system that can be made more effective through ETI involvement".*

The scope and deliverables for the Task were set out in Variation Order 005.

The work on this Task was carried out between 18 April and 28 June 2013.

Approach

The Consortium approach to this Task was to:

(i) from general principles, create six Host Space Environments (HSEs) representative of at least 75% of the national housing stock in rural, suburban and urban settings. These HSEs serve as realistic "base cases" against which the carbon savings performance of selected technology packages was assessed and gaps identified.

(ii) devise technology packages appropriate to each dwelling type/location, after the identification of particular technological problems associated with each HSE, comprising best available and promising emerging technologies – treated as systems of interacting technologies. Semi-quantitative methods (based on standard public domain software) were used to estimate the impacts of these packages on carbon savings, costs, and on the networks supplying the HSEs.

(iii) produce a shortlist of technologies / systems that could result in a material reduction in carbon emissions if the identified gaps were addressed and the technologies were deployed at scale

(iv) devise and apply selection criteria (aligned to the Consortium's understanding of the ETI's needs); and produce a list of three priority technologies which would justify further consideration by the ETI.

(v) summarise next steps.

In considering the nature of the above "gaps", the Consortium is aware that they are characterised by a range of technical, systems and non-technical factors. However, at ETI's request, the Consortium has limited its consideration of "gaps" to a purely technology / engineering perspective.

Technology shortlist

The following 15 technologies/systems were identified for shortlisting:

Heat distribution	Fan-assisted radiators
Heat source	ASHP
	Hybrid ASHP
	Fuel cell mCHP
Storage	HDTS / PCM
Monitoring & control	Sensors / actuators
	HEMS gateway / HAN
Heat network	Low Temperature district heating network
Electricity distribution	Low Voltage control
	D-FACTS (Distributed Flexible AC Transmission System)
	DSR / thermal storage
Distributed generation	Community-scale CHP (biomass / biogas)
	Community-scale energy from waste
Service level	Cloud management Service
	Energy Management Service

In the Consortium's view, these technologies, as part of well designed, properly installed, commissioned and managed heating systems, have the potential to deliver significant carbon savings (a full set of assumptions is included in *Appendix F*), whilst at the same time minimising adverse impacts on local networks (in respect of electric heating systems).

Priority technologies recommended for further investigation

At the request of the ETI, the Consortium devised for the ETI's consideration a set of criteria for selecting a limited number of priority technologies / systems for further investigation. On the basis of these criteria and the analysis carried out to date, the following technologies are recommended for further investigation by the ETI:

- Community scale biomass / biogas CHP
- LV Voltage control technologies
- Energy Management Services and advanced network controls systems.

Technical considerations would need to include, in addition to technology specific factors, systems design (where "system" includes building fabric, controls, management, storage, heat generator, heat emitters, etc.), optimisation and packaging. Non-technical factors would also need to be considered including: supply chain coordination, installer competency, sale/lease and energy services models, finance packages and system (as oppose to product) efficacy guarantees, etc.

In addition to the technologies identified above, assessment of the short-listed technologies on the basis of the proposed criteria also highlights hybrid ASHP, High Density Thermal Storage (HDTS) and HEMS / HAN as high priority technologies. These technologies were pre-selected by the ETI for assessment in Task 5a. The analysis undertaken has validated the pre-selection of these technologies, which in the Consortium’s view merit further consideration (beyond the scope of the Task 5a assessment).

2 Introduction

The key objective of WA1 Task 3 was to identify a short-list of technology development opportunities for specific technologies which are likely to have a role in smart heating systems that, under certain scenarios, have the potential to make a significant contribution to reducing national carbon emissions. The development opportunities have, at the ETI's request, been considered from the technology / engineering standpoint only. This short-list has been drawn up on the basis of the Consortium's research and analysis. It is presented for the ETI's consideration and, we understand, more detailed investigation. The aim of this process is to identify technology development opportunities that would contribute to addressing the identified technical gaps and that might also present commercial opportunities for ETI engagement. As requested therefore, we have, as part of this study, proposed a set of criteria for ETI's consideration. However, identifying these specific development opportunities is beyond the scope of the Task 3 Step 1 study.

To identify the short-list of technologies, we have considered how technologies are combined into smart heating systems and the issues associated with integrating these systems into buildings. Through this analysis, we have sought to identify the barriers to widespread deployment of these technologies and the technology gaps that need to be addressed. While the focus of this analysis is the technologies and systems, we recognised that many of the most significant barriers are non-technical and include factors such as costs, supply-side capacity, business models and agents, and consumer perception and behaviour. Drawing on the knowledge of the Consortium, we have attempted to capture these non-technical barriers and gaps at a high level. Further investigations would be required to characterise the gaps at a level of detail consistent with the due diligence required to understand and reduce the commercial risk associated with any investments or activities the ETI decide to carry out.

To provide a comprehensive assessment of the issues associated with implementing new, low carbon heating systems, it is also necessary to consider the impact of technology selection on the wider energy system and the influence that the nature of the local area might have on technology choice. To provide a framework for this analysis, we have developed the concept of Host Space Environments (HSEs), which are archetypes of local areas, typical in terms of mix and density of buildings, to real towns, cities and rural settlements. We have constructed from general principles and publicly available data six specific HSEs for the ETI. The form and construction of the HSEs is described in the following section.

This report presents the findings of the technology gap analysis and identifies the short-list of technologies and proposed criteria for further down-selection. The report is structured as a concise summary report and a detailed set of appendices, which provide further detail on the approach and on the analysis of particular component technologies and systems. The summary report is structured as follows:

- **Section 3** provides an introduction to the HSE concept and the specific set of HSEs used in this work.

- **Section 4** contains the technology gap analysis at the building level and assessment of impacts of technology deployment at the wider HSE level, particularly in terms of costs and carbon saving.
- **Section 5** presents the short-list of technologies and brief rationale for their inclusion.
- **Section 6** provides the proposed criteria for further down-selection and the Consortium view on priority technologies for further investigation.
- **Section 7** presents proposals for structuring further work.

3 Introduction to the HSE concept

As part of the work in Task 3, Step 1 the Consortium developed the concept of Host Space Environments (HSEs) from general principles. This was done to ensure that we identified technology packages appropriate for use in a range of typical dwellings and locations.

HSEs are virtual constructs of groups of dwellings (and other buildings where appropriate), designed to be representative of the UK housing stock in specific types of locations. They are characterised according to a range of parameters to form the "base case" upon which the impact (including energy and carbon savings, network impacts, etc.) of different existing and emerging technology packages can be assessed. Depending on the range of parameters, HSEs can be made as coarse grain / simple or as fine grain/ sophisticated as is required or can be accommodated within given time and budget envelopes for investigation. The granularity can range from a grouping of house types according to certain parameters (built form, location, etc.) to GIS mapping / postcode representation of actual districts in real cities and detailed consideration of occupancy factors, heat networks, etc. They can be limited to considering heat provision or can be made more sophisticated to include consideration of, for example, export of solar generated electricity, electricity storage, etc. Within the available budget and time envelopes, the Consortium has created the six HSEs for the ETI from published data and with sufficient granularity to enable reasonable and robust conclusions to be drawn about the performance of technology packages and the identification of technology and system gaps for further assessment. In any future pieces of work, the HSEs could be designed for and used at increasing degrees of granularity and sophistication to address wider issues and increasing complexity.

The HSE granularity used in Step 1 provided a sufficient basis on which to assess technology packages, identify technology gaps and make recommendations to the ETI on which technology areas would be worthwhile assessing further for possible ETI engagement. Further work beyond Step 1 would consider the carbon performance achievable with different technology packages, aggregated over the housing stock, in relation to a given position on a given decarbonisation trajectory. This assessment of performance at scale is needed to confirm whether incremental improvements of currently know and emerging technologies will be sufficient to achieve the carbon savings necessary; or, if not, what kind of disruptive technologies will be needed.

The following section sets out the six HSEs developed by the Consortium for this task.

3.1 HSEs and House types

For the purposes of this Task, the national housing stock was categorised into six generic and typical HSE settings as follows:

- Rural village
- Market town
- Suburban (without a centre)
- Suburban (with a centre)

- Urban (without a centre)
- Urban (with a centre).

The six HSEs have been constructed to be representative of over 75% of the national housing stock. The house types in each HSE are also representative of the stock which we would expect to find in specific locations. Thus, for example, the urban HSEs would contain more flats and terraced dwellings than the rural HSEs where there are more detached houses. Using the standard source literature (e.g. the English House Condition Survey[1], neighbourhood statistics[2]), the actual dwelling types and their respective proportions, conditions and densities in each of the six HSEs can be reliably established. The housing stock has been classified into 12 house types, each of which is described by the following characteristics:

- main heating fuel (gas, electricity)
- dwelling type (detached, semi-detached, terraced, flats)
- standard of energy efficiency (good, poor)
- wall construction type (cavity wall insulation, unfilled cavities and solid wall).

3.2 Factors affecting heating technology suitability

The nature of a building's construction, its usage and occupancy patterns and preferences can have implications for the selection of heating systems. The mix of building types, density of buildings and features of the local environment can also influence choice of heating system and can be assessed within the framework of the HSEs. Factors that have been taken into account include:

- number of buildings and mix of building types
- fabric performance and thermal mass of buildings
- heat load density and demand profile
- impact of heating technologies on the local distribution network (and wider system impacts)
- space availability (e.g. domestic gardens and surrounding green space).

There are a number of other factors that are too location specific to form part of a limited set of generalised HSEs but that can be important influences on heating system selection and design for a particular area. These factors include:

- proximity to large heat users
- availability of waste heat
- access to mains gas
- mix of tenure type and socio-economic characteristics of an area
- availability of renewable resources (e.g. wind, solar, biomass etc.)

[1] English Housing Condition Survey, Communities and Local Government, 2012, https://www.gov.uk/government/organisations/department-for-communities-and-local-government/series/english-housing-survey
[2] http://www.neighbourhood.statistics.gov.uk

- tolerance to other environmental impacts, such as noise, visual amenity, traffic (e.g. fuel deliveries), etc.

While not part of the definition of the HSEs, the impact of these factors can be considered as sensitivities.

Technologies, and the technology packages in which they operate, are parts of complex systems (within buildings, between buildings, and the networks serving buildings). Buildings with different technology packages and occupancies will have different energy / heat demand profiles. (However, at the level of granularity selected for this work, standard occupancy patterns were applied as this was appropriate and sufficient for this level of investigation). The way in which these different demand profiles sum and then interact with local supply networks can have significant impacts that need to be addressed and managed. HSEs can help us understand these impacts in the rural, suburban and urban settings. The proportions of residential and non-domestic buildings therefore need to be considered for each HSE. The methodology used to assess the number of non-domestic connections within each of the HSEs is described in *Appendix A – Host Space Environments.*

Different technology packages (whether individual heating or community heating based; with or without storage) will have different impacts on demand profiles and hence the local energy supply networks. The Consortium has carried out a semi-quantitative analysis of impacts in order to give an indication of where technology development (or help with early deployment via trials for example) would be required.

The Consortium recognises that the cost of technology packages will be an important factor so far as take-up is concerned. However, HSEs are not, in their simple form capable of incorporating and utilising cost data. The cost implications of technology packages have therefore been estimated separately. For existing technologies (e.g. fabric insulation, conventional air source heat pumps, etc.) cost data exists. The Consortium has used this information to assess the cost implications of particular technology packages. However, cost per se, has not been the arbiter of plausibility for designing technology packages. For new and emerging technologies, the Consortium has used an indicative cost figure (or range, if estimates exist), recognising that these figures may well change over time (e.g. if manufacture increases and / or sales / leasing become a significant share of the market, costs will reduce).

3.3 Summary of the six HSEs

The six HSEs developed for this study are summarised in the table below. Further detail on the six HSEs and the standard building types within the HSEs is provided in the appendices *(Appendix A – Host Space Environments).*

Table 1. Summary of the six Host Space Environments

Community Type	Predominant dwelling type	Non-dom /resi ratio	Garden area	Description
Rural Village	Detached, semi	Low - medium	High	Small settlements of dwellings and local amenities surrounded by agricultural land or other green space.
Market Town	Detached, semi, terrace, flats	Medium	Medium	Larger communities with town centre. Rural in nature, surrounded by agricultural / green space.
Suburban residential	Semi, Terraced, detached	Low	Medium	Typical edge of town housing estates. Homes have gardens but limited other green space. Non-domestic area limited to small shops, pubs, schools.
Suburban with local centre	Semi and terraced	Medium	Medium	Similar housing density to suburban residential but in proximity to a local centre, including larger retail, leisure and office uses.
Urban (residential)	Terraces, flats (converted and purpose-built)	Low-medium	Low	Inner-city residential – terraced houses and flats. High built density with green space limited to parks / allotments.
Urban centre	Flats, Terraces	Medium - high	Low	High density flats (purpose built and conversions) and terraced housing. Diverse non-domestic uses, including commercial offices, large retail, leisure, pubs, restaurants etc.

3.4 Problem statement

The table below provides a summary of the problem statements relevant to each Host Space Environment, both at the building and network / district heating level. These problem statements were derived following discussions with the ETI (on 27 June). They have been drawn up on the basis of the Consortium's understanding of these discussions, recognising that the level of discussion did not allow a detailed definition to be finalised. At the ETI's request, they are derived from a technology / engineering perspective.

The general problem statement can be summarised as follows. Occupants of dwellings want affordable, responsive heating to the standard and at the times they choose. Currently available systems provide what occupants want but at too high a carbon footprint to be consistent with national decarbonisation goals for 2050. Very low carbon footprint heating* will be required across the UK's housing stock in order to achieve carbon savings consistent with decarbonisation trajectories. Current market penetration of low carbon heating systems is minute, compared with the national stock of gas fired central heating systems. They are very expensive (at least three times the cost of mature gas-fired systems), disruptive and complex. High cost, disruption to occupants, poor supply chain competency and complexity are the principal barriers which need to be overcome in order to make a robust start on the heat decarbonisation challenge. Achieving these decarbonisation goals will require different technological/systems solutions to be designed and implemented. Factors which would need to be considered include: location, occupant behaviours and preferences, standard of energy efficiency and fabric insulation, housing density, commercially available products, or yet to be developed technologies, etc. Some technological solutions will have impacts within HSEs and on networks serving HSEs (eg local electricity distribution systems). Different house types and settings (as described by the six HSEs) will present different opportunities and challenges in respect of the general problem statement. The key specific factors for each HSE and house types are given below.

*(The scope of this Task did not include cooling requirements. However, the Consortium is aware that summer time overheating is already becoming a problem for some newer house designs in the UK. In any further consideration of technologies for space heating in the context of the Smart Systems and Heat Programme, the Consortium recommends that the space cooling challenge should receive appropriate attention so that in finding and implementing low carbon heating solutions and demand reduction measures, the cooling needs of occupants are not exacerbated.)

	HSE	Technology suitability – building level	Network-level implications
1	**Village**	• Off-gas dwellings, although representing a small percentage of the stock, are most likely to be found within this HSE. This limits certain technology choices, although the higher cost incumbent fuel (e.g. heating oil) can favour uptake of low carbon technologies in these areas (e.g. heat pumps). • This HSE could be favourable for biomass boilers uptake, given the predominance of larger dwellings with adequate space. Local availability of stock and fuel delivery, may restrict their uptake • Communications might be constrained in remote rural areas, limiting some demand response and active network management options.	• Scenarios involving a high level of district heating penetration are less likely to be applicable • Potential high impact of electricity heating technologies (e.g. ASHPs) on the local distribution network, given the reduced number of dwellings in the HSE (200 dwellings) if DSR/ LV control is not implemented. In that case, high grid reinforcement costs would arise
2	**Market town**	• Although this HSE could be favourable for biomass boilers uptake, given the predominance of big dwellings, local availability of stock and fuel delivery, might restrict their uptake	• Scenarios involving a high level of district heating penetration are less likely to be applicable (unless there are particular location specific factors, such as reliable long-term availability of waste heat from industrial / commercial development, that can improve the economics of district heating). • Potential high impact of electricity heating technologies (e.g. ASHPs) on the local distribution network, given the reduced number of dwellings in the HSE (200 dwellings) if DSR/ LV control is not implemented. In that case, very high grid reinforcement costs would arise
3	**Suburban residential**	• Noise concerns in densely constructed areas for ASHPs • The fact that >15% of the HSE is comprises poorly insulated semi-detached houses and terraces might hinder ASHPs uptake, given the additional insulation capital costs required for a successful ASHP installation. There is a prevalence of terraced houses in this HSE; ~50% of the poorly insulated terraces in the UK have solid wall insulation, adds to this fact	• Heat density is likely to be low for district heating (relatively low density housing and lack of non-domestic buildings). • New generations of district heating networks (e.g. low temperature heat network) could be applied in this HSE. Particularly suitable for new build housing developments.

4	**Suburban with local centre**	• The fact that ~20% of the HSE is characterised by poorly insulated semi-detached houses and terraces might hinder ASHPs uptake, given the additional insulation capital costs required for a successful ASHP installation. The prevalence of terraced houses in this HSE, and the fact that ~50% of the poorly insulated terraces in the UK have solid wall insulation, adds to this fact.	• Heat demand density is likely to be relatively low, although the mix of uses around local centres may improve feasibility of district heating systems. • New generations of district heating networks (e.g. low temperature heat network) could be applied in this HSE. Particularly suitable for new build housing developments.
5	**Urban (residential)**	• Noise concerns in densely populated areas could restrict ASHP uptake. • The fact that ~20% of the HSE comprises poorly insulated terraces and flats might hinder ASHPs uptake, given the additional insulation capital costs required for a successful ASHP installation	• Air quality concerns (NOx and CO) of burning biomass in urban areas could restrict their application in these spaces, at a community scale • Higher density of the residential stock increases the potential for district heating, although lack of diversity of uses (largely residential) may restrict viability.
6	**Urban centre**	*Flat predominance: 70%* • Space constraints have implications for a number of technology choices. • Heavily flatted areas limits applicability of biomass boilers. Air quality issues are also a concern. • Noise concerns in densely populated areas can restrict potential for ASHP. Lack of external space around dwellings can restrict opportunity for ground source systems. • High proportion of electrically heated homes without gas connections (e.g. ~25% of electrically heated flats) – constrains potential for gas appliances (mCHP, hybrid heat pumps etc) • High existing penetration of combi boilers in space constrained dwellings. Requirement for DHW storage will constrain suitability of certain technologies. • Lack of space is a constraint for integration of thermal storage, restricting demand flexibility.	• Air quality concerns (NOx and CO) of burning biomass in urban areas could restrict their application in these spaces, at a community scale • Higher heat density and mix of uses can improve viability of district heating systems (actual viability will be dependent on location specific factors).
	General considerati ons for all	• Retrofitting of low temperature radiators for ASHPs, running at <60 deg. C , represents a significant disruption and requires additional space (30-50% bigger than conventional)	• Energy demand management might not always be compatible with end-user comfort constraints. Might hinder EMS uptake • Local availability of stock might restrict community scale biomass

HSEs	• Stirling Engine (SE) mCHP systems, given their high heat to power ratios and the power capacities currently available , could be better suited to higher thermal demand dwellings, predominant in suburban and rural areas • Local availability of fuel stock might restrict biomass boiler application	CHP application • There are a number of other factors that are too location specific to form part of a limited set of generalised HSEs but that be important influences on heating system selection and design for a particular area. These factors include: - Proximity to very large heat users - Availability of waste heat - Access to mains gas - Mix of tenancy and socio-economic characteristics of an area - Availability of renewable resources (e.g. wind, solar, biomass etc.)

3.5 Representation of the overall dwelling stock

The intention of the HSEs is to represent a large proportion of the housing stock using a limited number of typical area descriptions. As a result, the HSEs are necessarily highly generalised, such that each HSE is broadly representative of a large proportion of the housing stock. One metric that can be used to map the HSEs onto the stock in order to make a high-level assessment of how much of the stock each HSE can be said to represent is the residential area fraction, i.e. the fraction of land area in the local area that is used for domestic buildings. The distribution of the GB building stock by residential area fraction of the local community (census ward level) is shown in the chart below. The range of residential area fraction that is typical of each HSE is shown on the chart.

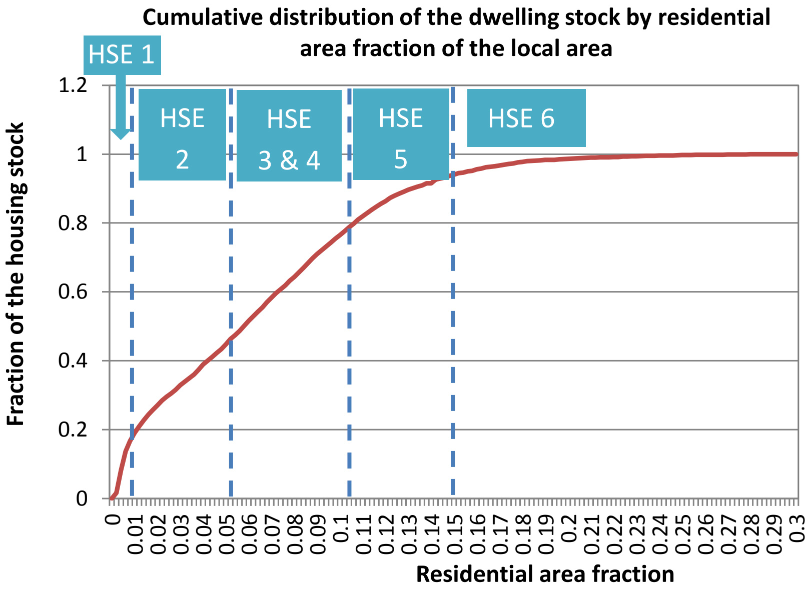


Figure 1, Cumulative frequency of GB dwelling stock by the residential area fraction of the local area (census ward level)

On the basis of the segmentation of the stock between the HSEs shown above (based on matching the typical residential fraction of the HSEs to census ward level data on the stock), it is possible to derive a rough order of magnitude estimate for the amount of the stock represented by each HSE / dwelling type combination. This disaggregation of the stock by HSE and house type is tabulated below.

This table provides an indication of the overall amount of the stock that the various problem statements discussed above are applicable to and also the extent to which technology packages that are well-suited to a particular HSE are applicable to the stock (see Section 4.5)

Table 2, Approximate disaggregation of the dwelling stock between the HSEs and broad house type descriptions

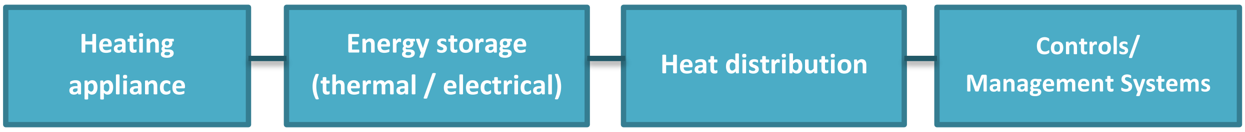
HSE	Detached	Semi	Terrace	Flat	TOTAL
1	8%	6%	4%	0%	**18%**
2	8%	5%	6%	5%	**23%**
3	3%	10%	7%	0%	**19%**
4	0%	12%	8%	0%	**20%**
5	0%	0%	10%	2%	**12%**
6	0%	0%	2%	6%	**8%**
TOTAL	**19%**	**32%**	**36%**	**13%**	**100%**

4 Gap analysis of technology packages

4.1 Technology deployment scenarios

The HSEs provide a framework for assessment of heating technologies and packages of technologies (systems) that could provide significant carbon reduction if deployed at scale. The HSE framework is used to assess the issues associated with integrating these technologies and systems into buildings and wider local areas and the impact that their deployment might have in terms of carbon emissions reduction. On this basis, we identified a priority list of technologies that appeared to be promising in terms of future low carbon heating systems, fit for various building and area types. We also identified the main barriers to the deployment of these priority technologies and the gaps, both technical and non-technical, that would need to be addressed.

The technology packages or systems are made up from a set of components that were categorised as follows:



These technology packages were initially assessed at the building level. We then considered what the impact of the heating system selection is at the HSE level, particularly in terms of the impact of technology deployment on the electricity distribution network and also the potential requirement of controls and active management infrastructure upstream of the individual buildings. Through the assessment at the HSE level, we also considered whether the characteristics of particular area types lead to consideration of alternative heating system options, such as district heating. We also took into account that, generally speaking, the standard of thermal insulation across the nation's stock is in need of significant improvement and that in order for technology packages to be most effective, they would therefore have to include optimum levels of thermal insulation on each building element consistent with practical constraints.

In addition to the assessment of barriers to deployment of systems and the associated gaps, we have also quantitatively estimated the cost implications of particular systems and CO_2 emissions reduction potential. We have taken a view on the level of penetration of the technology packages in order to arrive at our cost estimates.

Modelling the uptake of technologies or systems has not been undertaken as part of this work. Instead, published scenarios for deployment of technologies have been used as a basis for the assessments. The scenarios have been taken from the DECC 2050 Pathways analysis[3], which sets out 16 different heat technology pathways that differ in terms of the level of electrification and predominant type of non-electric fuel that is assumed. From these 16 pathways, we have selected

[3] 2050 Pathways Analysis, July 2010, DECC, www.gov.uk/2050-pathways-analysis

six technology deployment scenarios for this analysis. The table below summarises how the selected scenarios are classified in terms of level of electrification and type of non-electric fuel.

Table 3. Classification of selected scenarios

	Primary non-electric source			
Electrification level	**1. Gas**	**2. Solid**	**3. District**	**4. Mixed/none**
1. Very low		*Low elec.*		
2. Low	*High mCHP (No DH)*	*High DH*		
3. Medium	*Mixed*			
4. High		*High HP*		*High HP (No DH)*

Detail of scenarios in *Appendix B – Technology deployment scenarios.*

The levels of deployment by technology assumed in these scenarios are shown in detail in the table below. These levels of technology penetration have been used as the basis for the assessment of cost and carbon impacts at the HSE level.

Table 4. Technology deployment by scenario

							DH scale techs	
Scenario Name	**ASHP**	**GSHP**	**FC mCHP**	**SE mCHP**	**Other gas/solid**	**Other elec**	**CHP**	**Other**
Low elec.				0.24	0.05		0.63	0.08
Mixed		0.3	0.2	0.1			0.33	0.07
High HP	0.5	0.3					0.2	
High DH		0.2			0.1		0.7	
High HP (No DH)	0.6	0.3				0.1		
High mCHP (No DH)			0.9			0.1		

Not all of these scenarios are plausible to apply to all six HSEs. For example, the scenarios involving a high level of district heating penetration are less likely to be applicable to the rural HSEs with low housing densities. The final two scenarios have therefore been included to assess the impact of high penetration of microgeneration in the absence of district heating. The 'Mixed' scenario has been modelled for all HSEs. The applicability of the technology deployment scenarios to HSEs of rural, suburban and urban character is summarised in the matrix below.

Table 5. Suitability of scenarios to HSEs

Scenario Name	Rural	Suburban	Urban
Low elec.			
Mixed			
High HP			
High DH			
High HP (No DH)			
High mCHP (No DH)			

4.2 Building-level technology packages

A range of building level technology packages were devised, whereby a package typically includes a heating appliance, an energy storage medium, heat distribution / emitters and some controls. The packages were built up from a range of key technologies within each of these categories, as shown below (note the technologies highlighted are not exhaustive) and for their selection the process shown in Appendix E1 was followed.

Heating appliance

- ASHP
- GSHP
- Hybrid HP
- Gas absorption HP
- Fuel cell mCHP
- Stirling Engine mCHP
- Biomass boiler
- Hybridised solar thermal
- Gas boiler
- Direct electric

Energy storage (thermal / electrical)

- Hot-water cylinder
- PCM / HDTS
- Cold vapour cycle
- Batteries at home

Heat distribution

- Conventional radiators
- Low temperature radiators
- Fan-assisted 'smart' radiators
- Underfloor heating

Controls / Management systems

- Room controls
- In-home display
- Consumer gateway
- HEMS controller
- Smart meter

Figure 2. Technology packages

A range of building-level technologies has been assessed in detail from a technological perspective. The assessment has focussed on the following issues:

- **Integration Issues** – What are the issues associated with integrating the component technologies together into a system?
- **Dependencies** – What factors influence the applicability of the technology package to various building types? This assessment covers how plausible each technology is for each type of building

- **Barriers** – What are the main barriers that are currently acting to limit the deployment of the technologies?
- **Gaps** – On the basis of the foregoing assessment, what are the main gaps that need to be addressed for the technology to achieve large-scale deployment? Technical gaps have been assessed. A high level indication of the non-technical gaps has been provided.

The detailed assessment of the technology packages is included in the appendices *(Appendix E – Technology gap analysis).* In the following, the major barriers and gaps that have been identified are summarised. These barriers and gaps are grouped by primary heating technology, although we also identify gaps related to other technologies in the system that could be relevant to systems involving a range of heating appliances.

SECTION 1 – HEAT PUMPS

Table 6. Heat pump technology gap analysis assessment

Tech.	Gaps / barriers	Detail on barrier / gaps	Required development
ASHP	Temperature of heat / Compatibility for retrofit to existing heating systems	• Some deployment limits apply to older / higher heat loss buildings. Very high temperature ASHP allowing temperatures up to 75°C fit most of the cases. However, high temperature ASHP have limited deployment opportunities in the domestic sector and reduction of heat demand in these buildings should be the starting point - There are three integration possibilities for different installations: outdoor monobloc, indoor monobloc and split	• Cost-effective fabric improvement in older / higher heat loss homes • High temperature heat pumps – refrigerants development. - Installations requiring temperatures >75°C, building insulation is probably a better choice than further increasing the outlet temperature capability of ASHP • Hybridisation is a potential solution to reduce the dependency of the performance on the initial assessment by the installer • Performance optimisation by design – well informed installers able to minimise HP output temperature
	Requirement for hot-water cylinder/ Space	• Immersion heater usually required to boost DHW temperature • If replacement of a Combi boiler supplying instant DHW, additional space is required within the building for DHW water tank	• Integration of ASHP- solar thermal for space constrained environments: - If ASHP provides only space heating, just a small buffer water tank is required by variable speed ASHPs - Currently commercialised for high and regular DHW requirements (e.g. hotels). Cost constraints for residential buildings • Hybrid products are smaller and some offer instant hot water (avoiding DHW tank requirement)
	Noise	• Evaporator / external fan generates some noise – can limit applicability in dense suburban and urban areas	• Design of fan and casing to reduce noise • Change in permitted development rights (noise threshold) • Gas Absorption Heat Pumps: lower noise levels, given that they do not require compressors
	Aesthetics	• Visual impact of external units	
	Cost	• 3-4 times condensing gas boiler cost • Mature components – cost reduction potential may be limited	• Larger cost reduction from installation-reducing risks through better installer qualification • Technical solutions to reduce material cost (all aluminium heat exchangers, high speed compressors, etc: 5-10% reduction in equipment) and high temperature heat pumps costs
	Behavioural changes	• If used with conventional radiators might result in a change in heating habits, given the slower heating rates of this systems compared to gas boilers	• A growing range of existing ASHP (Air/Water) products can provide the required water temperatures for direct retrofit requiring no modifications on the existing radiators
	Grid impacts	• Potential requirement for substantial grid reinforcement to support mass deployment	• Development of systems incorporating dynamic price signal input • Development of heat storage tanks adding flexibility to the grid • 100 m^2 house, ~20 MWh_{th}/ year: 800 L thermal storage tank; 1,200 € for

			equipment + 800 € for installation- without tax) • Development of control solutions to use the thermal inertia of the building as heat storage to add flexibility to the grid
	Lack of skilled and experienced installers	• High dependency of the performance on the installer • The performance of the installation will depend on: - the initial assessment of the installer regarding the ASHP requirements (heating capacity and temperature range) - the quality of the installation, (may include work on the existing radiator loop to ensure suitable water flow distribution) - the settings of the control parameters	• Increase resourcing / capacity of Microgeneration Certification Scheme (or similar) to maintain quality of accreditation standards of installers (i.e. increase in the installation base is required while maintaining appropriate barriers to entry. There is a risk of installation companies that are not trained in heat pump installation moving into the market, driven by incentives). • Heat pump associations have played an important role in European heat pump markets. Associations have supported R&D, system testing and installer training. Heat pump associations have also provided dispute resolution services for underperforming heat pump installations.
GSHP	Requirement of hot-water cylinder/ Space	Internal space limitations: • Water tank is required External space: • Limited applicability due to space requirements for boreholes or ground loops • Space for ground exchangers. Integration issues: - compatibility with the heat pump capacity and building needs - compatibility with the area available around the building	• Large ground exchanger fields can be used as seasonal heat storage
	Cost	• Boreholes are a significant additional cost compared to ASHP • Vertical ground collectors are more expensive than horizontal ones (~3-4 times the cost of a condensing gas boiler) • Solar assisted GSHPs are cheaper than pure GSHPs	• Technical solutions to reduce ground exchangers installation costs: smaller drilling rigs, standardised installation process. • Regionalised drilling industry. This reduces the transportation time for drilling rigs and also means that local contractors become expert in the particular ground conditions. • Solar assisted GSHP with unglazed solar collector has capital costs lower than pure GSHP
	For solar assisted GSHP: solar collector integration	• Compatibility with heat pump capacity and ground exchangers sizing • Compatibility with area available on the building roof • suitable brine flow rate in the ground exchangers and unglazed solar collectors	• Development of installer base • Integration of all system elements (ground exchangers, unglazed solar collectors, heat pump and control) has to be supported by a competent installer • Currently, solar assisted GSHPs are developed for office or big

		• Possibility to produce DHW with unglazed solar collectors during summer	residential buildings (500-7000 m^2), not for single family houses. Commercialisation in process
Hybrid ASHP (packaged-integrated, unpackaged-extended)	Cost	• 2-3 times condensing gas boiler costs • Overall cost reductions 10-20% by 2020	• See ASHP
	Integration ASHP - boiler	• Integration will allow optimisation of the system (in terms of costs or CO_2 emissions)	• Optimisation of the integration of the hydraulic connection and controls between the boiler and ASHPs for Hybrid ASHP with Extended HP coverage system
	Space	• See ASHP	• See ASHP
	Noise	• See ASHP	• See ASHP
Gas Absorption heat pump	Space	• Suitable for large scale residential buildings (hotels, nursing homes…)	
	Cost / lifetime		• Technical solutions to reduce material cost (all aluminium heat exchangers, high speed compressors, etc)
	Back-up system depending on ambient T	• If the ambient temperature is lower than -5 deg. C a back-up boiler is required	
	Technical development	• Efficiency improvement • Ammonia used typically as refrigerant. Hazardous, leads to high pressure	• Development of thermodynamic solutions to increase G.U.E. (Gas Utilisation Efficiency) • Refrigerant developments

Table 7. mCHP technology gap analysis assessment

Tech.	Gaps / barriers	Detail on barrier / gaps	Required development
LT PEM mCHP	Requirement for auxiliary boiler and HW tank & potentially larger thermal store to optimise operation/ Space	• Volume of these systems ~ 2.5 bigger than conventional condensing boilers	• Development of wall-hung systems might be necessary for customer uptake in the UK • Other mCHP technologies (e.g. SE mCHP) offer commercially available wall-hung units and are able to produce instantaneous water heating. However, this combi systems are not commercially available in UK (the Remeha eVITA combi SE mCHP is available in Germany and The Netherlands)
	Low water output T – appropriate heat distribution retrofitting	• Low water output temperatures (~60 deg. C) might require the retrofit of appropriate heat distribution systems such as low T radiators of under floor heating	• HT PEM mCHP provide higher output temperatures that address this problem
	Requirement for external reformer for fuel processing	• LT PEM FCs have low tolerance to CO that implies the need of fuel processing • ~80% of the BoP cost is due to the fuel processor	• Improvement in fuel processor and system configuration • HT PEMFC have higher tolerance to CO and do not require an external reformer
	Durability / on/off cycle life	• Currently, lifetimes of ~40,000 h. Potential for improvement • LT PEM FC, however, offer the longest lifetimes along FCs (compared with SOFCs affected by durability and cycling issues and HT PEMFC affected by harsher temperature conditions. Lifetimes ~20,000 h)	• R&D in this area
	Integration with thermal storage	• Significant if the fuel cell is electricity led to avoid heat rejection in times for high electricity-low heat demand profiles	• Development of thermal storage (low TRL) and integration with LT PEMFC – companies are studying this at the moment with views to commercialisation
	High costs	• Capital costs ~ five times higher than a conventional boiler • Ene-farm residential LT PEM (launched April 2013. Panasonic, 0.75 kW system, Japan): £18,700/kW (i.e. capex ~£14,000)	

HT PEM FC	Application development for the domestic market	• Small number of low nameplate capacity systems commercially available (e.g. Clear Edge offers systems from 5 kW) limits the application of this technology to systems with higher thermal demand (multifamily residential buildings)	• Feasibility studies and prototype development for the domestic market
	Supply chain development	• Small supply chain opportunities for Membrane Electrode Assemblies (MEAs)	• Increase competition in MEAs supply (e.g. at the moment, BASF main player)
	Lifetime	• Membrane lifetime is seen by many researchers as the bigger barrier for commercialisation of HTPEMFC • Catalysts durability, especially in acid based systems	• R&D in new materials
	Space	• Volume occupied by a 5 kW HT PEM unit is 10 times bigger than a 60 kW condensing gas boiler • Volume occupied by a 5 kW HT PEM unit is 4 times higher than a 0.75 kW LT PEM • Weight 5 kW HT PEM vs 60 kW condensing gas boiler (kg): ~1,000 kg vs <100 kg	• Simplification of the system
SOFC mCHP	Requirement for thermal storage to optimise operation	• Thermal storage provides a solution to the adverse impact of on-off cycling on SOFCs due to thermal stress (but note that space constraints might apply)	• Thermal storage development and integration with SOFCs • Other mCHP technologies (e.g. SE, ICE can ramp up and down rapidly)
	Long start-up times	• Due to the high operating temperature of this technology, start-up times are long.	• The integration of SOFC and electricity storage could provide a solution to this constraint - Could provide fast response to load following - Development of bespoke DC / DC converter between SOFC, battery and load necessary - Projects undergoing for this integration
	High costs	• Capital costs ~ 6-7 times higher than a conventional boiler (Enefarm Type S, 0.7 kW~£?27,000/kW. i.e. capex ~£?17,000)	• Materials innovation - There has been a general trend to try to decrease operating temperatures of SOFCs as high temperatures require expensive materials/construction (however, a shift below c.650C is required to benefit from standard steels and therefore cheaper materials/manufacture)
	Size	• Space requirements to accommodate mCHP and associated thermal storage	
SE mCHP	Efficiency improvement	• Improve efficiency at low power	

High costs	• 2 - 3 times the costs of a condensing gas boiler	• Reduction through economies of scale and technical innovations
Lack of customer awareness	• Together with high capital cost, this might be another reason for its small uptake, given that it is commercially available. After ICE mCHP, the mCHP technology has been in the market for longest time	
Supply chain development	• Volume production: development of automated assembly of stacks • PM synchronous generator implies the use of Rare Earths, which could mean a resource constraint. Competition with wind turbines, batteries.	

SECTION 3 – BIOMASS BOILER, HDTS and HYBRID SOLAR THERMAL

Table 8. Biomass boiler, HDTS and hybrid solar thermal technology gap analysis assessment

Tech.	Gaps / barriers	Detail on barrier / gaps	Required development
Biomass boiler	Local availability of stock and fuel supply; space for appropriate storage	• Constraints in fuel supply • Biomass fuels require careful storage to avoid deterioration and air quality risk to operators	• Supply chain development • Sensors to track key parameters such as humidity, water content and fungal growth (impacting on air quality in the store)
	Hassle – fuelling, de-ashing, and maintenance	• Alkaline nature of biomass implies fouling and corrosion, resulting in a high economiser failure rate • Higher maintenance requirements than biomass boilers (emptying ashbin, cleaning flue tubes)	• Study of economiser failure in biomass boilers, development of predictive tools for slagging and deposition control in boilers
	Air quality impacts	• Air quality concerns (NOx and CO/CO_2) of burning biomass in urban areas could restrict their application in these spaces . Importance of combustion control systems (problem more challenging than in gas boilers, as reaction temperatures are higher, and allow the reaction of atmospheric O_2 and N_2)	• Filter cleaning technology and combustion control mechanisms under development to reduce particle emissions
	Back up boiler and thermal storage integration	• Domestic biomass boilers will usually provide the base load for the heating system, and a back-up boiler sized to meet the peak load will be needed in most cases • The technical characteristics of biomass boilers, that require them to operate continuously in order to achieve the higher efficiencies, make integration of biomass boilers with thermal storage systems important	• Thermal storage development • Appropriate control systems
	Space	• Space requirements both internal (boiler) and external (fuel storage) • 10-15 kW biomass boiler ~ 1.5-2 times the volume of a condensing gas boiler	

Thermal store / HDTS	De-stratification of thermal store	• Affects heat source capacity control • Can be created due to incorrect BoP design (e.g. over-pumping by fixed speed pumps)	• Appropriate design team and installer base • There are commercial solutions proposing “stratification by design” – integration of several modular salt hydrate PCMs storages (< 5 kWh) with different melting points into a PCM thermal store. Modules are separated, avoiding de-stratification by an incorrect BoP design (See appendix)
	Low TRL	• Although HDTS will have a key role for the future of smart heat energy systems, it is still at an early stage of development	• Development, demonstration and commercialisation of heat-source tailored applications • Further research/development/demonstration of metal hydrides as thermal storage for the domestic sector • Further research/development/demonstration of PCM salt hydrates for storage for the domestic sector (avoid paraffin’s safety issues)
	Technical barriers	• Several barriers associated with different types of PCMs (e.g. although salt hydrates present the advantage of being not flammable, as is the case for paraffin-based PCMs, and of having twice the energy density of the latter, they present issues associated with corrosion)	• Further development and demonstration of HDTS e.g. for PCM integrated in HW tank storage, there is scope for development of the design parameters for optimal performance: 1. PCM shape (e.g. PCM tanks with inner core, with inner balls, or with inner tubes) 2. Operating temperature
	Costs	• The Technology Innovation Needs Assessment published in 2012 reported capital costs for daily PCM heat storage for small scale systems (i.e. suitable for homes) of £530/kW	• Supply chain and economies of scale development
Hybrid solar thermal and gas boilers	Space	• Storage tank essential for solar water heating	• Integration of PCMs in HW tanks Due to high PCMs costs, this solution might just be appropriate in systems with space constraints, in the short term
	Lack of customer confidence in / awareness of technology	• Awareness of solar thermal technology is reasonably good, although some negative perception due to issues with installations of earlier generations of the technology. • Scepticism about the effectiveness of solar thermal in UK.	• Increase customer confidence in the technology - Remove information barriers for the potential consumer to easily find an installer • Customer training about the optimal use of the technology - Adopters may not know how best to use solar heated water to minimise back-up fossil fuel consumption
	Integration issues	• Solar thermal technology could provide ~60% of household’s hot water in a cost-effective manner *(EST, 2011)*	• Optimisation of system integration

4.2.1 Cross-cutting issues and enablers

The technology gap analysis has identified a number of cross-cutting issues that are common to several of the technologies. These common issues are summarised in Table 9.

It is clear that high density thermal storage and smart control systems have a role to play in a range of technology packages. When integrated with primary heating appliances, these technology packages (or systems) facilitate demand reduction, more cost-effective operation and enable smart control strategies, such as demand side response, which can be beneficial to the operation and management of the electricity supply system. These key enabling technologies are discussed in more detail in *Appendix C – Key enabling technologies.*

In the Appendix, an analysis of Heat Pump and Fuel Cell mCHP integration issues is presented, and a description of energy storage at the building and Host Space Environment level is provided. Regarding the control strategy, options for control strategy and their associated barriers are also presented as well as the main barriers at the building (costs, lack of incentives for homeowners, land of standard protocols) and Host Space Environment levels, in the form of Demand Side Response coupled with heat pumps or mCHP (consumer acceptance, lack of incentives to homeowners to participate in DSR schemes, costs, lack of standardisation of protocols within the homes and between home and Demand Response application).

4.3 Host Space Environment level assessment

The preceding sections assessed the barriers and gaps associated with integration of low carbon heating systems within buildings. In this section, we consider the impact of high levels of deployment of low carbon heating options within local areas, using the HSEs as the framework for the assessment. The technology deployment scenarios used for this analysis were introduced in Section 4.1 and are taken from the DECC 2050 Pathways analysis.

When considering technology deployment at the area-level, it is necessary to consider network technologies that are deployed outside the confines of individual buildings. Under low electrification scenarios, the DECC 2050 Pathways consider the potential for high levels of penetration of district heating, served by combined heat and power (CHP) technologies and alternative sources, such as waste heat. Under high electrification scenarios, the DECC Pathways envisage a large proportion of heat demand being met by air and ground source heat pumps. The impact of high levels of electrification of heat on local electricity distribution networks is a widely recognised challenge and significant resources are being employed to develop solutions, technical and commercial, to mitigate these impacts and reduce network investment costs. In this section we assess the impact of deployment of district heating and smart network technologies. Further discussion of the technologies and their development issues is given in *Appendix D – Network Solutions.*

In the following section, the selected technology deployment scenarios are assessed at the HSE-level in terms of their cost implications and carbon reduction impact.

4.3.1 Cost analysis

The scale of required investment will be an important factor in assessing the technology and systems options for future low carbon heating infrastructure. Government will seek to identify pathways to decarbonisation of the economy that incur least resource cost to the UK. Consumers and businesses will not be persuaded to invest in low carbon heating technologies that are not cost-competitive with incumbent systems, at least not without generous subsidies or stringent regulations.

A high-level analysis of the capital cost implications of the technology deployment scenarios introduced in Section 4.1 has been undertaken for each of the relevant HSEs. Given the time horizons for large-scale deployment of low carbon heating technologies, the cost analysis has been performed on today's costs and on the basis of forecast costs for 2030. The capital cost implications, presented as £/dwelling, are shown in 3[4] (the capital cost assumptions for each of the technologies are given in the appendices).

In the rural HSEs, the *High HP (no DH)* scenario is least cost under today's cost assumptions. Note that this is partly due to the assumption that the majority of the mCHP systems installed in the *High mCHP* scenario are fuel cell based and the high current costs of fuel cell mCHP products ($20,000/kW). In the suburban and urban HSEs the least cost scenarios are those that include a significant penetration of district heating networks. The *Low Elec*. scenario in particular, which involves high district heating penetration and Stirling engine mCHP in those dwellings not connected to a heat network, compares favourably against other scenarios that involve higher penetration of heat pumps and fuel cell mCHP.

Under 2030 cost assumptions in the suburban and urban HSEs the capital costs related to the *High HP* and *Mixed* scenarios have dropped considerably relative to those of the more district heating based scenarios. The assumption here is that while some cost reduction may be achieved in centralised thermal plant, such as biomass CHP, there is limited scope for cost reduction in the district heating infrastructure. Despite the assumption of limited cost reduction for DH, the *Low Elec*. scenario remains the least cost scenario under 2030 assumptions. This is in part due to a relatively conservative assumption on the scope for cost reduction of heat pumps. While the market for heat pumps in the UK is currently limited, the major components in heat pumps (such as the compressors) are very mature in other markets and manufactured in large volumes (for example the commercial HVAC market). The development of the UK heat pump market is unlikely to drive significant cost reduction in these components. The installation cost of a heat pump system in the UK is estimated to be 35 – 50% of the total installed cost in the current market. Some cost reduction in this element of the total cost is expected as the market grows and the supply chain becomes more developed. The largest cost reduction has been attributed to fuel cell mCHP systems. This technology is currently pre-commercial in the UK, with only a handful of installations to-date (total experience across Europe is around 1,000 units; the largest market is Japan, where a few tens of thousands of units have been installed to-date). Significant cost reductions are expected to be achieved for fuel cell mCHP as the manufacturing

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[4] The capital costs analysis does not account for the time to turn-over the heating system stock or any replacement costs (all costs are undiscounted).

capacity of fuel cell stacks increases. This could be partly driven by other markets, such as automotive. It has been assumed that fuel cell mCHP systems achieve costs of $3,500 - $5,000/kW by 2030 (Staffel and Green, 2012[5]).

The impact of the more aggressive assumption for cost reductions in mCHP can be seen clearly in eth 2030 cost assessment for the rural HSEs. In this case the High mCHP option is significantly the least cost solution.

[5] Staffel I., Green R., The cost of domestic fuel cell micro-CHP systems, 2012

Table 9. Common cross-cutting issues across technologies

	GENERAL	HPs: ASHPs	HPs: GSHPs	HPs: Hybrid ASHP	mCHP: FC mCHP	mCHP: SE mCHP	Biomass boiler
SPACE	• Combi boilers (75% of new installed boilers 2011). High penetration driven by space constraints for DHW/thermal storage in many newer homes	Require DHW tank	Not suitable for flats	-Smaller than ASHP -Some offer instant HW	Back up boiler, DHW tank and thermal storage for flexibility of system (wall hung units seem necessary for UK uptake)	Back up boiler can be integrated in SE mCHP	Not suitable for flats Back-up boiler required
DESIGN	• Match capacity of heat system with demand • Technical improvement by design: e.g. stratification by design in PCMs systems - under development	Mismatching of HP capacity and heat demand addressed as an important failure <u>Hybrid ASHP</u> Sizing an hybrid heat pump for a given installation is often less critical than for pure ASHP or GSHP			Minimise system components (e.g. Balance of plant with high failure rates)		In systems not correctly designed, the fossil fuel boiler will take over the load intended to be supplied from biomass, with the subsequent carbon savings reduction that this implies
INSTALL	• Lack of skilled and experienced installers for tailored system design. Performance is determined by: a) Initial installer assessment b) installation quality c) controls parameters set by installer • Technical solutions could reduce installation costs (standardisation) • <u>ASHP</u>: EST trials revealed critical importance of installation in ASHPs (e.g. Tuning of control parameters, such as the “heat curve” (water temperature) has a high influence on system performance. Work on the radiator loop sometimes necessary to improve flow distribution)						
INTEGRATION WITH THERMAL STORAGE	Enables selling demand side response services and arbitrage opportunities	Thermal storage enabling flexibility of grid (peak shaving, decentralised generation) Thermal storage is less cost effective with Hybrid ASHP as bi-energy already offers greater flexibility			<u>PEMFC:</u> Thermal storage integration with electricity led PEMFC to avoid heat rejection in times of high electricity-low heat demand profiles <u>SOFC:</u> When integrated with thermal store can be run throughout extended periods of time avoiding on-off cycling that causes thermal stress <u>SE mCHP</u>: high thermal SE output requires the storage (with ability to decouple heat production from demand) to be big enough to enable running for long hours (or high thermal demand) before significant electrical generation occurs		The technical characteristics of biomass boilers, that require them to operate continuously in order to achieve the higher efficiencies, make important the integration of biomass boilers with thermal storage. Efficiency highly affected by cycling
CONTROLS	Enables selling demand side response services and arbitrage opportunities	• HPs equipped with control system based on air T measurement at least and internal thermostat • Ideally Communication between HP and grid – Design of systems incorporating dynamic price signal input (particularly interesting for Hybrid ASHP)			Optimised mCHP controls to minimise operating costs and maximise CO_2 savings – Different control strategies (i.e. heat/electricity/least cost led), have different implications for each FC mCHP technology		

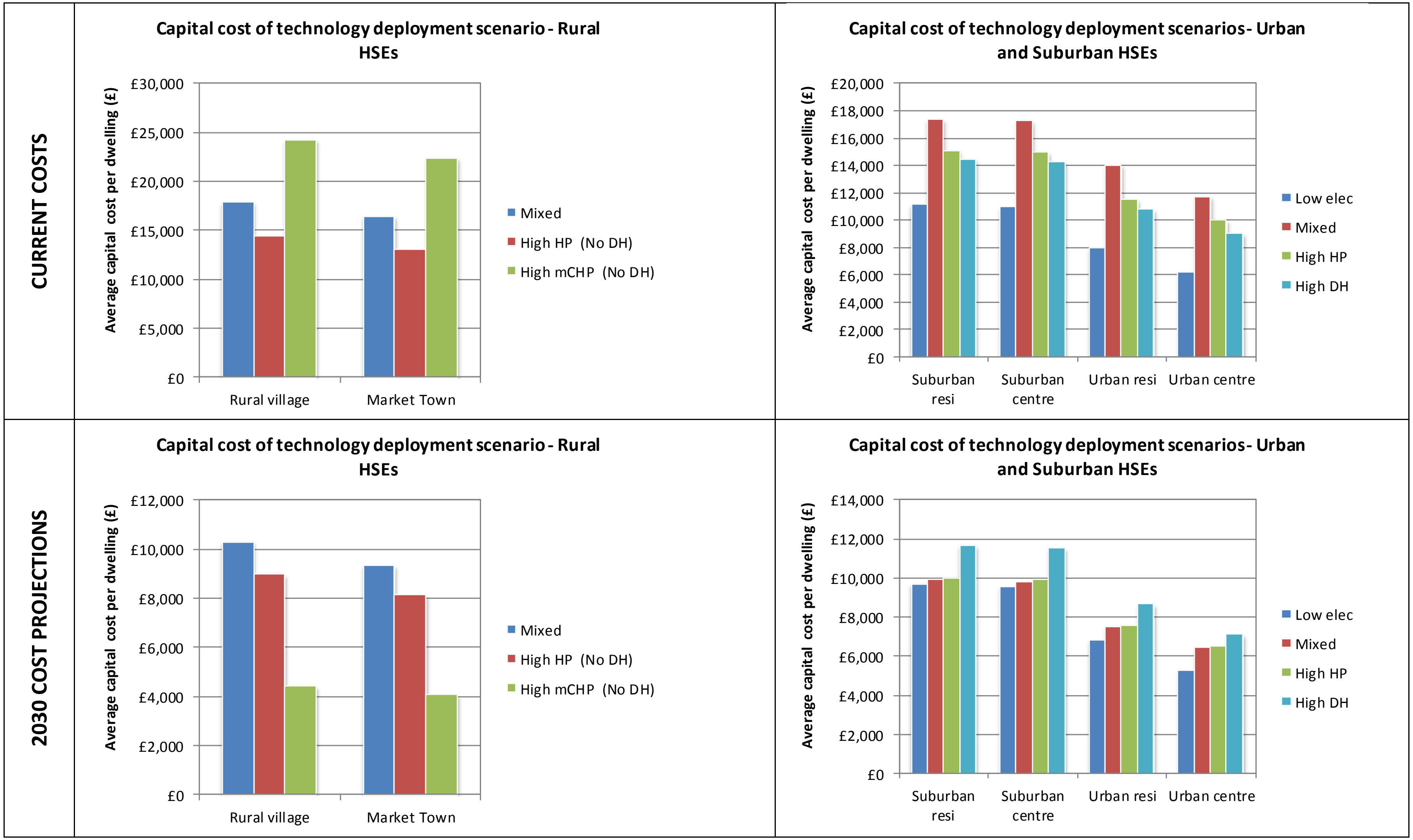


Figure 3. Capital cost implications of technology deployment scenarios

4.3.2 Grid reinforcement costs

The costs presented in the preceding section are those related to the installation of technologies within the dwellings. Deployment of certain technologies will result in costs being incurred to reinforce the electricity distribution network, particularly in the case of those technologies that involve electrification of thermal demand and those technologies that have potential to feed electricity back to the network. There are a range of technologies and strategies that can be deployed to mitigate these costs, as described in *Appendix D – Network Solutions*.

In this section we present an analysis of the costs related to the impact of heating technologies on the electricity distribution network, under a range of control strategies.

Firstly, the network reinforcement costs related to an uncontrolled strategy (i.e. business-as-usual reinforcement) is tabulated below for each of the HSEs and each of the relevant technology deployment scenarios.

Table 10. Reinforcement costs across HSEs related to business-as-usual reinforcement

HSE \ Scenario	Reinforcement cost (£/connection)					
	Low electric	Mixed	High HP	High DH	High HP (No DH)	High mCHP (No DH)
Village		6 – 7			850 – 970	0
Market town		100 – 140			2,000 – 2,500	0
Suburban residential	0	110 – 140	770 – 930	150 – 190		
Suburban with local centre	0	120 – 160	790 – 960	150 – 200		
Urban (residential)	0	0	300 – 340	0		
Urban centre	0	0	140 – 160	0		

No significant network reinforcement costs are incurred in the low electrification scenario or in the *High mCHP* case. The scenarios that have an impact on the electricity distribution network that requires reinforcement are those that include an element of electrification of heat load. The reinforcement costs for these four scenarios are shown in the chart below for each of the relevant HSEs. The reinforcement cost is disaggregated between the voltage levels.

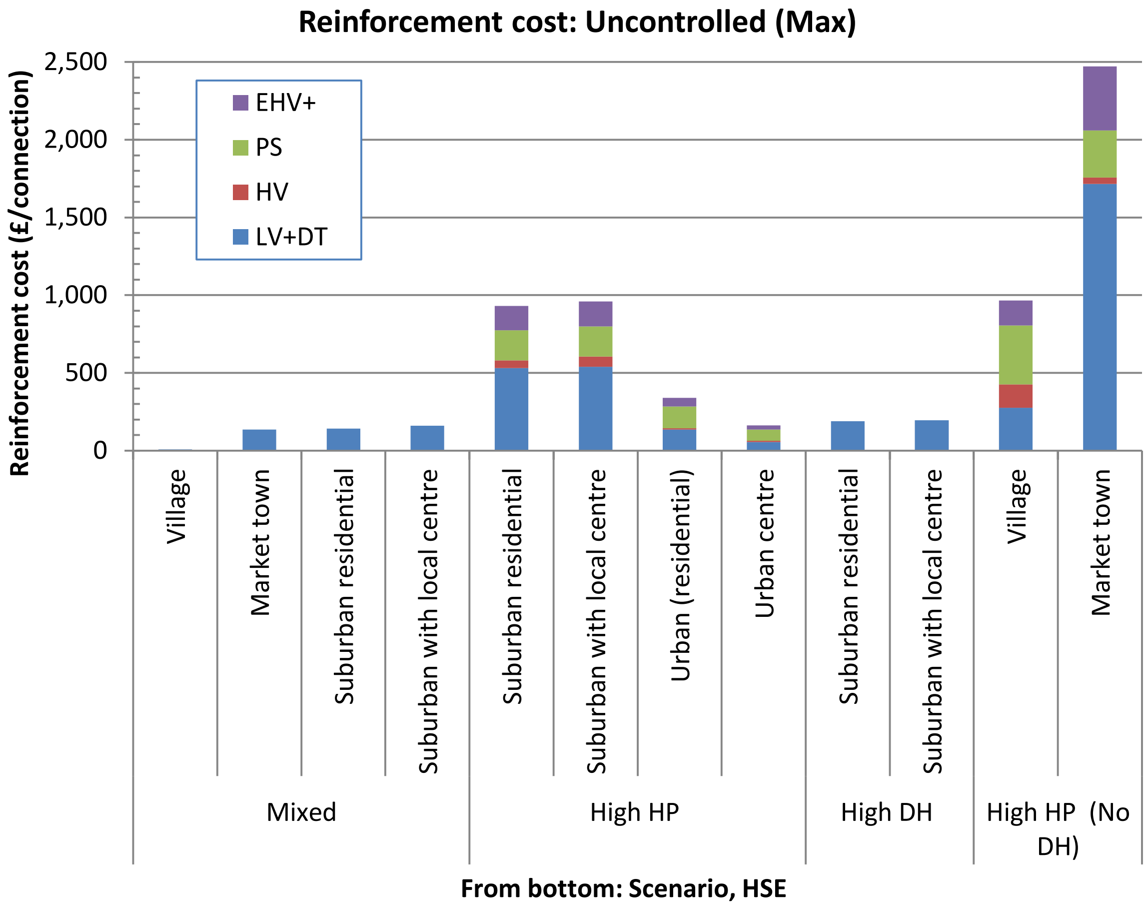


Figure 4. Reinforcement costs across scenarios and HSEs (LV + DT = Low voltage network and distribution transformers; HV = High Voltage network; PS = Primary Substations and EHV = Extra high voltage network)

There is a large variability between the cost impacts of high heat pump penetration between the six HSEs. Generally, the cost implications tend to be greater in the more rural HSEs, particularly the Market Town HSE, in which a network reinforcement cost of nearly £2,500 per connection is triggered by the High HP scenario (80% penetration of heat pumps). It is also clear that the low voltage network and distribution transformers are the most significant component of the reinforcement cost.

We focus on the High HP scenarios for the following analysis of the impact of mitigation measures, as these are clearly the scenarios with greatest implications for the networks. A full set of results for each scenario, HSE and control strategy is provided in the appendices (*See Appendix D – Network Solutions*).

Given the high concentration of reinforcement costs in the LV network, it is expected LV voltage control will provide significant benefits. A comparison of reinforcement costs across the HSEs between the uncontrolled case and case with LV voltage control is provided in the figure below (all cost ranges relate to the High HP deployment scenarios).

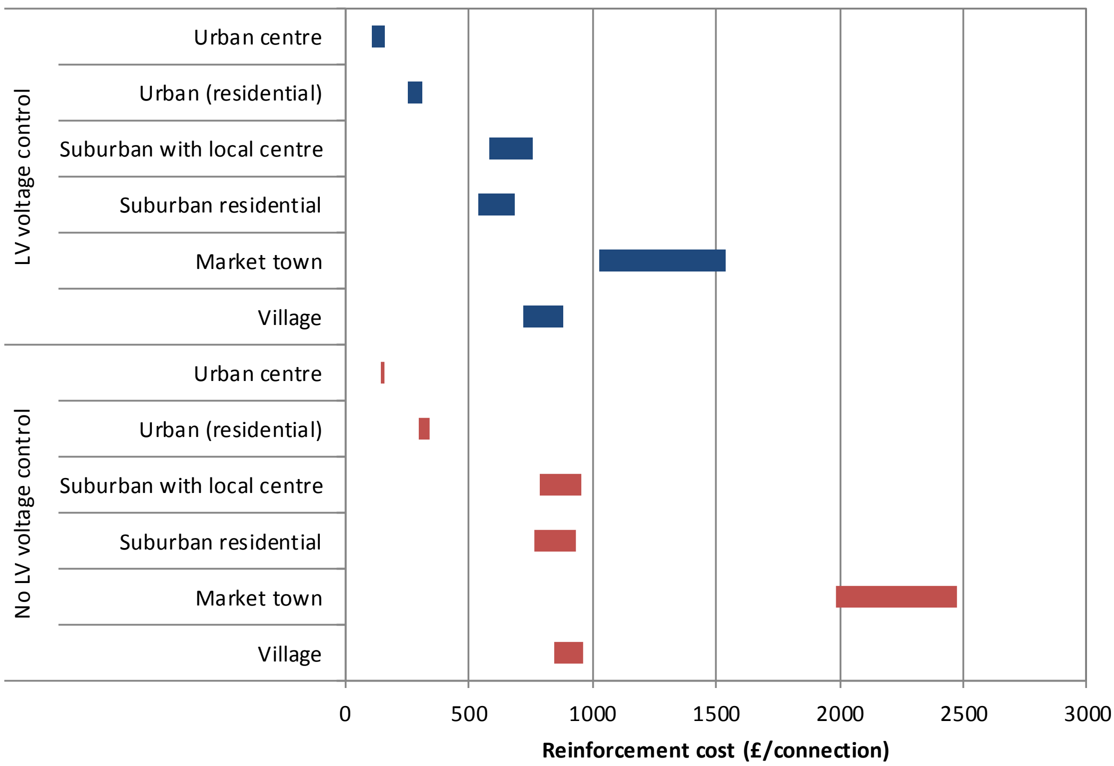


Figure 5. Reinforcement costs across HSEs between uncontrolled case and with LV voltage control

Reductions in the reinforcement cost in the LV voltage control case are seen across the HSEs. The impact is most significant in the Market Town and two suburban HSEs.
The further reinforcement cost reductions that can be achieved under other control strategies are shown in the figures below for a selection of HSEs. The control strategies that have been assessed are:

- Grid storage
- Demand Side Response (DSR)
- Energy efficiency (10% load reduction)
- D-FACTS (Distributed Flexible Alternative Current Transmission Systems).

The impact of these measures has been assessed when combined with LV (low voltage) control and without.

Demand Side response is the control strategy that achieves the greatest further reduction in reinforcement costs. This is consistently the case across the HSEs (although the range of potential costs under the DSR case is large).

D-FACTS and energy efficiency also provide benefit and are fairly comparable to each other in terms of the impact (although the cost of fabric efficiency measures is not factored into this analysis). The benefit achieved by the introduction of grid storage is expected to be marginal on the basis of this analysis.

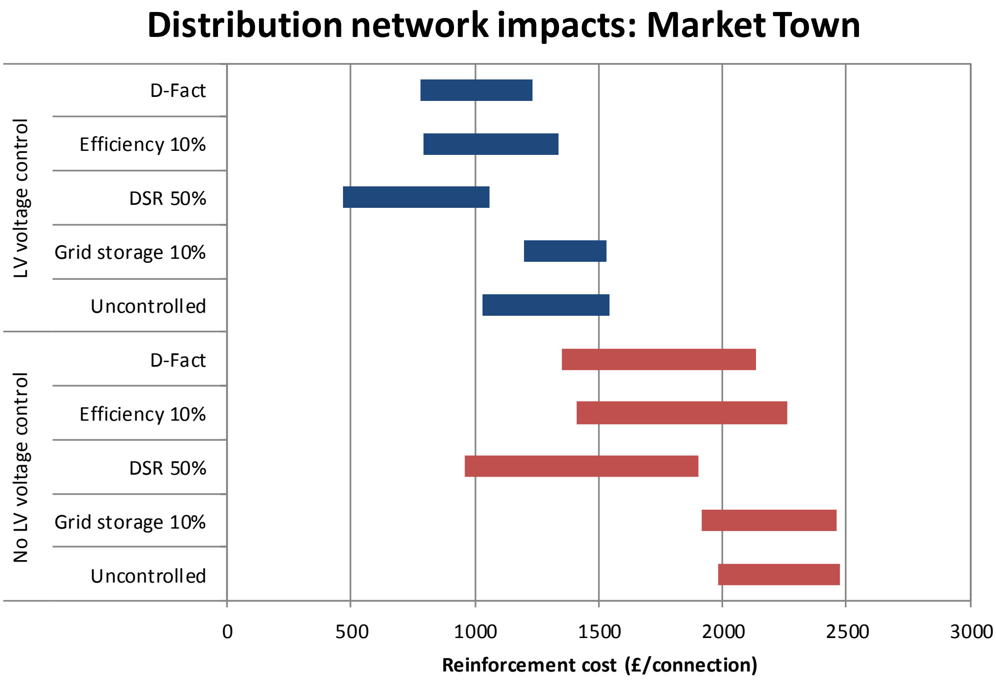


Figure 6. Distribution network impacts in Market Town

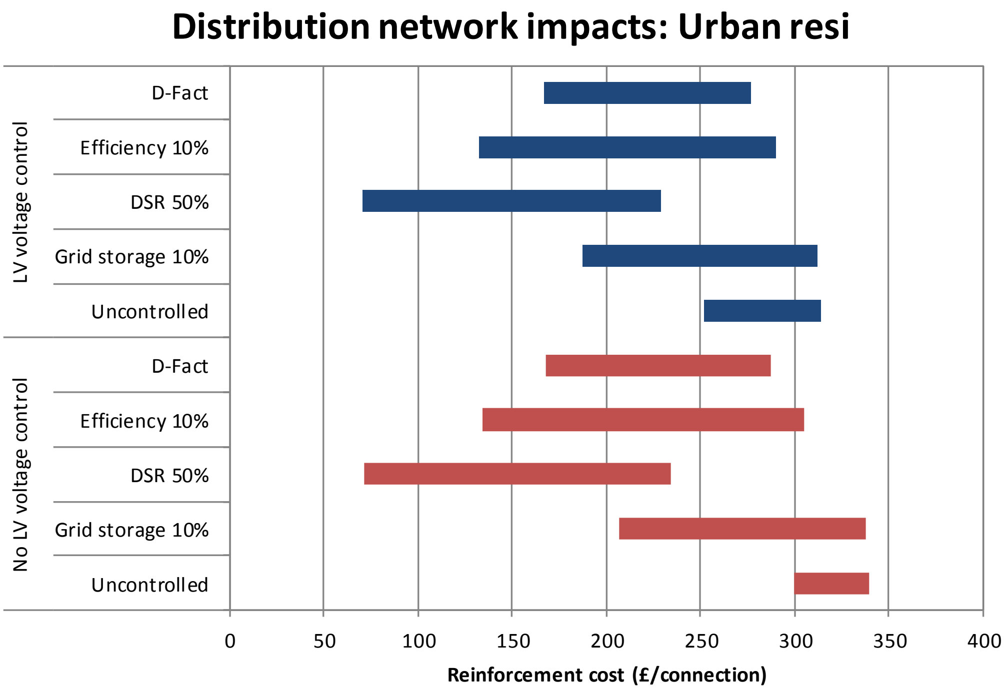


Figure 7. Distribution network impacts in Urban residential

4.4 Carbon emissions impact

The extent of the CO_2 emissions reduction that technologies can achieve is a key criterion in the selection of heating technologies and systems that will be applicable in the 2030 and 2050 time horizons. In this section we present a high-level analysis of the potential scale of CO_2 reduction delivered by the various technology deployment scenarios.

The basis of this analysis is an assessment of the CO_2 reduction at the dwelling level. The Element Energy Housing Energy Model (HEM) has been used to assess the CO_2 reduction delivered by each technology in each of the twelve standard house types. In combination with the primary heating technology, it is assumed that a package of energy efficiency measures is also applied to each house type (the efficiency measures included in the package are detailed in the appendices: *Appendix F – Cost and Carbon* emissions assessment).

The results of this assessment, in terms of carbon reduction compared to the baseline house types for each technology package, are provided in the appendices (*Appendix F – Cost and Carbon* emissions assessment). The key findings are as follows:

- The largest CO_2 reductions are achieved by the biomass boiler, due to the very high fraction of renewable heating achieved in this case – assuming that the biofuel is accredited to come from sustainable sources.
- ASHP deliver a marginal improvement in gas heated homes (based on an ASHP Seasonal Performance Factor, SPF, of 2.5). GSHPs provide a slightly greater improvement due to their higher SPF (3.1).
- Generally, larger CO_2 reductions are delivered by all technologies in the electrically heated homes.

Based on the CO_2 reduction assessment at the house type level, an analysis of the CO_2 impact of the technology deployment scenarios across the HSEs was undertaken.

The CO_2 reductions delivered by each of the technology deployment scenarios in the HSEs is shown in Figure 8 as a percentage reduction on the baseline emissions.

Given that, through this process, we are seeking to identify high priority technologies that could play a significant role in low carbon heating systems on timescales up to around the 2030s, we are interested not only in the levels of CO_2 reduction that could be delivered under today's energy mix assumptions (compared with current levels attributed to residential heating provision), but also in the CO_2 emissions performance under a future set of assumptions. Potentially the most significant change anticipated to occur over the period to 2030 is a significant drop in the carbon intensity of the grid electricity mix, primarily due to the expected large-scale deployment of off-shore wind turbines. To assess the impact of a reduction in grid CO_2 emissions intensity, we have analysed the CO_2 emissions associated with each of the technology deployment scenarios under an assumed grid CO_2 intensity of 0.2 $kgCO_2/kWh$. These results are also presented in Figure 8.

- Under current assumptions the greatest CO_2 reduction is delivered by those scenarios that involve large-scale penetration of district heating. High heat pump scenarios achieve the lowest CO_2 reduction across all scenarios.
- The strong CO_2 benefit delivered by the district heating scenarios is sensitive to the assumed penetration of renewable fuel. However, even under an assumption of 100% of district heating load is served by gas CHP, the CO_2 emissions performance is better than heat pump performance under current grid CO_2 intensity assumptions.
- Under the assumption of a grid CO_2 intensity of 0.2 $kgCO_2$/kWh, the High HP scenarios provide the greatest CO_2 reduction across all HSEs. Note that the comparison between high heat pump scenarios and high DH is relatively close at this grid CO_2 intensity (assuming a high renewable fuel source penetration in the DH scenarios).
- It is interesting to note that the CO_2 emissions performance of mCHP deteriorates very significantly as the grid CO_2 intensity falls. This is most clearly seen by comparison of the High mCHP scenario between 2013 and 2030 assumptions. The implication of this is that the window of opportunity for mCHP is short, if decarbonisation of the electricity sector proceeds as planned. This has knock on implications so far as identifying technology gaps and development opportunities for the ETI's consideration – ie, only if cost reduction can be fast-tracked via ETI involvement would such involvement be commercially worthwhile
- No change in the CO_2 intensity of net-bound gas supply is assumed in this analysis. A reduction in the gas CO_2 intensity could extend the opportunity for mCHP to deliver material CO_2 reduction. This could be achieved by introduction of biomethane into the gas grid (supply issues and potential to complicate the fuel processing equipment required by fuel cells) or renewably generated hydrogen.

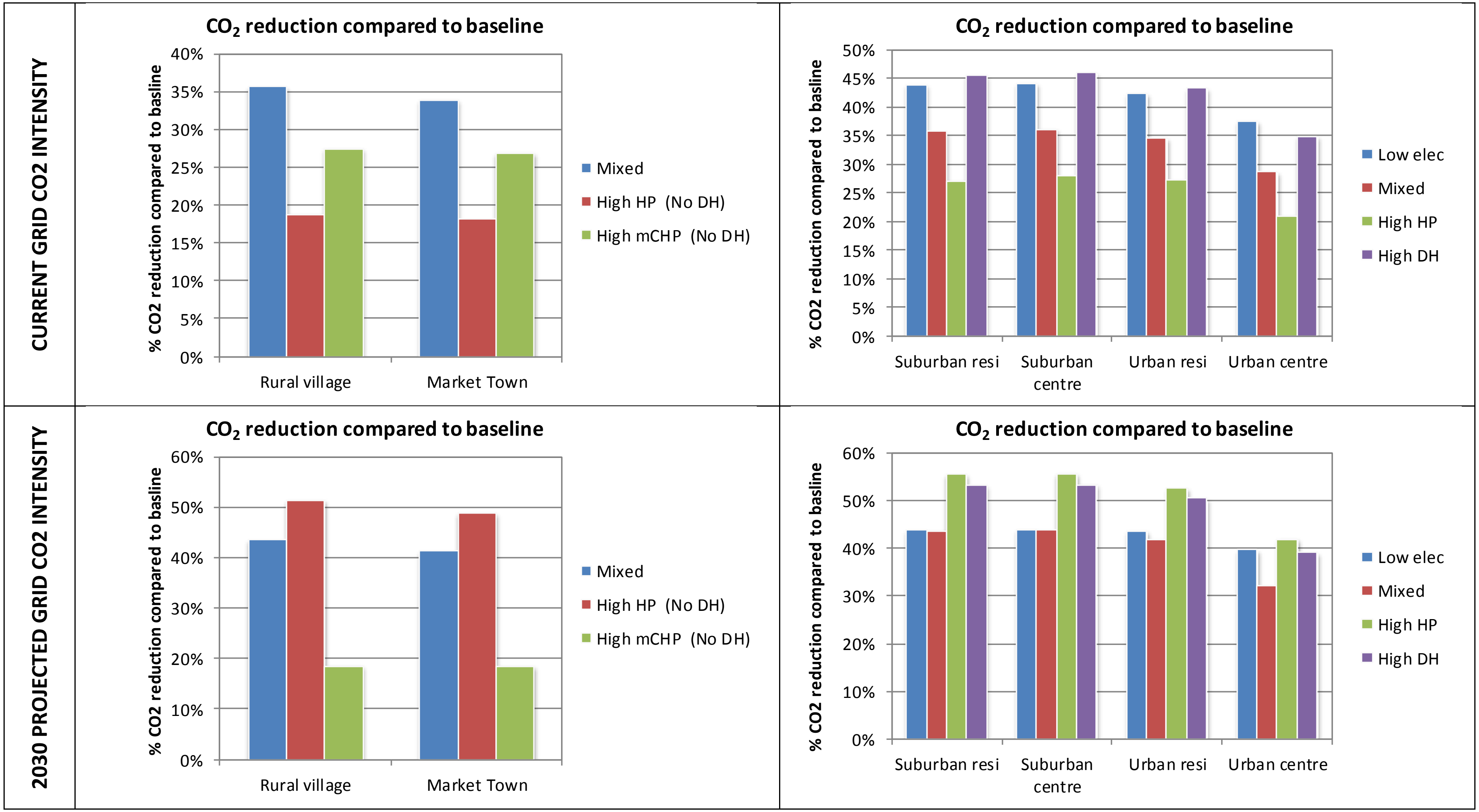


Figure 8. CO_2 reductions by each of technology deployment scenarios in the HSEs as a percentage reduction on the baseline emissions

4.5 Packages of solutions

Assuming that technology packages will include appropriate and feasible levels of fabric insulation upgrade, the following table presents examples of the allocation of suitable packages of technologies to the different HSEs. A collection of packages with potential for decarbonisation of the domestic heating market up to the medium term at the building and community level are presented, although the list does not intend to be comprehensive nor to prioritise certain specific packages for each HSE.

HSE	Heat distribution	Heat source (building level)	Storage	Manage, monitoring & control	Heat network	Electricity distribution	Distributed generation	Manag. Services	Comments
Village	Conventional radiators	Biomass boiler	HDTS	HEMS/HAN		LV control/ DSR		EMS	
	Conventional radiators	SE mCHP	HDTS	HEMS/HAN		DSR		EMS	SE mCHP systems, given their high heat to power ratios and high capacity of currently available systems, are better suited to dwellings with high thermal demand (e.g. larger, older dwellings)
Market town	Conventional radiators	Biomass boiler	HDTS	HEMS/HAN		LV control/ DSR		EMS	
	Conventional radiators	SE mCHP	HDTS	HEMS/HAN		DSR		EMS	SE mCHP systems, given their high heat to power ratios and their power capacities currently available, could better suit systems in which a high thermal demand is necessary, as bigger dwellings

Suburban residential	Fan-assisted radiators	ASHP	HDTS	HEMS/HAN		LV Voltage control / DSR		EMS	Noise constraints in densely constructed areas
		SE mCHP	HDTS	HEMS / HAN		DSR		EMS	
	Fan-assisted radiators		Community-scale TES	HEMS/HAN	Low T Heat network		Large HP	EMS	Low T heat network can benefit areas with lower densities
Suburban with local centre	Fan-assisted radiators	ASHP	HDTS	HEMS/HAN		LV Voltage control / DSR		EMS	
		SE mCHP	HDTS	HEMS/ HAN		LV Voltage control/ DSR		EMS	
	Fan-assisted radiators		Community-scale TES	HEMS/HAN	Low T Heat network		Large HP	EMS	Low T heat network can benefit areas with lower densities
Urban (residential)	Fan-assisted radiators	ASHP/ H-ASHPs	HDTS	HEMS/HAN		LV Voltage control / DSR		EMS	Noise constraints in densely constructed areas. Predominance of terraces makes space constraints a smaller issue than in urban centre
		FC mCHP	HDTS	HEMS / HAN		DSR		EMS	
	Fan-assisted radiators		Community-scale TES	HEMS/HAN	Low T Heat network		Large HP	EMS	
			Community-scale TES	HEMS / HAN	DH network		Community-scale biomass CHP	EMS	
Urban centre	Fan-assisted radiators	ASHP/ H-ASHPs	HDTS	HEMS/HAN		LV Voltage control / DSR		EMS	Space constraints, given predominance of flats

		FC mCHP	HDTS	HEMS / HAN		DSR		EMS	
	Fan-assisted radiators		Community-scale TES	HEMS/HAN	Low T Heat network		Large HP	EMS	
			Community-scale TES	HEMS / HAN	DH network		Community-scale biomass CHP	EMS	

5 Short-list of technologies / systems and rationale

The following technology short-list has been identified as the most promising technologies of those assessed in this work. These are technologies that have potential to be deployed at scale and deliver significant carbon reduction or to be key enablers of significant carbon reduction as part of integrated systems. For each technology, a brief summary of the rationale for selection is provided.

Table 11. Short-list of technologies

Cluster	Category	Technology	Rationale for interest
Building-level	Heat distribution	Fan-assisted radiators	• High potential applicability in low temperature distribution heating systems • Less disruptive and lower cost for retrofit than underfloor heating • Fan-assist provides more rapid heat-up characteristics and even temperature distribution within the space
	Heat source	ASHP	• Anticipated to be a key technology in the electrification of heat • More widespread and lower installed cost than ground source systems • Promise of very low carbon heat as grid decarbonises
		Hybrid ASHP	• Potential to mitigate some barriers to ASHP deployment, such as compatibility with existing heating systems and reliance on immersion heater to provide DHW • High potential for standardisation • For retrofits, can be an integrated solution or as an extension to the existing gas boiler
		Fuel cell mCHP	• Highly efficient form of localised energy generation • Potential to provide balancing services / reserve and peak-shaving services to utilities • Opportunity for arbitrage based on the spark spread
	Storage	HDTS / PCM	• Potential to be a key enabler within smart heat systems, e.g. to enable demand response using heat pumps or FC mCHP • Enable householders to utilise off-peak electricity for heating • Significantly reduced volume compared to traditional storage mediums for an equivalent energy capacity • Potential for a variety of form factors enabling storage to be better integrated into constrained spaces • Potential to be used as a high thermal mass fabric component
	Management, monitoring & control	Sensors / actuators	• Enable energy demand reduction through more sophisticated control strategies and software development • Enable DSR and increased home automation via communication with a HEMS gateway device

Network-level			• Potential for development to control microgeneration and smart appliances • Algorithm and software development
		HEMS gateway / HAN	• Potentially a key component in the smart home system. • Enabler of better electricity system utilisation and system balancing via demand-side response • Could also enable control of microgeneration and smart loads, such as EV charging and refrigeration
	Heat network	Low T district heating network	• Well-suited to new build, energy efficient buildings • Lower losses than from higher temperature distribution systems • Increased potential to utilise waste heat • Increased potential to utilise renewable energy sources, including large-scale heat pumps.

	Electricity distribution	Voltage control	• LV voltage regulation techniques include a range of technologies, such as:
			  • Solid state transformer
			  • In-line voltage regulator
			  • Conservation voltage reduction
			  • Voltage reduction based frequency control
			• These LV voltage control technologies have potential to increase the capacity of distributed generation, heat pumps of EVs that can be connected by mitigating voltage problems

		D-FACTS	• Soft Normally Open Points • Static Synchronous Compensator (STATCOM) • Unified Power Flow Controllers
		DSR / thermal storage	• Demand response technologies manage electricity demand in response to supply conditions. • DSR is an umbrella term relating to a number of technologies that facilitate demand response, e.g. HEMS/HAN, smart thermostat, auxiliary switches etc. • Optimisation of DSR potential also requires advanced control systems at the network level
	Distributed generation	Community-scale CHP (biomass / biogas)	• Potential to deliver very low carbon heat at community-scale via district heating systems • Cost competitive with microgeneration technologies in areas of suitable heat density • Facilitates better emissions control than smaller-scale distributed biomass plant (solid biomass fuel)
		Community-scale energy from waste	• Potential to deliver low carbon heat at community-scale via district heating schemes • Integration of waste management with energy provision has synergistic benefits for communities (e.g. landfill

			reduction)
		Cloud management service	• Cloud computing promises a lower cost means of implementing smart homes systems • Cloud based server enables reduced distributed computing and data storage resource, with no loss of quality of service
Service-level		Energy Management Service	• The EMS functionality is key to providing an attractive consumer offer to stimulate uptake of HEMS • A common functional specification and interoperability standards will facilitate widespread roll-out EMS functionality can be developed to enable real time control of consumer loads: • Enables maximisation of the contribution of DG and DR to network balancing • Reduces the constraints on increased penetration of low carbon technology Reduced losses and improved security of supply

6 Criteria and proposed priority technologies / systems

In this section we propose, as requested by the ETI, a set of criteria that could be applied as the basis for down-selecting from the longer-list of technologies provided in the preceding section to a short-list for more detailed assessment. The proposed technologies are shown in Figure 9.

The ETI has asked the Consortium to propose a set of criteria to use to select up to four technology development opportunities. We have based our proposed criteria on what we understand the ETI's objectives to be – i.e.:

- To engage in technology development in some capacity so as to accelerate deployment in the market
- where an ETI financial investment is contemplated, the scale per investment is low millions of pounds
- To identify technologies that, when deployed at scale, can deliver a significant CO_2 saving for the UK
- Identify technologies that can be demonstrated in field trials in three to four years.

There are certain tensions between these objectives. For example, the technologies that provide the greatest opportunities for the ETI to engage are likely to be at lower TRL, with significant gaps to overcome. Engagement in these technologies is unlikely to deliver near term financial returns. There are several technologies that have the potential to deliver large CO_2 reduction and that could be demonstrated in the near term, but the opportunities for the ETI to engage are limited as the technologies are at advanced stages of maturity.

The ETI will have a much clearer understanding of the relative priority of these objectives and, as a result, may assess technologies differently against certain criteria or apply a different weighting to the criteria when making the down-selection. We have assumed that, within the low carbon technology space, priority should be given to those technologies that can make a significant contribution to CO_2 emissions reduction and provide an opportunity for the ETI to engage (e.g. potential to offer commercial benefits, be demonstrated on a timescale consistent with SSHP Phase 2 demonstrations).

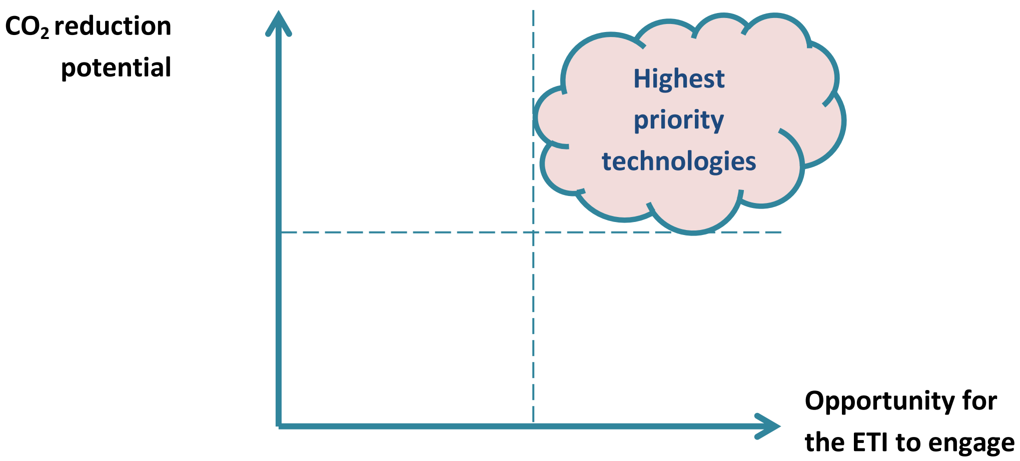


Figure 9. Mapping of highest priority technologies

Table 12, Proposed criteria for the ETI to apply to select down-select to a limited number of priority technologies from the short-list

CRITERIA	DETAIL
Carbon reduction impact	Carbon intensity of heat produced
	Implications of decarbonising grid electricity mix of carbon intensity of heat
	Role in enabling smart system (how significant is its impact on carbon reduction / cost-effectiveness of other low carbon heating technologies?)
Cost-effectiveness	Cost-effectiveness of carbon reduction at current / expected market entry prices
	Potential cost-effectiveness accounting for realistic technology cost curves
	Impact on fuel poverty
Potential for deployment at Scale	Applicability of the technology to the UK market (building stock, energy infrastructure)
	Resource constraints
Barriers and market constraints	Severity of demand-side barriers to achieving technical potential
	Severity of supply-side constraints
	Potential for policy / regulatory influence
Technology maturity	Technology Readiness Level
	Timescales for commercialisation
Alignment with the ETI objectives	Likely opportunity for the ETI to engage with technology development
	Potential readiness for a field trial in a 3 – 5 year period
Other benefits to UK plc.	Opportunity for UK manufacturing / service sector
	Jobs creation potential
	Security of supply

On the basis of the technology short-list, these criteria and the supporting evidence presented in this report, the following technologies are recommended to the ETI for further investigation. This short-list has been identified following a scoring of the short-listed technologies against the proposed selection criteria (see Appendix G). As noted above, the ETI may attach different levels of priority to the various criteria, resulting in a different scoring and different technology selection.

- Community scale biomass / biogas CHP
- LV Voltage control technologies
- Energy Management Services and advanced network controls systems.

Technical considerations would need to include, in addition to technology specific factors, systems design (where "system" includes building fabric, controls, management, storage, heat generator, heat emitters, etc), optimisation and packaging. Non-technical factors would also need to be considered including: supply chain coordination, installer competency, sale / lease and energy services models, finance packages and system (as oppose to product) efficacy guarantees, etc. For the community scale biomass/biogas CHP, the fuel supply chain and accreditation of fuel to be from sustainable sources are additional factors which would need to be investigated.

In addition to the technologies identified above, assessment of the short-listed technologies on the basis of the proposed criteria also highlights hybrid ASHP, High Density Thermal Storage (HDTS) and HEMS / HAN as high priority technologies. These technologies were pre-selected by the ETI for assessment in Task 5a. The analysis undertaken has validated the pre-selection of these technologies, which in the Consortium's view merit further consideration (beyond the scope of the Task 5a assessment).

7 Next steps

In response to the ETI’s request, the Consortium has considered what further work could usefully be carried out as a follow-on from this Task. As part of the further work to address the priority technology gaps, the Consortium recommends the following work:

(i) a more detailed carbon performance analysis to compare the residential stock heating carbon footprint with where that footprint needs to be in order to be consistent with a given carbon emissions reduction trajectory – i.e. would the priority technologies, developed and deployed at scale make such a contribution to the decarbonisation of residential heating as to be consistent with the 2050 carbon emissions reduction target and decarbonisation trajectories;

(ii) re-scope Task 5b, incorporating learning from Task 5a and the ETI’s comments; identify technology development priorities, e.g. costs to consumer (dependent on business model), performance enhancement, functionality preferences, supply chain factors; identify potential development partners / suppliers; propose options for the ETI to become involved to accelerate deployment; assess technology/system maturity, the scale of development costs and likely timeframe for development and deployment; likely benefits to the ETI; and

(iii) with the ETI and potential partners, create project development briefs (ie Systems Road Maps and Technology Road Maps).

8 Appendices

Appendix A – Host Space Environments

A.1 House types

The six HSEs have been constructed from general principles and publicly available data to be representative of over 75% of the national housing stock. The house types in each HSE are also representative of the stock which we would expect to find in specific locations. Thus, for example, the urban HSEs would contain more flats and terraced dwellings than the rural HSEs where there are more detached houses. Using the standard source literature (e.g. national housing statistics, the English House Condition Survey, etc), the actual dwelling types and their respective proportions, conditions and densities in each of the six HSEs can be reliably established. The housing stock has been classified into 12 house types, each of which is described by the following characteristics:

- main heating fuel (gas, electricity)
- dwelling type (detached, semi-detached, terraced, flats)
- standard of energy efficiency (good, poor)
- wall construction type (cavity wall insulation, unfilled cavities and solid wall).

Depending on the range of parameters, HSEs can be made as coarse grain/simple or as fine grain/ sophisticated as is required or can be accommodated within given time and budget envelopes for investigation. The granularity can range from a grouping of house types according to certain parameters (built form, location, etc.) to GIS mapping / postcode representation of actual districts in real cities and detailed consideration of occupancy factors, heat networks, etc. They can be limited to considering heat provision or can be made more sophisticated to include consideration of, for example, export of solar generated electricity, electricity storage, etc. Within the available budget and time envelopes, the Consortium has devised the six HSEs with sufficient granularity to enable reasonable and robust conclusions enable worthwhile recommendations to be drawnmade about the performance of technology packages and the identification of technology and system gaps for further assessment. In any future pieces of work, the HSEs could be designed for and used at increasing degrees of granularity and sophistication to address wider issues and increasing complexity.

The HSE granularity used in this Task provided a sufficient basis upon which to assess technology packages, identify technology gaps and make recommendations to the ETI on which technology areas would be worthwhile assessing further for possible ETI engagement.

A.2 Carbon performance assessment

For each HSE, the Consortium determined a representative baseline of energy efficiency and carbon performance for each dwelling type against which the impact of plausible technology packages was assessed. Software based on SAP / BREDEM (as used for Building Regulations compliance testing) was used to estimate the carbon emissions associated with each dwelling type and each HSE for the base case – i.e.: as found with little or no improvements; with best available technology packages (with current products); and then with packages incorporating new and emerging technologies. The Consortium explored how these technologies could be sensibly packaged to get the necessary functionality.

A.3 Non-domestic buildings

The impact of non-domestic buildings on HSEs and the networks serving them has been addressed at a level of detail appropriate to the degree of granularity used to construct the six HSEs for Step 1. The amount of non-domestic space has been determined in relation to the area of domestic buildings using a residential to non-residential area ratio derived from land-use statistics (Generalised Land Use Database). This database provides information on the usage of land area within each Census Ward in England and Wales. Wards have been classified on the basis of rural / urban character and the density of developed area, in order to identify characteristic land use ratios for areas of different types. The numbers of non-domestic buildings have been estimated from the area of non-domestic land use by using Valuation Office Agency figures for the number of premises and non-domestic floor space at local authority level. The typical mix of non-domestic usage class (e.g. commercial offices, retail, education etc.) has also been determined from the Valuation Office Agency data. This allows typical heat and electricity loads to be assigned to the non-domestic buildings within each of the HSEs. Consideration of non-domestic buildings is particularly important when heat network solutions are being explored. They can serve as "anchor heat loads" and their demand profile can help "smooth out" the peaks commonly associated with domestic heat demand (i.e. increase the diversity of demand).

The Consortium has taken into account in its analysis the ways in which heat generating / supply technologies interact with heating system controls and the building fabric; and the way in which aggregated profiles could interact with the networks. Broad assumptions have been made about occupancy patterns, internal temperatures, heat demand profiles and consequential impacts on local networks.

Characterisation of the 12 house types, baseline energy consumption and CO_2 emissions

	Fuel	Dwelling type	Condition	Wall construction (% of house type)			Number of houses in UK stock	Cum. % of stock	Heat load (kWh)	Elec load (kWh)	CO_2 ($kgCO_2$/yr)
				CWI	CWU	SWI					
1	GAS	Detached	G	52%	38%	11%	4,231,699	15.9%	18,191	4,074	5,497
2	GAS	Semi	G	41%	38%	21%	4,403,293	32.4%	18,191	4,074	5,497
3	GAS	Detached	P	39%	41%	19%	873,342	35.6%	24,963	4,158	6,756
4	GAS	Semi	P	28%	37%	35%	1,008,517	39.4%	24,963	4,158	6,756
5	GAS	Terrace	G	37%	31%	32%	7,084,273	66.0%	13,036	3,080	3,946
6	GAS	Terrace	P	22%	27%	51%	1,983,577	73.4%	19,557	3,152	5,244
7	GAS	Flat	G	36%	33%	31%	2,740,089	83.7%	6,875	2,510	2,489
8	GAS	Flat	P	16%	30%	54%	724,219	86.4%	10,568	2,562	3,229
9	ELC	Terrace	G	40%	30%	30%	445,041	88.1%	12,467	3,319	7,263
10	ELC	Terrace	P	18%	19%	63%	122,922	88.5%	20,350	3,391	10,923
11	ELC	Flat	G	48%	35%	17%	1,443,066	93.9%	5,095	2,753	3,611
12	ELC	Flat	P	14%	41%	46%	243,038	94.9%	8,507	2,697	5,155

A.4 Six HSEs – descriptions

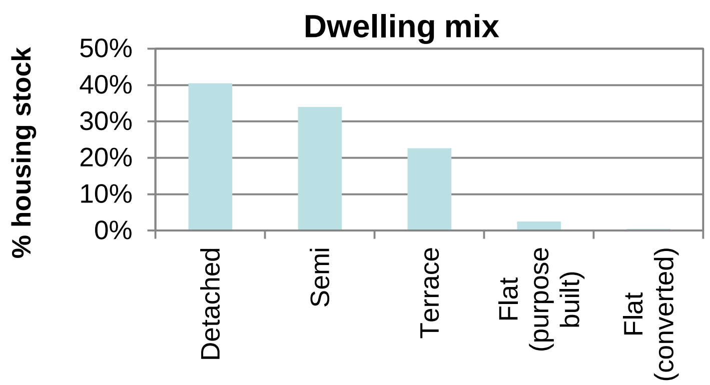
In the following pages the six Host Space Environments will be characterised, providing their description, the distribution of house types (detached, semidetached, terrace and flats) and an example of them.

The scale, non-resi / resi ratio and percentage of house types across HSEs is also provided in two additional tables.

HSE 1: rural village

Description

Typically comprise small settlements of a few hundred to a couple of thousand dwellings, with local amenities such as small retail, supermarket, pubs, restaurant, school, community centre surrounded by agricultural land or other green space. Potentially off-gas.



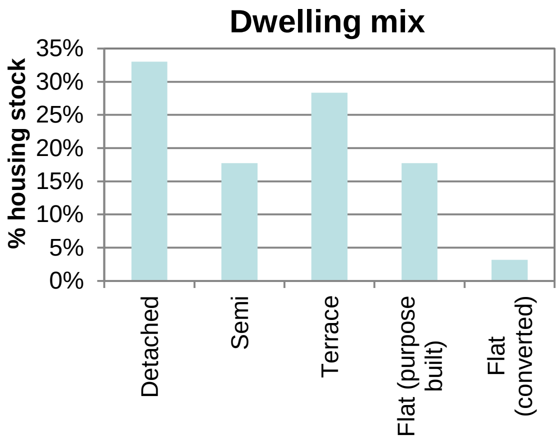
Example: Cottesmore (Rutland, East Midlands)

- Household count: 1,340
- Residential area fraction: 0.005
- Non-domestic / residential ratio: 0.68
- Dwelling types: predominantly detached and semi-detached

HSE 2: market town

Description

Comprises larger communities of a few thousand dwellings with a town centre, rural in nature, surrounded by agricultural / green space



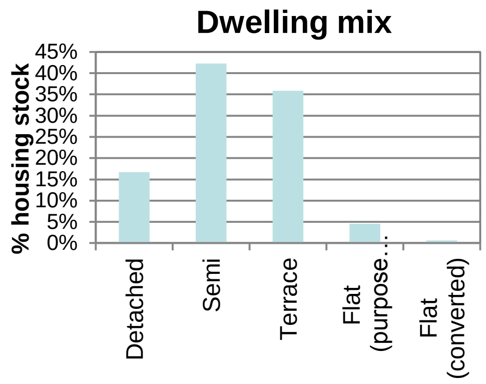
Example: Warwick South (West Midlands)

Household count: 4,034
Residential area fraction: 0.04
Non-domestic / residential ratio: 1.13
Dwellings: Mixed (all house types likely to be present)

HSE 3: suburban residential (without a centre)

Description

Typical of edge of town housing estates comprising a few thousand dwellings. Homes have gardens but limited other green space. The non-domestic area is limited to small shops, pubs, schools, etc.



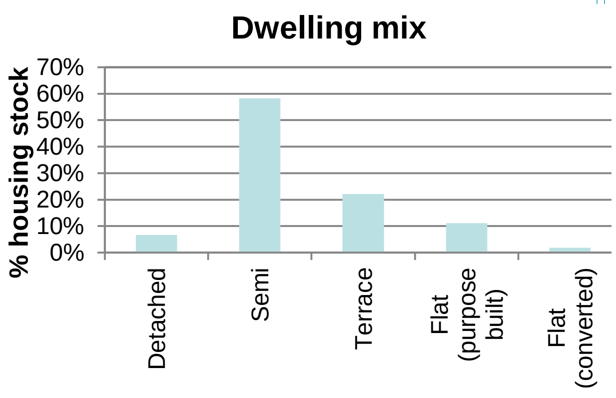
Example: Hoddesdon North (Broxbourne, East of England)

Household count: 2,364
Residential area fraction: 0.1
Non-domestic / residential: 0.09
Dwellings: dominated by semis and terraces, some detached

HSE 4: suburban centre

Description

Typically has a housing density similar to that found in the suburban residential space but in proximity to a local centre, including larger retail, leisure and office uses.



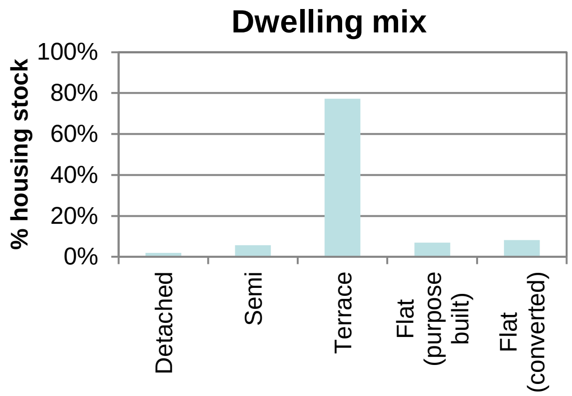
Example: Eccleshill (Bradford, Yorkshire & Humber)

- Household count: 5,700
- Residential area fraction: 0.1
- Non-domestic / residential ratio: 0.4
- Dwellings: dominated by semis and terraces, some detached

HSE 5: urban residential (without a centre)

Description

Comprises a few thousand terraced houses and flats typical of inner-city residential spaces. The density of buildings is high with green space limited to parks / allotments.



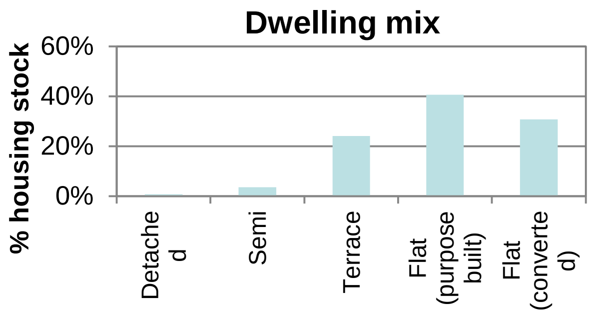
Example: Easton (Bristol, South West)

- Household count: 5,008
- Residential area fraction: 0.2
- Non-domestic / residential ratio: 0.25
- Dwellings: Largely terraced housing

HSE 6: urban centre

Description

Has a density similar to that found in HSE 5. Dwellings mainly comprise flats (purpose built and conversions) and terraced housing. In close proximity to the residential areas are a diverse set of non-domestic buildings including commercial offices, large retail, leisure, pubs, restaurants etc.



Example: Fulham Broadway (Hammersmith & Fulham, London)

- Household count: 4,847
- Residential area fraction: 0.2
- Non-domestic / residential ratio: 0.6
- Dwellings: Flats and terraces

A.5 Detailed HSE data

Detailed data on the construction of the HSEs is provided in the tables below.

Scale, non-resi / resi ratio and percentage of house types across each HSE:

HSE	Scale (No. dwellings)	Non-resi to resi fraction	Detached	Semi	Terrace	Flat
1	200	0.5	45%	35%	20%	
2	1,000	0.5	35%	20%	25%	20%
3	3,000	0.1	15%	50%	35%	
4	3,000	0.4		60%	40%	
5	5,000	0.5			80%	20%
6	5,000	1.0			30%	70%

House type split across each HSE (12 house types characterised by fuel, type and insulation condition):

	1	2	3	4	5	6	7	8	9	10	11	12
	GAS	GAS	GAS	GAS	GAS	GAS	GAS	GAS	ELC	ELC	ELC	ELC
	Detached	Semi	Detached	Semi	Terrace	Terrace	Flat	Flat	Terrace	Terrace	Flat	Flat
HSE	G	G	P	P	G	P	G	P	G	P	G	P
1	37%	28%	8%	7%	15%	4%	0%	0%	1%	0%	0%	0%
2	29%	16%	6%	4%	18%	5%	11%	3%	1%	0%	6%	1%
3	12%	41%	3%	9%	26%	7%	0%	0%	2%	0%	0%	0%
4	0%	49%	0%	11%	29%	8%	0%	0%	2%	1%	0%	0%
5	0%	0%	0%	0%	59%	16%	11%	3%	4%	1%	6%	1%
6	0%	0%	0%	0%	22%	6%	37%	10%	1%	0%	20%	3%

HSE characteristics, energy demands and CO_2 emissions.

									Loads (MWh)						
									Resi			Non-resi			
HSE	Scale (No. dwellings)	Non-resi to resi fraction	Detached	Semi	Terrace	Flat	Non-dom floor area (m2)	Non-dom connections	Heat load (MWh)	Elec load (MWh)	CO2 emissions (tCO2/yr)	Heat load (MWh)	Elec load (MWh)	CO2 emissions (tCO2/yr)	
1	200	0.5	45%	35%	20%		9,920.00	24	3,646	795	1,081	1,587	744	718	
2	1,000	0.5	35%	20%	25%	20%	47,100.00	113	16,000	3,792	5,013	7,536	3,533	3,410	
3	3,000	0.1	15%	50%	35%		25,080.00	53	49,770	11,003	14,896	4,013	1,881	1,816	
4	3,000	0.4		60%	40%		85,680.00	182	50,699	11,334	15,288	13,709	6,426	6,202	
5	5,000	0.5			80%	20%	176,500.00	450	58,068	15,459	19,695	28,240	13,238	12,777	
6	5,000	1.0			30%	70%	335,500.00	855	43,579	14,249	17,149	53,680	25,163	24,287	

Appendix B – Technology deployment scenarios

The detail of the scenarios used for the analysis is presented in the table below.

	Primary non-electric source			
Electrification level	**1- Gas**	**2 - Solid**	**3 - District**	**4 - Mixed/None**
1 - Very low		**Low elec.** • 63% community scale biomass CHP • 5% individual building scale biomass boilers • 24% SE mCHP • 7% power station heat off-take DH • 1% geothermal heating		
2 - Low	**High mCHP (No DH)** • 90% FC mCHP • 10% resistive heating	**High DH** • 70% community scale biomass CHP • 10% individual dwelling biomass boilers • 20% GSHP		
3 - Medium	**Mixed** • 33% community scale biogas CHP • 20% FC mCHP • 10% SE mCHP • 30% GSHP • 20% power station heat off-take DH			
4 - High		**High HP** • 50% ASHP • 30% GSHP • 20% community • scale biomass CHP		**High HP (No DH)** • 60% ASHP • 30% GSHP • 10% resistive heating

Appendix C – Key enabling technologies

Heat pump system integration issues

HEATING WATER LOOP INTEGRATION

- **match water temperature requirements and ASHP capabilities**
- **match building heat demand to ASHP capacity**
- **provide high enough flow rate –** ASHP requires higher flow rates than a conventional boiler
- **provide balanced flow in heating water loop –** same level of temperature required in all rooms

ENERGY MANAGEMENT SYSTEM INTEGRATION

- **Optimised HP controls** –HPs equipped with control system based on air temperature measurement at least and internal thermostat ideally
- **Communication between HP and grid –** Design of systems incorporating dynamic price signal input
- **Compatibility with communication protocols –** Recommended to purchase controls from the heat pump manufacturer to avoid integration issues
- **Integration with thermal storage**–Enabling grid flexibility (by decentralised energy generation or peak shaving opportunities) triggered by suitable incentives

FC mCHP system integration issues

HEATING WATER LOOP INTEGRATION

- **match water temperature requirements and LT PEM FC capabilities**
- **HT PEM FC and SOFC suited with existing heat distribution systems** (i.e. conventional radiators)

ENERGY MANAGEMENT SYSTEM INTEGRATION

- **Optimised mCHP controls to minimise operating costs and maximise CO_2 savings –** Different control strategies (i.e. heat/electricity/least cost led), have different implications for each FC mCHP technology (Appendix)
- **Integration of mCHP and thermal storage –** Optimal integration and design of FC mCHP and thermal storage is important to: a) maximise operational hours and to minimise on-off cycles and b) sell demand side response services and arbitrage opportunities
- PEMFC: Thermal storage integration with electricity led PEMFC is of remarkable importance to avoid heat rejection in times of high electricity-low heat demand profiles
- SOFC: When integrated with thermal store can be run throughout extended periods of time avoiding on-off cycling that causes thermal stress
- **Integration with electricity storage**
- SOFC: Integration of electricity storage with SOFC could allow to the system to have a fast response to load following

C.1 Energy storage

Building level scale thermal store

Building-scale thermal storage using high density storage systems has been extensively covered in WA1 Task 5a. Please refer to the Task 5a report for details.

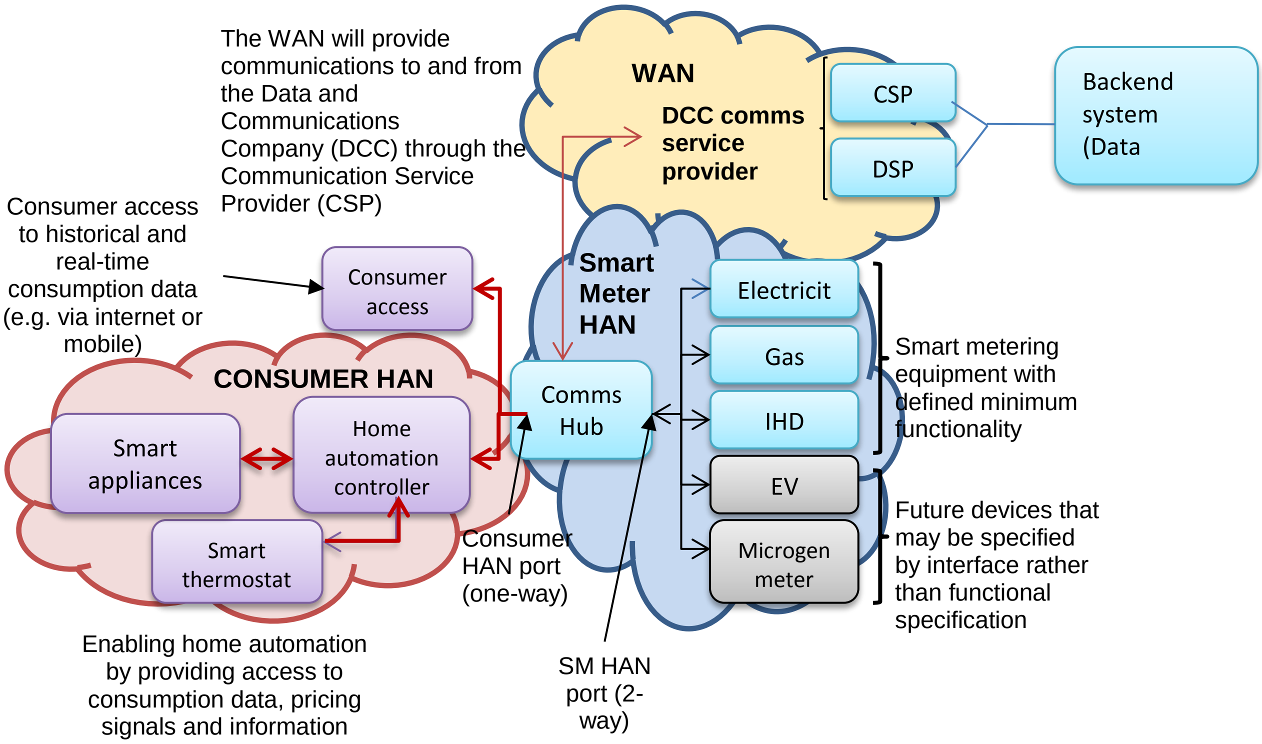
Large scale thermal store

Several thermal storage types are available to integrate at a larger scale. A shorter description of their state of development is provided in the table below.

Underground Thermal Energy Storage (UTES)
Two types: Borehole TES and Aquifer TES - Applications: Systems with at least 100 kW energy requirement (mainly heat) and storage volume > 10,000 m^3 Potential to store waste industrial heat (Rehau Ltd.) - System components 1. Heat source (solar thermal panels: the most common, solar absorbers: lower T than solar thermal, but more cost effective, waste heat from CHP/industry) 2. Thermal Storage 3. Heat Distribution (and additionally short term buffer tank, GSHP and peak load boiler)
PCMs
They tend to progressively lose stored thermal energy, and so are not viable candidates for long-term heat storage
ZEOLITES
- Applications: Industrial installations and small CHPs for larger residential buildings - Can store 3-4 times the amount of heat that water - Good for seasonal heat storage - Low TRL: Prototype demonstration (Fraunhofer institute developing 750 L prototype) - Further development undergoing towards reduction of production costs and tailoring to different applications
LARGE WATER TANKS
- Deployed in countries with large district heating network (e.g. Avedøre- Copenhagen, large scale district heating scheme integrated with two large water tank stores of 20,000 m3 which provides heat and electricity to ~200,000 and 1.3 million households, respectively)

C.2 Control strategies

Controls can be implemented at a variety of levels – from the individual room-level, to the whole house and upstream of the house (e.g. infrastructure to enable external access to data, remote control or to aggregate buildings into a coordinated control strategy). The diagram below illustrates simplistically how technologies within the home might be integrated into internal and external control / communications systems.



A number of control strategies can be envisaged that provide differing kinds of functionality, from managing thermal energy demand better within the home to enabling external third-parties to remotely control household appliances as part of a strategy to effectively manage the wider energy system. A summary of the main options for control strategy and the associated barriers is presented in the table below.

	Area	Smart Control	Equipment	Assumption	Benefit	Barriers
1	Room	Manage thermal Demand by optimising thermal usage	Heating Source Thermostat Human sensor	a) Thermostats and human sensors are installed in all rooms and remotely gathered b) Heat for each room will be provided through valves from central heating c) Thermo valves in each room are independent and can be controlled remotely	The optimisation of thermal usage reduces the total thermal demand of a house.	a) Communication between sensors and controllers. (A suitable communication may vary. (e.g. PLC, Zigbee, wifi)
2	House	Manage Electricity Demand by optimising electricity usage	Electric Equipment (e.g. Heat Pump)	a) Thermostats, human sensors and lighting sensors are installed in all rooms and remotely gathered b) Thermo valves in each room are independent and can be controlled remotely	The optimisation of electricity reduces total electricity usage of grid.	a) Communication between sensors and controllers.
3	House	Manage Electricity Demand by optimising electricity usage	- Heat Storage - Heat Source - micro Generation	a) The heat source can be controlled remotely. b) The data of thermal storage can be gathered remotely.	The optimisation of electricity mitigates total electricity usage of the grid.	a) Communication between sensors and controllers.
4	House	Manage Electricity Demand by electricity grid	Electric Equipment (e.g. Heat Pump, mCHP) Heat Storage	a) The heat storage could be a tank for central heating or a battery.	The timely reduction of electricity usage or electricity generation could mitigate detoriation of the grid.	a) O&M - Up to date software for demand response to controller. Communication setup may need professional. b) User acceptance. Simple control for consumer. (e.g. one push button for the type of control selection, allow opt-out from DR at certain point)
5	House	Manage Electricity Demand by	-Electric Equipment	a) A smart meter could receive current tariff	The installation cost is relatively cheap.	a) Motives of consumers may be different and may not reduce electricity usage.

		consumer will	Heat Storage			
6	Community (Electricity Grid)	Manage Electricity Demand by optimising electricity usage	- Heat Storage - Heat Source	a) The community generates their own electricity for their use. b) The electrification of heat source proceeds c) Equipment for receiving demand response signals is widely installed.	Renewable energy generated will be used. Voltage faults due to high demand may be reduced. The construction of backup power plant for intermittent renewable energy may be hold-down. Prevention of black-outs	a) Communication between a DR application and dwellings.(b) Incentives for users participating DR is not yet defined. c) Consumer acceptance of comfort level of temperature d) Uncertainty on who is responsible for paying the incentives

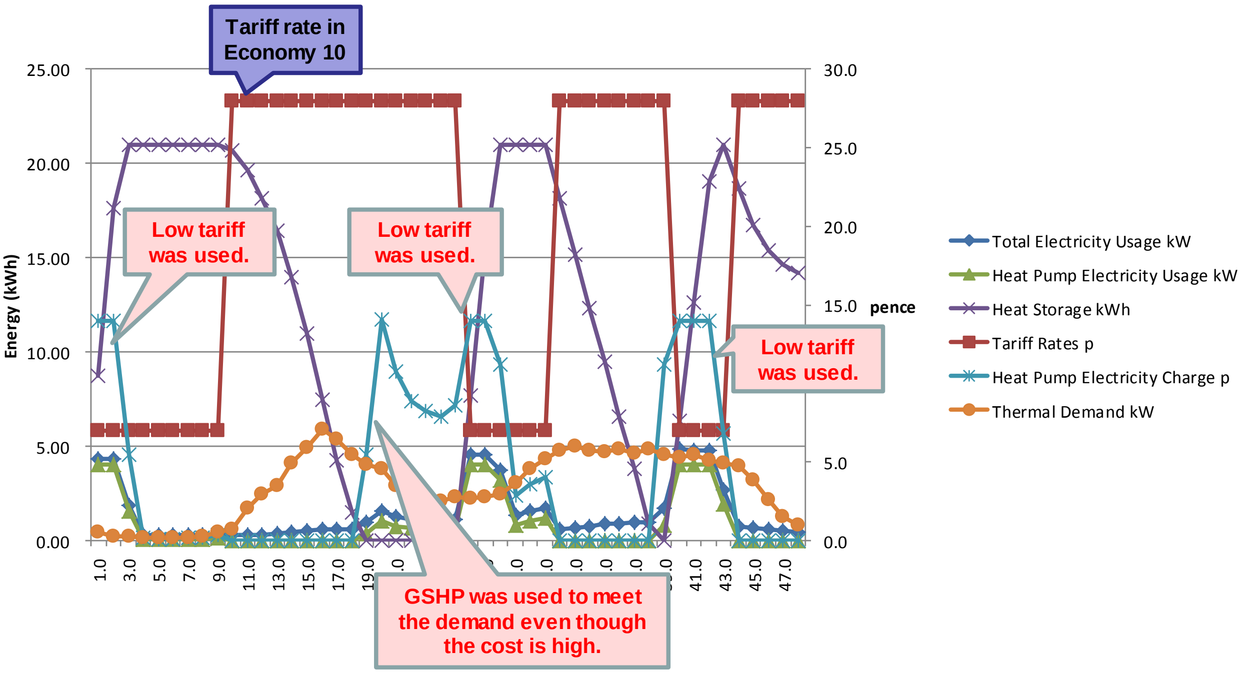
C2.1 Building level control strategies:

The main barriers identified for control systems at the house level are as follows:

- Relatively high costs of the components for more sophisticated controls (e.g. individual room control, control of specific appliances)
- Lack of incentives for the homeowners (main drivers are on-peak electricity tariffs, desire for home automation, potential security benefits)
- Lack of standardised protocols for communication between sensors and controllers (e.g. HEMS).

One of the key drivers for control systems for home-owners will be to minimise energy costs. Control of the heating appliance to take advantage of variations in energy prices is a means of achieving this. Energy storage will be essential to enable these control strategies while also ensuring that the thermal demands of the home are met at all times. An analysis has been performed to assess the potential for thermal storage to enable control strategies that maximise the benefits of varying energy prices.

In the example below, an analysis is shown of the operation of a ground source heat pump in a detached house (House type 1). The dwelling is assumed to have a thermal store (TES) available, sized to store three hours of the peak heat load of the dwelling (in this case, this is a 21 kWh thermal store).

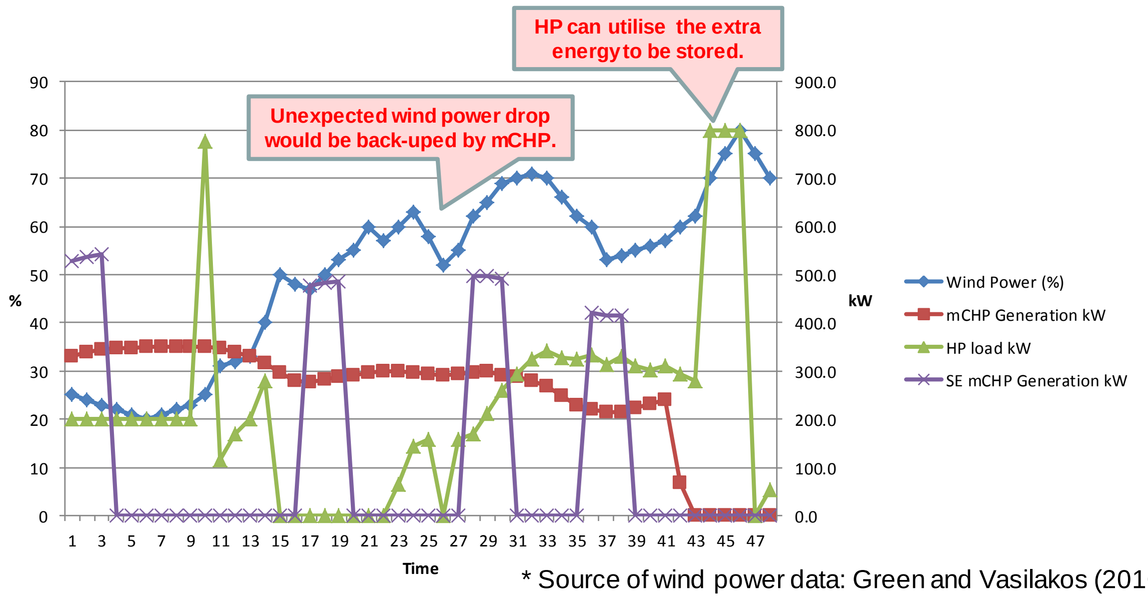


The TES is charged overnight using low-tariff electricity (note that the x-axis in this figure represents the half-hourly time period). The stored heat is drawn during the morning heating peak such that it has become depleted by mid-morning and the heat pump runs again. In the case of an Economy 10 tariff, which has a lower price tariff in the early afternoon, the TES can be largely filled using off-peak electricity, in advance of the late afternoon / evening peak heat demand (note some operation of the heat pump during the morning peak period has been necessary). In the case of an Economy 7 tariff, it would not have been possible to store sufficient heat to avoid usage of peak price electricity under the assumed TES capacity.

If the TES consisted of a traditional hot-water tank, the volume of store required to provide this thermal capacity is dependent on the ‘delta T’, i.e. the range of temperature that the storage medium (in this case water) is raised through. Assuming that the heat pump is coupled with a system of low temperature radiators, a delta T of 10°C might be achieved. On this basis, a very large volume of hot-water storage would be required, which could not be easily accommodated in most homes. This demonstrates the potential benefit of higher density thermal storage mediums in combination with heat pumps, in order to facilitate more optimised control strategies.

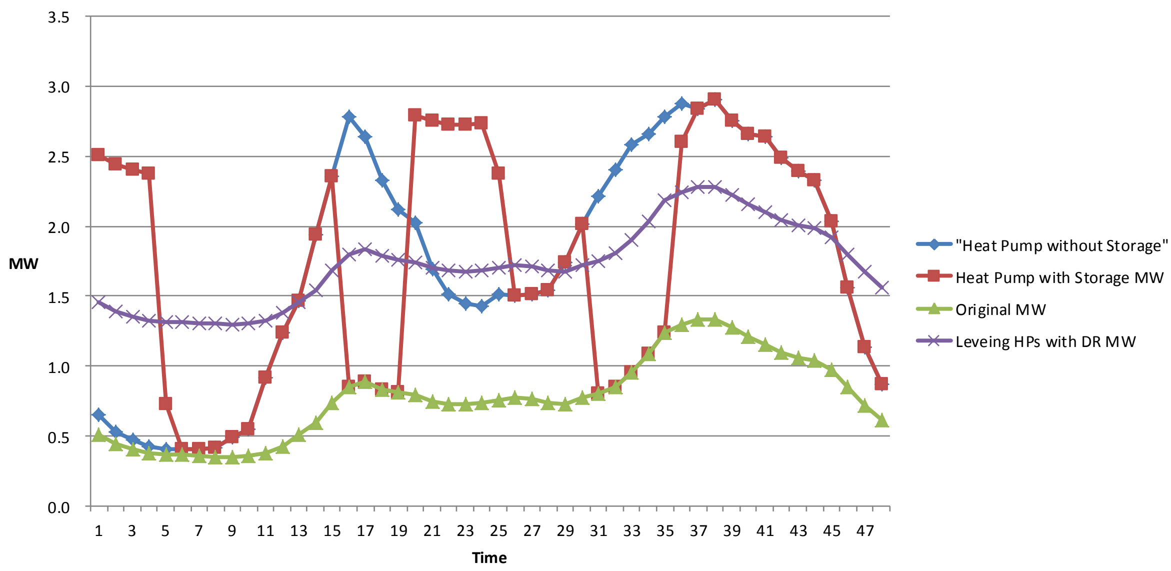
C2.2 HSE level control strategies:

Control strategies may also be implemented to provide demand side response services, particularly in relation to heat pumps and mCHP systems. Energy supply companies may wish to call on demand side response services to mitigate the impact of technology deployment on local electricity networks, to control demand to utilise the electricity generating capacity most cost-effectively (e.g to operate at times of surplus wind generation) and to use distributed generation to support the network or avoid use of inefficient generating plant. In the figure below, examples are provided of how mCHP could be used as a reserve at times when wind output drops and, conversely, how heat pumps could be operated to utilise electricity at times of high wind availability. In each case, the scheduling of the thermal plant meets the thermal demand of the dwellings, given the assumptions regarding TES availability.



* Source of wind power data: Green and Vasilakos (2010)

The impact of widespread heat pump deployment on distribution networks is a key issue facing distribution network operators and energy policy-makers. The potential cost impacts of high heat pump deployment scenarios and potential solutions to mitigate these impacts are discussed in more detail in Section 3.3.2. However, the use of demand side response is one of the options for managing the impact of heat pumps and reducing the need for network reinforcement. The potential scale of this reduction in peak load growth that can be achieved via an optimised demand side response strategy is shown in the diagram below, compared to the case when heat pumps are installed without storage or are installed with storage but operated in an uncontrolled way (the figure is based on analysis of the Urban Centre HSE and High HP technology deployment scenario).



Achieving this kind of impact through demand side response relies not only on installation of heat pumps coupled with adequate thermal storage (thermal storage volumes for each house type as shown in the Figure above are assumed in this analysis), but also on widespread participation by consumers. This could be through pricing signals[6] or direct load control.

There are a range of barriers to the use of control systems to implement wider demand-side response objectives:

- Consumer acceptance, e.g. Time of Use / dynamic pricing tariffs, direct load control etc.
- Lack of an economic driver for householders to participate in demand side response schemes
- Cost associated with the control, communications and data-handling infrastructure.
- Lack of standardisation of communication protocols, within the homes and between the home and the demand response application (i.e. the HEMS controller or cloud-based HEMS service)

[6] Reference to evidence on the effectiveness of price signals

Appendix D – Network Solutions

D.1 Distribution network control technologies

Mitigating impact of integration of low carbon demand and generation technologies in local electricity distribution networks

Integration of low carbon demand technologies (Heat Pumps or Electric Vehicles) and generation technologies (e.g. micro-CHP or PV generation) in distribution networks may cause excessive voltage drop or raise effects or thermal overloads of distribution circuits. These can be alleviated through or traditional network reinforcements (asset replacement) or through various emerging technologies, such voltage regulation technologies, grid storage technologies, power electronics technologies for distribution networks and demand side management. Some of these technologies can mitigate multiple problems and their effectiveness will be very specific to the local area, level of penetration of low carbon load / generation technologies, design characteristics of local distribution networks.

Voltage regulation technologies

Traditionally, *voltage regulation* in *real time* in distribution systems is achieved through the application of 33kV / 11 kV on-load tap changers located in primary substations. These on-load tap changers can alter the transformer turns ratio in a discrete number of steps changing the secondary voltage from -15% to +15%. Integration of low carbon technologies at consumer premises may cause voltage deviation beyond acceptable limits triggering network reinforcements. Alternatively these can be mitigated through various emerging technologies that provide voltage control closer to customers' premises to avoid overvoltage caused by increased generation and under-voltage on feeders with increased demand. These technologies include traditional or solid-state distribution transformer (11kV/0.4kV) or in-line voltage regulators (traditional autotransformer based power electronics based) inserted in 11kV or 0.4kV distribution networks that can regulate voltage 'downstream' from the connection point. Also, voltage regulators that are sometime used at consumer premises for energy efficiency purposes may be used to maintain the voltage within the statutory limiters.

The solid state transformer is a power electronic device that replaces the traditional transformer at 50 Hz using the next modules [She et al.2012]; the 50 Hz AC voltage is changed by means of power electronics to high frequency in the range from several to tens kHz and then step up or step down by means of a high frequency transformer, then is returned to 50 Hz AC voltage by other power electronic module. In addition of the reduction of volume and weight by using a high frequency transformer the SST brings, according the topology, possible features such as load voltage regulation, bidirectional power flow control, voltage sag compensation, harmonic isolation, fault current limitation. However, the efficiency of the traditional transformer is higher when compared with SST, although the additional functionalities of SST need to be considered for a fair comparison. There is a growing interest in conducting demonstration projects to fully understand the functionality and costs.

In-line voltage regulator, an autotransformer equipped with OLTC installed in LV and/or HV circuit, can regulate voltage at 'downstream' connection points. The in-line voltage regulator can be installed in a substation or along the feeder, depending on the network characteristics, primarily length and the level of penetration of different low carbon generation and demand technologies. This technology has a significant potential although it has not been fully demonstrated. Interest expressed with LCNF programme.

Conservation voltage reduction techniques, can *reduce energy consumption* and improve energy efficiency by constantly lowering in a controlled mode the distribution network voltages to almost the minimum permitted limits. These technologies can also be used to mitigate voltage problems in distribution networks. Significant amount of technology deployed for energy efficiency purposes, while the opportunity and scope for network support not fully understood.

Voltage reduction based frequency control has been historically used for voltage reductions demand control when this is required to support *frequency regulation at* the national level. The introduction of voltage regulation technologies such as voltage regulators, OLTC transformer and solid-state transformer can enhance this service without affecting the quality of voltage supplied. This will be particularly relevant in systems with significant penetration of intermittent removable generation. No evidence of demonstration, although some of these concepts under investigation under LCNF programme.

Network Storage

There are several storage technologies that can be used for mitigating distribution network overloads and voltage problems [Arup 2011]. Some of them are well known battery base technologies as Sodium Sulphur (NaS) Batteries, Flow Batteries, Lead Acid Batteries, Lithium ion (Li-ion) Batteries and Sodium Nickel Chloride Batteries; emerging technologies include Pumped Heat Electricity Storage, Flywheels, Superconducting Magnet Energy Storage and Super Capacitors. The economic case of implementing these storage technologies will be driven by the value they may bring and their cost.

Hot Water Tanks

Hot water (HW) storage cylinders are present in 13.7m UK households [ERP 2011]. A 100 litres cylinder, which has water heated above 50°C, could store about 6kWh with a possible loss, of around 1.5 kWh in 24 hours according to [SAP 2009]. This can be used to re-distribute operation of heat pumps and hence manage distribution network constrains.

In some other jurisdictions, large hot water tanks are installed to support operation of heat networks that may be run by large-scale heat pumps.

FACTS and Power Electronics for Distribution systems

Soft Normally Open Points

Normally distribution system can have a radial or a meshed configuration, but by placing soft normally-open point (SNOPs) which are power electronic devices installed in place of a normally open point in a medium voltage distribution network [Bloemink and Green 2010], a flexible hybrid configuration is constructed which allows control of active and reactive power flows between each end point of its installation sites, power transfer between feeder lines and isolated disturbances faults between feeders. When some appropriated devices and controllers are incorporated, these features are extended to diminish losses, precise balancing of main feeder currents, reactive power compensation and electric storage. Role and value of this technology for distribution networks, its cost and actual performance characteristics are not fully understood. There is interest to undertake some of this under LCNF programme.

Static Synchronous Compensator (STATCOM)

A STATCOM comprises a voltage source converter VSC which is connected in shunt to a single node. This device can provide voltage regulation and dynamic reactive power support through the application of power electronics [Bloemink and Green 2013]. The major STATCOM constrain is that cannot exchange real power with the network. Role and value to distribution networks not well understood and is currently investigated under an LCNF project.

Unified Power Flow Controllers UPFC

The UPFC configuration comprises a series and shunt converters connected back to back which are connected via a common dc link [Bloemink and Green 2013]. The series element of the UPFC can exchange real and reactive power due to the presence of the shunt converter. According the capability curve of the UPFC is determined not only by the device ratings, but also by the network topology, constraints, and operating point as well as the device placement. The UPFC can provide active power exchange, reactive power support and post fault restoration as well. The role and value of this technology for distribution networks, and its cost and actual performance characteristics are not fully understood.

D.2 District heating

In the UK, the barriers for district heating network development, where less than 5% of the heat demand is provided by these schemes, are mainly economical and institutional, rather than technical.

Although district heating is common in northern Europe, it has not been widely developed in the UK for several reasons. Firstly, heat distribution networks have high costs associated with them. Structural costs drivers are important in the UK given the mix of its housing stock, small number of high heat density areas with flats and apartments compared to other countries where district heating is successfully deployed, and this fact has hindered a more extended deployment. Development of the state of the art low temperature district heating, which is suitable for areas with lower heat density, could enable the implementation of these schemes in the UK. Secondly, there is a lack of expertise and experience in the supply chain that together with the extensive natural gas network where gas central heating is common, does not make district heating an obvious solution for the UK. Despite these facts, district heating networks could be built in specific locations in which it is more economically feasible, such as where there is a source of waste heat available, in high density areas, or where it replaces electric heating systems. Moreover, community CHP schemes together with thermal stores could offer further benefits such as helping to balance the intrinsically uneven supply of renewable energy sources.

Future directions of DH industry

LOWERING OPERATING TEMPERATURE OF NETWORKS

- State of the art LT distribution (4th generation), provides water at ~55 deg. C
- Customers can be connected to return pipes, which: a) provides low grade heat for space heating and requires additional heat source for DHW inside building but b) ensures lower return T (and higher overall system efficiency)
- Material and installation cost reduction (polymer pipework rather than steel is viable, welding work avoided and transport cost reduction)

COMMUNITY SCALE HEAT STORAGE

- Borehole Thermal Energy Storage (BTES),
- Aquifer Thermal Energy Storage (ATES),
- Phase Change Materials (PCM),
- Large water tanks
- Coupled with community scale CHP and Heat Pumps offers better economics of district heating schemes and enables the balance of uneven supply (e.g. wind). Economic performance is further enhanced by CHP aggregation in VPPs

DEVELOPMENT IN ELECTRICITY MARKET

- Different arrangements to operate energy generation: a) License Lite ; b) Private wire; c) Netting off

COST REDUCTION

- Huge difference in the cost of district heating technology between UK and other European countries, due to:
- *Pipeline costs* higher, as they need to be imported (no UK manufacturer). Potential for 50% price drop from current UK prices if supply chain to provide pipes were developed
- *Contingency estimates* are *greater* than for other technologies given the lack of familiarity with DH networks in the UK

<u>Low temperature distribution (with heat pumps)</u>

- Offers reduction in capital costs, heat losses and thermal stress compared to higher T DH, and enables the use of surplus heat
- Can benefit areas with low densities
- Important to obtain a low temperature return for an efficient performance
- Disadvantage: to deliver the same V of hot water higher volume has to be pumped with the consequent pumping energy implications
- There is an scheme in the UK, Greenwatt Way, in Slough, developing this heat scheme

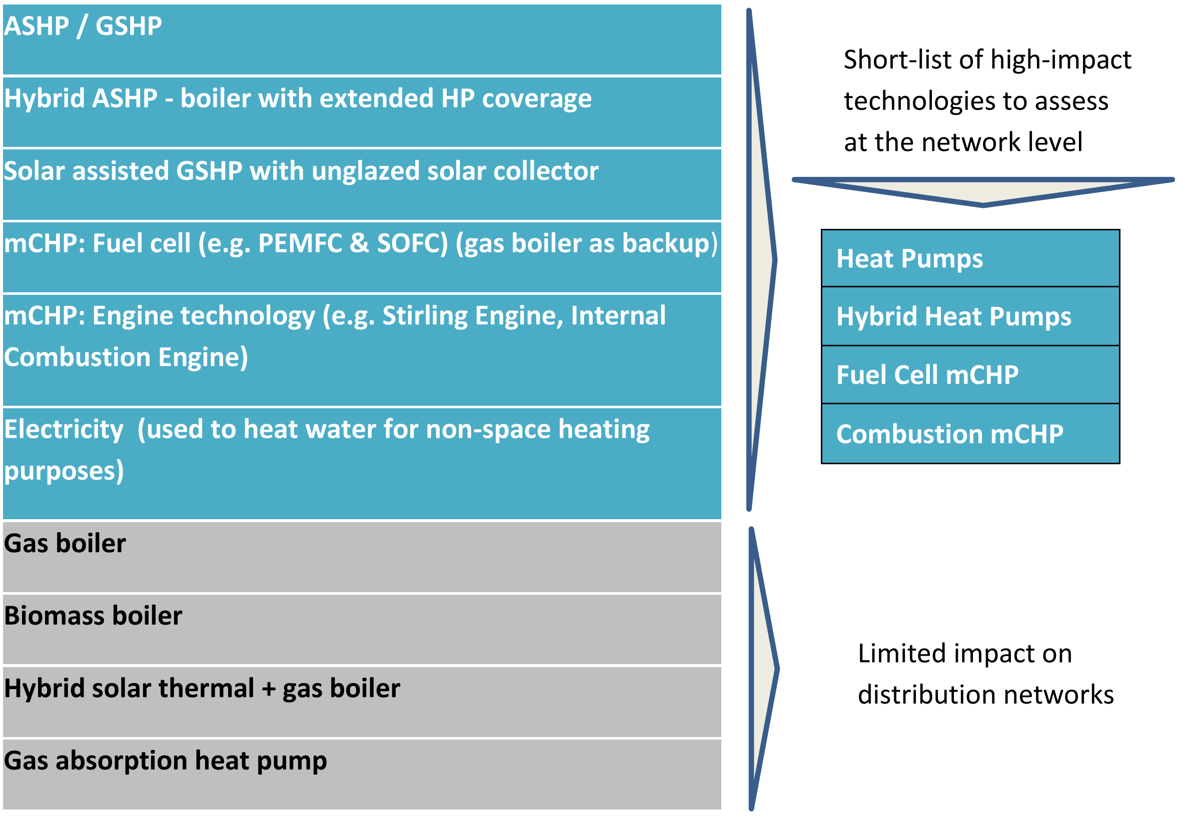
<u>Community-scale storage – wind twinning</u>

- **Storage design** – critical: high variation of energy storage depending on ΔT (e.g. the heat energy in 1 m^3 70/40 deg. C water tank is of 35 kWh and 70 kWh for ΔT of 30 and 60 deg. C, respectively)
- **Steel tanks –** unpressurised tank with direct connection; wide volume ranges (500-50,000 m^3), Deployed in Denmark (e.g. Avedøre-Copenhagen; 2x20.000 m^3

Appendix E – Technology gap analysis

E1. Technology selection criteria

Before carrying out the analysis at the building level, where integration issues, dependencies, barriers and gaps for each technology package were addressed – the suitability of each technology package to different house types was covered under “dependencies” –, the main technologies under the four categories forming the packages (i.e. heat source, heat distribution, energy storage and controls / management systems) were selected in order to cover the set of technologies that could play a role in the decarbonisation of the UK domestic heat system. Of those, a further filtering of the technologies with a potential high-impact in the network, led to the selection of a group of technologies for the impact assessment analysis at the HSE level (see figure below).



For the elaboration of the packages, a collection of sensible combinations of heat sources, heat distribution systems and storage with different levels of sophistication **–** from technically advanced packages at the moment (e.g. FC mCHP with back-up boiler, low temperature radiators and electricity and HDTS) to more conventional systems (e.g. gas combi boilers coupled with conventional radiators with no space available for hot water tank) – was chosen in order to have a representative set of technology packages likely to be relevant in the future domestic heat system. Certain level of controls was assumed for every package.

E2. Technology analysis

SECTION 1 – HEAT PUMPS

Technology	ASHP (for space heating and hot water)
System integration	
• ASHP - Heating water loop integration : - matching water temperature requirements of the radiators to the capabilities of the ASHP - matching between the heating demand of the building and the capacity of the ASHP - the flow rate in the water loop has to be high enough (the ASHP requires higher flow rates than a conventional boiler) - need of balanced flow within the heating water loop (same level of temperature required in all rooms) • Integration with smart energy management systems: - compatibility between communication protocols - energy demand management (through thermal inertia, DHW production, and potentially heat storage) is not always compatible with the end-user comfort constraints	
Key dependencies	
• If replacing a Combi boiler supplying instant DHW, additional space will be required within the building for DHW water tank • the system requires sufficient space around the outdoor unit (to ensure a good performance), sufficient distance between the outdoor unit and windows (to limit noise) and pathways (to limit icy patch formation) • If used with thermal storage, space within the building for thermal storage • With fan coils and conventional radiators as heat distribution systems (not an issue for under floor heating): - modification of heating habits of the users due to slower space heating speed than with gas or oil boilers (heating time doubles) as gas boilers are usually oversized	
Main barriers	
- high capital cost of system compared to gas boiler - relatively long pay-back periods with current energy prices - Lack of skilled installers. High dependency of the performance on: - the initial assessment of the installer and subsequent system design - the quality of the installation - the settings of the control parameters by the installer Noise from HPs could become an issue in densely constructed areas - Physical space requirement to install the system limits deployment opportunities - If the building is initially heated with radiators, the retrofit of underfloor heating system will bring significantly higher capital cost (the installation of high temperature or very high temperature ASHP, keeping the existing radiators, often offers shorter pay back periods)	

Technology	Hybrid (= packaged) ASHP - boiler with extended HP coverage (for space heating + DHW) and Integrated (non-packaged) Boiler + ASHP (for space heating + DHW)
System integration	
• **Hybrid ASHP - Heating water loop integration :** - matching between the heating demand of the building and the capacity of the Hybrid ASHP - the flow rate in the water loop has to be high enough (the ASHP requires higher flow rates than a conventional boiler) - need of balanced flow within the heating water loop (same level of temperature required in all rooms) • **Integration with smart energy management systems:** - compatibility between communication protocols • **Specific for Integrated (non-packaged) Boiler + ASHP (for space heating + DHW)** - suitable hydraulic connection module between Boiler and ASHP - compatibility of the ASHP control output signal with the control input of the existing boiler	
Key dependencies	
• If replacing a Combi boiler supplying instant DHW, additional space will be required within the building for DHW water tank • the system requires sufficient space around the outdoor unit (to ensure a good performance), sufficient distance between the outdoor unit and windows (to limit noise) and pathways (to limit icy patch formation)	
Main barriers	
• high capital costs of system compared to gas boiler (however, lower than for pure ASHP) • Lack of skilled installers. High dependency of the performance on: - the initial assessment of the installer - the quality of the installation - the settings of the control parameters by the installer • If the building is initially heated with radiators, the retrofit of underfloor heating system will bring additional costs. (the installation of high temperature or very high temperature ASHP, keeping the existing radiators, often offers shorter pay back periods) • Noise from HPs could become an issue in densely constructed areas • Physical space requirement to install the system limits deployment opportunities	

Technology	Gas absorption Heat pump
System integration	
• Does not work effectively at ambient temperature under -5°C, a back up heating system is required if lower ambient temperature is regularly low, due to lower system capacity • Suitable for large residential buildings such as nursing homes, hotels • GAHPs can be installed outside, integration issues due to space constraints can limit its deployment • Are not equipped with compressors, hence noise levels are lower compared to electric heat pumps	
Key dependencies	
• If replacing a Combi boiler supplying instant DHW, additional space will be required within the building for DHW water tank • the system requires sufficient space around the outdoor unit (to ensure a good performance)	
Main barriers	
• Technical barrier: In cases of existence of waste heat and requirement for cooling, application of GAHP could be (ecologically and economically) worthwhile • Typically ammonia is used as refrigerant which is hazardous and leads to high pressure of 20 bar in the system (Rechnagel Sprenger Schramek: Taschenbuch für Heuzung und Klimatechnik, 2013/2014,	

page 517)	
Technology	**Domestic Hot Water (DHW) produced by Heat Pump (HP) Electricity (used to heat water for non-space heating purposes)**
System integration	
• The HP needs a heat source, outside air can be a primary source. • To integrate a HP for DHW in the building, one has to consider the heat transport from outside to the DHW tank • The split HP has an exterior unit to harvest the air energy but single-unit HPs exist also. In this case, one has to install air pipelines to admit the outside air to the HP and to exhaust the cold air	
Key dependencies	
• To limit the piping costs, the HP can be installed close to an exterior wall. The HP can be noisy and their installation is not recommended within the living space. i.e. should be installed in a garage, basement or outdoors. If installation is indoors, sound proofing is recommended, which adds to the capital investment costs.	
Main barriers	
• To produce DHW at very low air temperature (like -10°C) the water heater needs direct electric heater as a typical HP does not operate at such low temp. This electric heater brings couple of disadvantages: the annual performance is lowered, the control of two energy sources inside the tank can hardly be optimised. • Lack of skilled installers. High dependency of the performance on: - the initial diagnosis of the installer - the quality of the installation, in particular for ground exchangers installation - the settings of the control parameters by the installer • Deployment is limited, limiting practical experience gained from real life	

Technology	**GSHP (for space heating + DHW) and Solar assisted GSHP with unglazed solar collector for space heating + DHW purpose**
System integration	
• Regarding the GSHP - Heating water loop integration : - matching between the heating demand of the building and the capacity of the GSHP - the flow rate in the water loop has to be high enough (the GSHP requires higher flow rates than a conventional boiler) - need of balanced flow within the heating water loop (same level of temperature required in all rooms) • Regarding the integration with smart energy management system: - compatibility between communication protocols - energy demand management (through thermal inertia, DHW production, and potentially heat storage) has to be compatible with the end-user comfort constraints • Regarding the ground exchangers integration issues : - compatibility with the heat pump capacity and building needs - compatibility with the area available around the building • Regarding unglazed solar collectors integration : - compatibility with heat pump capacity and ground exchangers sizing - compatibility with area available on the building roof - suitable brine flow rate in the ground exchangers and unglazed solar collectors - possibility to produce DHW with unglazed solar collectors during summer	
Key dependencies	
• Water tank required. Large ground exchanger fields can be used as seasonal heat storage	

- Sufficient area available around the building to install ground exchangers
- Sufficient space in the building to install heat pump, water tank and possibly a DHW tank
- Possibility to connect ground exchangers (outdoor) and heat pump (indoor)

Specific for solar assisted GSHP

- Sufficient area available on the roof to install unglazed solar collectors
- Possibility to connect ground exchangers, unglazed solar collectors and heat pump

Main barriers

- High capital costs of system compared to gas boiler. Solar assisted GSHP with solar collectors has capital costs lower than pure GSHP
- Lack of skilled installers. High dependency of the performance on:
  - the initial assessment of the installer
  - the quality of the installation, in particular for ground exchangers installation
  - the settings of the control parameters by the installer
- If the building is initially heated with radiators, their replacement will bring additional costs (the installation of high temperature or very high temperature ASHP, keeping the existing radiators, often offers shorter pay back periods.)

Specific for solar assisted GSHP

- Integration of all system elements (ground exchangers, unglazed solar collectors, heat pump and control) has to be supported by a competent installer

Gaps – requirement for development: Applicable to all Heat Pumps

TECHNICAL

- Technical solutions to reduce material cost (all aluminium heat exchangers, high speed compressors, etc)
- Technical solution to reduce installer risks (self tuning of control parameters, automated installation diagnosis, etc)
- Technical solution to reduce installation costs (standardisation)
- Technological development to improve the thermodynamic performance of the HP
- Research to find the most appropriate refrigerant fluid for the HP. Natural fluids are the most studied and seems to give good results
- Specific for gas absorption HPs: Thermodynamic solutions to increase G.U.E. (Gas Utilisation Efficiency)
- Specific for GSHPs:

\- Technical solutions to reduce ground exchangers installation costs : smaller drilling rigs, standardised installation process - Technical specifications for ground exchangers sizing

- Specific for Domestic Hot Water (DHW) produced by Heat Pump (HP) Electricity (used to heat water for non-space heating purposes)
  - Technological development to improve the thermodynamic performance of the HP
  - Research to find the most appropriate refrigerant fluid for the HP. Natural fluids are the most studied and seems to give good results

NON- TECHNICAL

- improve qualification of installers and ensure they are exposed to examples of good practice
- improve the image and public recognition of ASHP
- capital cost reduction through incentives and mass effect
- Provide attractive commercial propositions to consumers
- Incorporation into the Renewable Heating Incentive scheme

SECTION 2 – mCHP

Technology	LT PEMFC
System integration	

UNDER FLOOR HEATING WITH PCM AND HDTS

Underfloor heating - PCM

• Potential to integrate underfloor heating with low temperature radiators

A concrete floor with underfloor heating takes ~30 min. to warm up and >2h to cool down. Panel radiators warms up in ~5 min. and cools down in ~30 min. Combination of both could address underfloor heating temperature fluctuations

• Commercialisation of PCMs implies a total system approach, with a bespoke consideration for each dwelling (e.g. climate and occupancy factors) that integrates ventilation solutions and purging strategies

LT PEMFC – Balance of Plant

• BoP repairs might be necessary during the lifetime of the system (field tests show the highest rate of failure for these components). New designs minimising BoP could help to address this problem

mCHP – thermal storage

• Optimal integration and design of mCHP and thermal storage is important to maximise operational hours and to minimise on-off cycles

Controls

• Set controls tailored to the system

LOW T RADIATORS, BATTERIES AND HEMS

Integration mCHP- Electricity storage (e.g. lead acid batteries)

• Early stage of development, given the premature nature of batteries

Integration Electricity storage (e.g. lead acid batteries)- HDTS

• Integration of active cooling for both types of storage

- Lifetime of lead acid batteries is strongly affected by the operating temperature, halving every 8°C rise above ambient temperature (25°C). Active cooling is incorporated into systems to prolong lifetime and this might need to be augmented with a chiller system where ambient temperatures regularly exceed 30°C
- PCMs might need as well active cooling for their discharge
- This could raise the possibility to integrate active cooling for both systems

Integration mCHP –HDTS

• Thermal storage integration with electricity led PEMFC is of remarkable importance to avoid heat rejection in times of high electricity-low heat demand profiles

• Under development. Integration of mCHP and HDTS in demonstration stage

Key dependencies

LT PEMFC- heat led

• Space for hot water tank

Lack of space to fit a hot water tank could limit the potential for direct replacement of combi-boiler systems

• Space to accommodate the mCHP unit - integration

Both wall-hung and floor-standing units are under development. Wall-hung systems are likely to be required to maximise UK market size since most gas boilers are wall mounted

Commercial PEMFCs (0.75 kW) for domestic use -Japan

Weight: 100 kg (+125 kg for HW storage). Both elements integrated

Dimensions: 0.95 m x 0.6 m x 0.5 m

• Back up gas boiler needed to provide peak heating demand

• Economic performance linked to annual electricity demand

Economic performance has a strong dependency on the annual electricity demand (as electricity used on-site

is more valuable than exported electricity) • CO_2 savings linked to annual thermal demand CO_2 emissions reductions have a weak dependence with annual electricity consumption but are strongly correlated to annual thermal demand (while displaced grid electricity CO_2 rates are the same regardless of whether generation is consumed onsite or exported to the grid, in the economic case export attracts a lower value than onsite generation) • PEMFC mCHP well-suited to modern buildings with low heat demands, better than Stirling Engines (given their low heat to power ratio) • Important integration of LT PEMFC and thermal storage for older dwellings with higher thermal demands
Main barriers
LT PEMFC- heat led • Technical constraints • Cost • Supply chain
Gaps – requirement for development
<u>TECHNICAL</u> **Tailored system design - Understanding of the system** • E.g. Depending on the thermal loads it might be more beneficial to set the mCHP to work at minimum load during the summer than allowing it to oscillate in on/off cycling **Underfloor heating** • It is slow to react, loses heat to the ground and can cause temperature stratification - layers of different levels of warmth in a room • TRL: 7 - Lack of understanding of PCMs under real dynamic conditions **LT PEMFC – Heat led** • Technical constraints - The fuel processor (and system) configuration and its efficiency will also be a strong factor in the overall efficiency of the system - BoP has the highest rate of failure in the system. Improvement in this field needed - In order to maximise the potential of a mCHP unit, opportunities to achieve a variable heat-to-power ratio are under development - Design improvements that lead to system simplification (component reduction) and easiness of installation - Increase system durability • Costs associated with technology - More than 50% of the system costs are associated with BoP, which could adversely affect the pace of future cost reductions if there is little scope for learning - Installation costs £500-1000. Little potential for cost reduction <u>NON-TECHNICAL</u> • Supply chain - Development of the supply chain, major driver to decrease costs– new manufacturing techniques, economies of scale and standardisation - The IEA remark that there is a lack of suppliers of valves, pumps, blowers and sensors, plus extensive pipe-work components, and they have little incentive for reducing costs • Development of additional benefits associated with microCHP (i.e. DSR services and arbitrage opportunities) • Disruption could be an issue for dwellings without HW tank – development of wall hung unit and integration of mCHP with HDTS are key in this aspect - Current state of the art technology, such as the Panasonic Enefarm LT PEM, launched in 2013, is still not a wall hung unit. Other mCHP technologies (e.g. Stirling Engine), have launched wall hung units in the UK market (i.e. Baxi ecogen) • High capital costs - Ene-farm residential LT PEM (launched April 2013. Panasonic, 0.75 kW system, Japan): £18,700/kW • Lack of awareness - Survey in Germany shows a level of awareness of 2.7% for new retrofit home owners and 2% new build home owners. *Available at: http://www.iphe.net/docs/Events/Japan_311/2%20Ramesohl_E.ON_IPHE_1Mar2011.pdf*

Technology	HT PEMFC
System integration	
This technology presents several advantages compared to LT PEMFC, although at the moment its TRL is low (5-6): • Higher flexibility of fuel (enables H_2 reformate coming from methanol, ethanol, diesel…) and simpler reformers (implications for the use of biogas as feed) - These characteristics are due to the higher tolerance of HTPEM to CO (30,000 ppm for HT PEM vs 30 ppm for LTPEM; *Serenergy website*) • No need of humidification, compressor or radiator implies a low parasitic power consumption • Higher operating temperatures provide water output temperatures up to 65 deg. C that enable the coupling of this technology with conventional radiators	
Key dependencies	
• Small number of low nameplate capacity systems commercially available (e.g. Clear Edge offers systems from 5 kW) limits the application of this technology to systems with higher thermal demand (multifamily residential buildings) - Higher development and commercialisation of low capacity systems would enable the application of this technology to smaller dwellings • Space and weight constraints - Volume occupied by a 5 kW HT PEM unit is 10 times bigger than a 60 kW condensing gas boiler - Volume occupied by a 5 kW HT PEM unit is 4 times higher than a 0.75 kW LT PEM - 5 kW HT PEMFC vs 60 kW condensing gas boiler (width x depth x height,m): 1.5 x 0.9 x 2.2 vs 0.6 x 0.5 x 0.95 - Weight 5 kW HT PEM vs 60 kW condensing gas boiler (kg): ~1,000 kg vs <100 kg	
Main barriers	
• Cost • Technical - Membrane lifetime is seen by many researchers as the bigger barrier for commercialisation of HTPEMFC - Catalysts durability, especially in acid based systems	
Gaps – requirement for development	
TECHNICAL • Reduced membrane lifetime due to harsher conditions • Further development of lower nameplate capacity systems applicable to dwellings with lower thermal demand -1-2 kW HT PEMFC prototype stack assembling and validation for mCHP applications under development (e.g. HySA systems) NON-TECHNICAL • Supply chain and installer competency development - There are fewer manufacturers/less experience for HT PEM than for LT PEM - Small supply base of MEAs (Membrane Electrode Assemblies): e.g. BASF • Capital and installation cost reduction - Capex (comparison with LT PEM) Per kW £7,200/kW ClearEdge 5 kW, intended for multifamily residential buildings (vs £18,700 for 0.75 kW LT PEM) Per system ~£36,000 for 5 kW HTPEM vs £14,000 for 0.75 kW LTPEM - Installation (comparison with LT PEM) ~£3,000-£6,500 for HTPEM 5 kW (vs. £500-1000 for LTPEMFC) High potential for installation cost reduction	

Technology	SOFC

System integration

SOFC –least cost strategy: integration with a back-up boiler, enhanced overall control and operating year round 24/7

- Some form of intelligent control necessary for the success of mCHP technology
- Although it is sometimes assumed that a heat led strategy should be adopted for mCHP (as in larger-scale CHP systems, turned -on when there is heat demand and switched off or modulated in periods of low heat consumption), this might not be economically justified at the domestic level
- There are studies reporting that a least cost strategy leads to the maximum reduction of costs and CO_2 emissions compared to the baseline for SOFC [1]. Hence, the implementation of this strategy for SOFC is optimal (while the heat led strategy leads to the higher cuts on CO_2 emissions for SEs and ICEs)
- The fact that SOFC do no respond well to on-off cycling due to thermal stress, has implications for the control strategy, making necessary the operation at minimum output throughout (~20% of max. output) and the response to electricity or heat load where they exceed the minimum output
- Small economic benefit for the operation in least cost strategy vs heat lead (~5% for SOFC)
- Small environmental benefit to the operation in least cost strategy vs heat lead (2% for SOFC)
- New products to be launch by next year incorporate enhanced overall control (e.g. CFCL)

[1] Cost-effective operating strategy for residential micro-combined heat and power; A.D. Hawkes and M.A. Leach; Energy 32 (2007) 711–723

SOFC – Electricity storage

• The integration of these elements means the addition of a DC/DC converter between the SOFC, the battery and the electric load
• Integration of electricity storage with SOFC could allow to the system to have a fast response to load following
• Studies have showed that when operating a SE in a least-cost strategy there is a surplus of electricity all year around (except from the summer) in the morning and afternoon (~6-10 am, ~4-9 pm) that could potentially be stored [1]
• Demonstrations of the integration of SOFC and Electricity storage are under development

Available at: http://www.fuelcellseminar.com/media/8967/dem33-1%20napoli.pdf

Key dependencies

SOFC requirements include:
-mains gas connection,
-sufficient thermal demand (sufficient baseload),
-thermal storage (HW tank),
-physical space to accommodate the mCHP unit,
-integration (integrated, wall-hung systems required to maximise UK market size)

Main barriers

• High capital cost
- Need for innovative ownership and finance models (e.g. Green Deal type approach). Using mCHP as dispatchable generation likely to rely on aggregation, which removes some control from the consumer (loss of utility) - complexity (and associated costs) of exploiting thousands (or more) of mCHP systems as VPP.
- Enefarm Type S (0.7 kW, with 90 L hot water unit + backup heat source, launched April 2012,): £19,000
• Supply chain development
The IEA remarks that there is a lack of suppliers of valves, pumps, blowers and sensors, plus extensive pipe-work components, and they have little incentive for reducing costs

Gaps – requirement for development

TECHNICAL
• Main area for technical improvement: durability and cycling capability (SOFC does not respond well to frequent on-off cycling due to thermal gradients at high temp)
• Limit of durability (<20,000 h)
• Long start-up times

• There has been a general trend to try to decrease operating temperatures of SOFCs as high temperatures require expensive materials/construction (however, a shift below c.650C is required to benefit from standard steels and therefore cheaper materials/manufacture). • Scope to improve flexibility of the system to achieve a rapidly variable heat-to-power ratio NON-TECHNICAL • High costs (between. ~50-60% of the system) associated with valves, pumps, blowers, sensors, pipe-work. If there is little scope for learning in the production and use of generic, minor, components, this could adversely affect the pace of future cost reductions

Technology	SE mCHP
System integration	

CONVENTIONAL RADIATORS-HEAT LED, HDTS

Stirling Engine (SE) - Control strategy

• Although it is sometimes assumed that a heat led strategy should be adopted for mCHP (as in larger-scale CHP systems, turned -on when there is heat demand and switched off or modulated in periods of low heat consumption), this might not be economically justified at the domestic level.
• SE are typically operated heat led (at full output when space heating required) with a supplementary heat unit (integrated condensing boiler or integrated heat unit)
• Heat led strategy achieves the higher savings in CO_2 emissions for SEs compared to a condensing boiler (although there is small environmental advantage in comparison to a least cost strategy of <5%)
• Least cost strategy for SE and ICE, dependent on the cost of the electricity import costs, consists on following heat and electricity demand during the winter (although there is no clear pattern in summer)
• Small economic benefit for the operation in least cost strategy vs heat lead (~5% for SE)
• Technical characteristics of SEs, able to operate on-off in accordance to a predefined programme and to modulate electrical output rapidly

SE-HDTS

• Appropriate sizing and design of HDTS and Balance of Plant (BoP)
- The fact that SEs have high thermal output requires that the storage (with ability to decouple heat production from demand) to be big enough to enable running for long hours (or high thermal demand) before significant electrical generation occurs
- BoP design parameters will affect correct utilisation of HDTS (e.g. high flow rate through the SE could prevent thermal stratification)
- In a heat led strategy, where heat is required in addition to that provided to the mCHP, the HDTS is discharged first, and the supplementary boiler will provide the rest of the capacity
- Some SE mCHP are combi units- provide instantaneous hot water (e.g. Remeha eVITA, not in UK market: Germany and the Netherlands)

SE – Electricity storage

• Studies [1] have showed that when operating a SE in a least-cost strategy there is a surplus of electricity all year around (except from the summer) in the morning and afternoon (~6-10 am, ~4-9 pm) that could potentially be stored

Cost-effective operating strategy for residential micro-combined heat and power; A.D. Hawkes and M.A. Leach; Energy 32 (2007) 711–723

SE-Underfloor heating or LT CR

• Possible to combine the SE (providing hot water and electricity) with a condensing boiler that enables space heating via underfloor heating/LT CR
• Integration studies of SE with hydronic radiators and underfloor heating, studied in [2], reflect the importance of correct system design

Available at: http://etd.uwaterloo.ca/etd/abdebruy2006.pdf

CONVENTIONAL RADIATORS- LEAST COST STRATEGY
Stirling Engines (SEs) have high heat to power rations (5:1). This characteristic has implications for the control strategy, as following the electricity load could imply either dumping or inefficiently storing thermal demand. Hence, the integration of SE electricity led with a good designed thermal storage is of high relevance in these systems **SE- HDTS** - In a least cost strategy, the HDTS would be charged and discharged at cost-optimal basis. This could impose specific requirements for the storage when integrated with mCHP following a least cost strategy (e.g. higher flexibility, study of how this could affect the HDTS) - The least cost strategy means in winter to follow heat/electricity although in the summer is not clearly defined. This strategy is influenced by electricity import price and surplus of electricity all year round (except from summer) in morning and afternoon peaks (~6-10 am, ~4-9 pm) **SE- Controls** • The importance of controls with mCHP run by a least cost strategy might be higher that in those systems working in a heat-led basis - This is due to the fact that TES have to be charged and discharged on a cost-optimal basis and that the electricity will be imported/exported depending on fuel prices, electricity export/import prices and how this interact with efficiency profiles
Key dependencies
• SE mCHP systems, given their high heat to power ratios and their power capacities currently available , could better suit systems in which a high thermal demand is necessary, as bigger dwellings • Some SE mCHP (e.g. BaxiEcogen) cannot be used with pre-payment electricity meters
Main barriers
• High capital costs E.g. Baxi Ecogen 1 kWe system, offered by British Gas, installed price: £6,000-£6,500 • Lack of confidence of costumers in the product (inertia towards boiler systems) • Lack of awareness • Trained installer base
Gaps – requirement for development
TECHNICAL • Commercial systems mostly targeted to small commercial applications and domestic market • Improve efficiency at low power NON-TECHNICAL • Reduction of high costs - Reduction through economies of scale and technical innovations • Increase in regulatory incentives - It has been reported that an increase in the FITs from the current 12.5 p/kWh to 17 p/kWh would be necessary to compete with the counterfactual heating technologies - Subsidy diversification could be necessary to reflect the different commercialisation state of the different mCHP solutions • Supply chain development - Volume production: development of automated assembly of stacks - Permanent Magnet synchronous generator implies the use of Rare Earths. Resource constraint? Competition with wind turbines. • Ensure good performance along lifetime - A mechanism to ensure regular maintenance and periodical emissions tests needs to be in place

SECTION 3 – BIOMASS BOILER, HDTS, HYBRID SOLAR THERMAL AND GAS BOILER

Technology	Biomass boiler

System integration

Equipment required for integration

• Plate Heat Exchanger –

- If a gas boiler were replaced by a biomass boiler, a plate heat exchanger could be needed between the biomass boiler and the heat distribution system, as this type of boilers generally operate at higher temperatures (for some of them higher than 100 deg. C) and pressures than conventional fossil fuelled boilers. Although the implications in cost and size would be small compared to the whole system, installation/integration issues could have an important role to ensure system efficacy.

• Back-up boiler –

- Domestic biomass boilers will usually provide the base load for the heating system, and a back-up boiler sized to meet the peak load will be needed in most cases. Correct sizing of the whole system is therefore important in order to maximise efficiency and reduce the associated carbon emissions
- The technical characteristics of biomass boilers, that require them to operate continuously in order to achieve the higher efficiencies, make important the integration of biomass boilers with thermal storage

Thermal store

• Design –

- De-stratification of thermal store that affects biomass boiler capacity control created due to over-pumping of secondary side of thermal store by fixed speed pumps was addressed in Carbon Trust analysis of domestic biomass boilers – found in one out of 5 systems and therefore an aspect to take into account in designing the system
- Carbon Trust analysis of domestic biomass boilers showed that in many occasions no blending valve was used in thermal store flow, reducing the effectiveness of the thermal store

Carbon Trust. Insights into biomass heat installations. Report on Biomass Heat Accelerator site development work. Analysis of historical biomass installations; Available at: http://www.carbontrust.com/media/129472/ctc810-insights-into-biomass-heat-installations.pdf

System design

- Important to correctly size boiler and thermal store capacity; and controllability and integration with the fossil fuel heating system. In systems not correctly designed, the fossil fuel boiler will take over the load intended to be supplied from biomass, with the subsequent carbon savings reduction that this implies
- the architect, services and structural engineers all have to be involved in the design of the biomass system to ensure full integration

Key dependencies

Biomass boiler

• Space requirements – internal (boiler) and external (fuel storage)

Biomass boiler (12 kW):

Floor mounted, 0.5 m x 0.7 m x 1.2 m.

Weight: 200 kg +40 kg hopper + 30 L internal water + chimney (if not supported)

Fuel storage: 500 L (350 kg) of wood pellets

Gas boiler (12 kW):

Wall-hung, 0.4 m x 0.3 m x 0.7 m

Weight: <50 kg

• Local availability of stock

• Fuel storage and delivery

• Sufficient supply of fresh air for correct combustion for certain boilers

• Air quality concerns (NOx and CO) of burning biomass in urban areas could restrict their application in these spaces. Importance of combustion control systems (problem is more challenging than in gas boilers, as reaction temperatures are higher, and allow the reaction of atmospheric O_2 and N_2)

• Biomass boilers better suited to higher constant load, as their efficiency is highly affected by cycling. Hence it is important to think of this technology as an integrated system with thermal storage

Main barriers
Biomass boiler • Cost • Space requirements (for boiler and fuel store) • Technical constraints associated with: - nature of biomass ash: alkaline nature implies fouling and corrosion, - air quality: filter cleaning technology and combustion control mechanisms under development to reduce particle emissions, - slower response of biomass boilers to changes in load compared to gas boilers - their integration with thermal storage: continuous nature of their operation (i.e. cannot be switched on and off as gas boilers) - higher maintenance requirements than gas boilers • Supply chain: availability of stock
Gaps – requirement for development
<u>TECHNICAL</u> *Biomass boiler* • Improvement of management of biomass ash - Due to its alkaline nature ash causes corrosion and fouling. Hence, lifetime of economiser in biomass boilers is lower than in gas boilers - Areas for potential development: study of economiser failure in biomass boilers, development of predictive tools for slagging and deposition control in boilers • Slower response of biomass boilers to changes in load compared to gas boilers - This means that up to three control loops are used to control the fuel feed rate, the primary and secondary air fans, and the delivery of energy to the load including the charging/discharging of the buffer vessel. The minimisation of emissions requires carefully controlled combustion • Increase flexibility on biomass boiler operation - Biomass boilers operate at their higher efficiency when they are running continuously, with a minimum operating capacity of ~30% of their maximum rating. They cannot be quickly switched on and off like gas boilers • Improvement in maintenance (emptying ashbin, cleaning flue tubes…) - Higher maintenance than gas boilers • Improvement of hot water tanks by water stratification and effective thermal insulation - Today's R&D activities focus, for example, on evacuated super-insulation with a thermal loss rate of λ= 0,01 W/mK at 90°C and 0,1 mbar and on optimised system integration - 2008, England, 13.1 million dwellings with HW storage cylinder: * 4.4 m HW storages with potential to be improved (£45 and 170kg carbon dioxide a year) *1.3 m HW storages with potential to include cylinder thermostat ~10% could be improved fitting cylinder thermostat (£30 and 130kg carbon dioxide savings a year) **EHS, Housing Stock Report 2008* <u>NON- TECHNICAL</u> *Biomass boiler* • Space constraints • Capital and operating cost reduction • Supply chain development (stock availability)

Technology	HDTS
System integration	
Thermal store integration • Design – - De-stratification of thermal store that affects biomass boiler capacity control, created due to over-pumping of secondary side of thermal store by fixed speed pumps was addressed in Carbon Trust analysis of domestic biomass boilers - found in one out of 5 systems and therefore an aspect to take into account in designing the system - Carbon Trust analysis of domestic biomass boilers showed that in many occasions no blending valve was used in thermal store flow, reducing the effectiveness of the thermal store *Carbon Trust. Insights into biomass heat installations. Report on Biomass Heat Accelerator site development work. Analysis of historical biomass installations. Available at: http://www.carbontrust.com/media/129472/ctc810-insights-into-biomass-heat-installations.pdf* **HDTS** - There are commercial solutions proposing the integration of several modular salt hydrate PCMs storages (< 5 kWh) with different melting points into a PCM thermal store ~ 4-5 smaller than conventional hot water tanks - Stratification in these systems is provided by design, as the modules are separated, avoiding de-stratification by an incorrect BoP design - This technology, which could be integrated with several renewable heat sources, is under development and further work is undergoing to tailor this storage to each application (e.g. PCMs melting points will be tailored for each application -20-60 deg. C for HPs, 50-90 deg. C for biomass boilers) - When integrated with Heat Pumps, domestic head demand could be delivered from 100% off-peak electricity consumption with a storage ~ two freezers (compared to HW thermal storage of ~1,000-1,500 L) - BoP design parameters will affect correct utilisation of HDTS (e.g. high flow rate through the heat source could prevent thermal stratification in the thermal store)	
Key dependencies	
HDTS • System characteristics enable integration in area-constrained dwellings - Space requirements for heat storage around 4-5 times lower than hot water storage. This number varies from 3-10 depending on the store design <u>Heat Battery (Sunamp Ltd., 4 kWh)</u> Size of thermal store: ~ 30-50 L <u>HW tank (4 kWh)</u> Size: 150 L - The highly configurable nature of this HDTS and its easiness to integrate –thermal store provided in cuboids, and not cylinders- enables its easy integration in dwellings: could be building-integrated (e.g. in bathroom wall void) or under-counter in the kitchen	
Main barriers	
HDTS • Low TRL - Development, demonstration and commercialisation of heat-source tailored applications • Technical barriers - Corrosion Although salt hydrates present the advantage of being not flammable, as is the case of paraffin-based PCMs, and of having twice the energy density of the latter, they present issues associated with corrosion - Heat loss control Heat transfer phenomenais still being explored. Solutions in their way to commercialisation provide vacuum insulation panel to solve this problem. This property needs to be tested in dynamic system demonstration - Supply chain 1.PCMs	

2.BoP The integration of the heat modules inside the thermal store is done through valves, and the IEA has remarked that there is a lack of suppliers of valves, pumps, blowers and sensors (which will be critical for several mCHP technologies)
Gaps – requirement for development
TECHNICAL *HDTS* • Technology development tailored to different heat sources and their integration into systems • Demonstration and commercialisation NON- TECHNICAL *HDTS* • Supply chain: lack of suppliers - IEA reported the lack of suppliers of BoP and their little incentive for reducing costs, which could be in conflict with such a valve-relying technology

Technology	**Hybrid solar thermal and gas boilers and HDTS**
System integration	
Gas boiler • Boiler size reduction due to solar thermal installation - Solar thermal can provide ~60% of household's hot water *(EST, 2011)* **Solar thermal system** • Electricity provided to power the pumps and controllers of the system is small compared with the overall heat delivered *(EST, 2011)* **Solar energy storage** • Underfloor heating + PCM - Although solar collectors might not be able to generate energy to charge water tanks during winter, they could provide low grade heat (~30-35 deg.C) to charge PCM material • PCM integrated in HW tank storage - PCMs (e.g. in the shape of rubber spheres) could be incorporated into HW tanks, increasing their thermal storage capacity by 2-3 times and providing a uniform outlet temperature from the tank until the PCMs have completely change of phase (avoiding the change in the temperature of HW on their own due to stratification) - This allow the operation of the collectors at a lower temperature, achieving a greater efficiency of the solar collector system **HDTS** • Thermochemical storage could be provided by zeolites integrated with ventilation systems in buildings	
Key dependencies	
• Space (when replacing a combi boiler) - Storage tank is essential for solar water heating, this may impede the take up of solar thermal systems • Due to its high costs, the integration of PCMs in HW tanks might just be appropriate in systems with space constraints in the short term • The integration of thermochemical storage provided by zeolites might come together with ventilation systems	
Main barriers	
PCM integrated in HW tanks	

• High costs - Only might may sense in systems with space constraints
Gaps – requirement for development
<u>TECHNICAL</u> • PCM integrated in HW tank storage - Development of the design parameters for optimal performance: 1. PCM shape (e.g. PCM tanks with inner core, with inner balls, or with inner tubes) 2. Operating temperature <u>NON-TECHNICAL</u> • Increase customer confidence in the technology - Remove information barriers for the potential consumer to easily find an installer • Customer training about the optimal use of the technology - Adopters may not know how best to use solar heated water to minimise back-up fossil fuel consumption

SECTION 4 – GAS BOILERS INTEGRATED WITH DIFFERENT HEAT DISTRIBUTION SYSTEMS AND COMBI boilers

Technology	Gas boiler with conventional radiators, HDTS and HEMS
System integration	
Integration of Heating Controls • The characteristics of the control system depend on: - Type of boiler Determines if the hot water is provided directly from the boiler or from a hot water cylinder (i.e. heat-only, system or combi boilers) Heat only boilers controls Programmable room thermostat, hot water cylinder thermostat , TRVs, motorised valves- control the flow of water from the boiler to hot water and heating circuits, automatic bypass valves – ensure minimum level of flow through the boiler when TRVs are operating, separate timing capability for hot water, boiler interlock Combi boilers controls Programmable room thermostat, TRVs, automatic bypass valves – ensure minimum level of flow through the boiler when TRVs are operating, separate timing capability for hot water, boiler interlock - Size of the dwelling Dwellings ≤150 m^2 At least 2 heating zones with independent temperature control and TRVs in all rooms without thermostat Dwellings ≥150 m^2 At least 2 heating zones and both independent temperature and timing controls and TRVs in all rooms without thermostat • Control design - The most effective way to improve boiler performance is through controls (burner, sequence, optimised start/stop and direct weather compensation controls) - Thermostat-boiler-pump Thermostats control the operation of the boiler and/or pump and they switch them on or off depending on the set temperature. For small systems, the thermostat usually controls only the pump. However, if the boiler were controlled as well, greater energy savings could be achieved, as the boiler can still fire when the heating time switch shuts off the pump *Available at: http://www.carbontrust.com/media/10361/ctg065_heating_control.pdf*	
Key dependencies	
Heating Controls • Dwellings with the most variable occupancy patterns will benefit more from programmable room thermostats • The sensors for weather compensation controls need to be mounted on a north facing wall in order to be accurate **HEMS** • Although there is scope for the integration of HEMS in order to manage lighting and appliances, the current cots of this technology makes necessary to expand the benefit of HEMS by applying it to DSR, associated with electricity consuming technologies such as heat pumps or electric vehicles. For a gas-fired system, the integration of this technology seems to be likely to be cost-effective in a medium-long term	
Main barriers	
Heating Controls • Trained and experienced installer base lacking - Installers able to correctly integrate controls into heating systems and to provide support to customers will be necessary in order to maximise control potentials (e.g. TRVs on radiators located near room thermostats may interfere with the correct sensing of room temperatures) *http://www.carbontrust.com/media/10361/ctg065_heating_control.pdf*	

HDTS (Thermochemical Energy Storage: metal hydride) • Low TRL (DECC funded a feasibility study to address commercial potential of this type of storage in the UK domestic market), as the majority of metal hydride development for thermal storage has been focused on their integration with solar power plants *Available at: http://www.eminate.co.uk/eminate/news/2012/eminate-awarded-feasibility-study-funding-from-uk-department-of-energy-and-climate-change-30-9-12.aspx*
Gaps – requirement for development
<u>TECHNICAL</u> • Further research/development/demonstration of metal hydrides as thermal storage for the domestic sector - Low TRL • There is scope to improve control methods so that tank and primary circuit losses are further minimised. Efficiency gains of 5% and 7% from more precise control of temperature have been demonstrated for gas fuelled systems. *Production efficiency of hot water for domestic use; P.J. Boait et al. Energy and Buildings. Volume 54, November 2012, Pages 160–168*

Technology	Gas condensing boilers with Low T radiators, HDTS and HEMS
System integration	
Low temperature radiators • Condensing boilers - Return temperatures of condensing boilers (~55 deg.C), lower than those for conventional fossil fuel boilers, make possible the diffusion of heat through distribution systems such as low temperature radiators or underfloor heating • Controls - Low temperature radiators react instantly to the controls of the thermostat, even in the extremely cold days, thanks to the combination of radiant and convected heat - Some LT radiators can be fitted with TRVs, avoiding electrical controls *http://acinewyork.org/sites/default/files/session/82730/ny12hvac4siegenthalerjohn.pdf* **HDTS** • Condensing boilers - The return temperature of the boiler will condition the design of the HDTS (e.g. the selection of the PCM used) - The condensing boiler return temperature is adequate for its integration with PCMs such as paraffins and salt hydrates, but is too low for sugar-alcohols, and salt and their eutectic mixtures based thermal stores	
Key dependencies	
Condensing boiler • Connections of condensing boilers should be made to internal drains, as external condensate pipes freeze in cold weather. This has been reported as a problem in condensing boilers (*which? website*) • Wall hung, size: of 0.95 m x 0.6 m x 0.5 m, weight: <100 kg **Low temperature radiators** • Retrofitting this type of radiators, running at ~60 deg. C (compared to 90 deg. C for conventional radiators), would constitute an important disruption for the system and would imply that enough space is available in order to fit the low temperature radiators (30-50% bigger than conventional) *http://energy-surprises.blogspot.co.uk/2012/09/getting-best-from-your-condensing-boiler.html*	

Main barriers
• Retrofit disruptions and space constraints imposed by low temperature radiators • Barriers associated with HDTS (low TRL, technical barriers for each specific thermal storage, supply chain constraints)
Gaps – requirement for development
TECHNICAL • Increase easiness to retrofit of low temperature radiators in current systems NON-TECHNICAL • Space constraints associated with bigger size of LT radiators compared to conventional

Technology	Combi gas boilers with HDTS
System integration	
Combi boiler • There are offers in the market for the incorporation of a gas saver in order to preheat the main cold water entering into the combi boiler, integrated with 50 L water tank, that increase the efficiency of the system, if retrofitted. This could imply a reconfiguration of the system in terms of controls and it could be important to make the customer aware of this in order to implement the changes needed *http://www.baxi.co.uk/docs/GasSaver_instructions_Nov_10p.pdf* **HDTS** • HDTS could play an important role in cases where combi boilers are being replaced. PCMs offer the possibility to be: 1. Integrated into heat appliance 2. Building-integrated e.g. in bathroom wall void 3. Under-counter in utility room or kitchen 4. Cycle-to-cycle heat recovery in domestic appliance	
Key dependencies	
Combi boilers • Suitable for small households with low hot water demands (can produce 10-20 L hot water/min when water heated to 35 deg. C) • Not suitable for big homes where multiple sources of water might be used simultaneously	
Main barriers	
Combi boiler – gas saver retrofit • Lack of customer awareness • Additional space requirements **HDTS** • In these cases with lack of space, in order for the boiler to be replaced for an alternative low-carbon technology, it would have to come together with some form of HDTS, given the space constraint, which implies a high cost of replacement. However, given that ~50% of the boilers in England are combi, the implications of the heating system upgrades in this kind of system for the decarbonisation of the heating sector could be remarkable • Lack of maturity. The integration of HDTS and low-carbon technologies (e.g. HPs, mCHP) is under development and demonstration	
Gaps – requirement for development	
• Consumer awareness enhancement • HDTS development	

Appendix F – Cost and Carbon emissions assessment

Package of energy efficiency measures

Detached, Semi, Terrace	Flats
CWI	CWI
Loft insulation	Loft insulation
Double glazing	Double glazing
High performance water cylinder	High performance water cylinder
Heating controls	Heating controls
Energy efficient appliances	Energy efficient appliances
External insulation	Internal insulation
Low energy light bulbs	Low energy light bulbs
Draught proofing	Draught proofing

The efficiency measures presented in the table above were taken into consideration in the modelling of the CO_2 emissions assessment for each house type.

CO_2 savings compared to baseline delivered by different heat sources across house types

The carbon reduction delivered by the main primary heating technology / energy efficiency packages compared to the baseline house types is shown in the table below. Note that some heating appliance technologies are assumed not to be relevant to certain house types. It is assumed that gas appliances are not installed in existing electrically heated house types and that Ground Source Heat Pumps, Hybrid solar thermal systems, and biomass boilers are not suitable for flats.

House type/ Measure	1	2	3	4	5	6	7	8	9	10	11	12
Fabric only	15%	15%	31%	31%	13%	34%	6%	25%	16%	34%	11%	24%
ASHP	14%	14%	34%	34%	12%	32%	6%	26%	52%	67%	36%	55%
GSHP	22%	22%	40%	40%	19%	38%	N/A	N/A	56%	70%	N/A	N/A
Hybrid ASHP	19%	19%	36%	36%	14%	35%	6%	25%	N/A	N/A	N/A	N/A
FC mCHP	26%	26%	43%	43%	28%	44%	28%	44%	N/A	N/A	N/A	N/A
SE mCHP	25%	25%	42%	42%	24%	42%	19%	37%	N/A	N/A	N/A	N/A
Hybrid solar thermal	19%	19%	38%	38%	19%	38%	N/A	N/A	N/A	N/A	N/A	N/A
Biomass boiler	58%	58%	68%	68%	56%	66%	N/A	N/A	76%	84%	N/A	N/A

For the calculation of the CO_2 savings for each house type, software based on SAP / BREDEM was used. Each of the 12 house types presented in the report can be subsequently broken down in different house types (coming from the 250 house types incorporated in the House Energy Model –HEM). A weighted average of the heat consumption, electricity consumption and CO_2 emissions associated with each of the 12 house types was estimated:

1. Without the implementation of any measures – Baseline (i.e. dwellings as currently are)
2. Only applying energy efficiency measures (see table above of "Package of energy efficiency measures")
3. Applying each of the seven heat sources, where appropriate, and energy efficiency measures.

The results shown in the table above are based on these calculations. Note that the savings presented are not cumulative.

F.1 – Capital cost estimates

The capital cost assumptions used in the assessment of the costs of each technology deployment scenario in each HSE are shown in the tables below, based on current prices and 2030 cost projections.

Table 13, Capital costs for low carbon technologies applied within the HSEs (£/dwelling)

				Technology costs (£/dwelling, current prices)											
													DH infrastructure costs		
House Type	Fuel	Dwelling type	Condition	ASHP	ASHP - boiler with extended HP coverage	Ground source heat pump	Biomass boiler	PEMFC mCHP: Fuel cell + gas back up boiler	SOFC FC mCHP: Fuel cell + gas back up boiler	SE mCHP: Engine technology (SE, ICE)	Hybrid solar thermal + gas boiler	CHP - DH	Urban	Suburban	Rural
1	GAS	Detached	G	12,900	12,175	24,000	10,000	26,667	26,667	6,500	6,600	3,687	8,275	10,863	10,863
2	GAS	Semi	G	12,900	12,175	24,000	10,000	26,667	26,667	6,500	4,950	3,687	8,275	10,863	10,863
3	GAS	Detached	P	16,650	14,988	32,400	10,000	26,667	26,667	6,500	6,600	4,993	8,275	10,863	10,863
4	GAS	Semi	P	16,650	14,988	32,400	10,000	26,667	26,667	6,500	4,950	4,993	8,275	10,863	10,863
5	GAS	Terrace	G	9,675	9,756	18,000	10,000	26,667	26,667	4,250	3,300	2,341	7,492	7,871	7,871
6	GAS	Terrace	P	12,900	12,175	24,000	10,000	26,667	26,667	6,500	3,300	3,326	7,492	7,871	7,871
7	GAS	Flat	G	7,350	8,013	10,800	8,000	13,333	13,333	4,250	825	1,377	4,098	4,427	4,427
8	GAS	Flat	P	7,350	8,013	10,800	8,000	13,333	13,333	4,250	825	1,898	4,098	4,427	4,427
9	ELC	Terrace	G	11,025	11,025	19,800	12,000	26,667	26,667	4,250	3,300	2,308	7,492	7,871	7,871
10	ELC	Terrace	P	12,900	12,900	21,600	12,000	26,667	26,667	6,500	3,300	3,305	7,492	7,871	7,871
11	ELC	Flat	G	3,675	3,675	5,400	9,500	13,333	13,333	4,250	825	1,127	4,098	4,427	4,427
12	ELC	Flat	P	7,350	7,350	10,800	9,500	13,333	13,333	4,250	825	1,696	4,098	4,427	4,427

Table 14, Capital costs for low carbon technologies installed within the HSEs (£/dwelling, 2030 prices)

				Technology costs (£/dwelling, 2030 prices)											
House Type	Fuel	Dwelling type	Condition	ASHP	Hybrid ASHP -	Ground source	Biomass boiler	PEMFC mCHP: Fuel	SOFC FC mCHP: Fuel	SE mCHP: Engine	Hybrid solar	CHP - DH	DH infrastructure costs		
													Urban	Suburbar	Rural
1	GAS	Detached	G	7,615	7,419	13,014	10,000	4,667	6,667	4,500	4,752	1,843	8,275	10,863	10,863
2	GAS	Semi	G	7,733	5,440	13,202	10,000	4,667	6,667	4,500	3,564	1,843	8,275	10,863	10,863
3	GAS	Detached	P	10,193	7,419	18,617	10,000	4,667	6,667	4,500	4,752	2,496	8,275	10,863	10,863
4	GAS	Semi	P	11,599	5,440	19,802	10,000	4,667	6,667	4,500	3,564	2,496	8,275	10,863	10,863
5	GAS	Terrace	G	5,800	4,451	9,901	10,000	4,667	6,667	2,250	2,376	1,170	7,492	7,871	7,871
6	GAS	Terrace	P	7,733	4,451	13,202	10,000	4,667	6,667	4,500	2,376	1,663	7,492	7,871	7,871
7	GAS	Flat	G	3,866	4,018	8,100	8,000	2,333	3,333	2,250	594	689	4,098	4,427	4,427
8	GAS	Flat	P	3,866	4,018	8,100	8,000	2,333	3,333	2,250	594	949	4,098	4,427	4,427
9	ELC	Terrace	G	5,800	4,451	9,901	12,000	4,667	6,667	2,250	2,376	1,154	7,492	7,871	7,871
10	ELC	Terrace	P	7,733	4,451	13,202	12,000	4,667	6,667	4,500	2,376	1,653	7,492	7,871	7,871
11	ELC	Flat	G	1,933	4,018	8,100	9,500	2,333	3,333	2,250	594	563	4,098	4,427	4,427
12	ELC	Flat	P	3,866	4,018	8,100	9,500	2,333	3,333	2,250	594	848	4,098	4,427	4,427

Appendix G – Scoring the short-list against the proposed criteria

In order to identify a small number of technologies to recommend for further investigation by the ETI, we scored the short-listed technologies against the proposed selection criteria (see Section 6). The scoring matrix used is shown below. Note that the scoring is somewhat subjective and will depend on the relative priority placed on the various criteria. The ETI's better understanding of their own requirements for subsequent engagement in particular technology fields may lead to a different scoring and final technology selection.

		Fan-assisted radiators	ASHP	H-ASHP	Fuel cell mCHP	HP + solar therma;	HDTS	Sensors / Actuators	HEMS / HAN	Low T DH	LV Voltage control	D-FACTS	DSR	Community biomass CHP	Community-scale EFW	Community-scale GSHP	Cloud management service	EMS
Carbon reduction impact	Carbon intensity of heat	0	1	1	2		0	0	0	0	0	0		3	2	1	0	0
	Implications of grid decarb	0	3	1	-2		0	0	0	0	0	0		-1	-1	3	0	0
	Scale of CO2 reduction enabled	1	0	0	0		2	2	2	2	2	1		0	0	0	1	1
Cost-effectiveness	cost effectiveness current prices	1	-1	-1	-2		0	1	-1	0	1	0		-1	-1	-1	1	1
	cost effectiveness accounting for cost curves	1	2	2	2		2	2	2	0	1	1		1	1	1	2	2
	Impact on fuel poverty	0	0	0	0		0	0	1	1	0	0		1	1	1	0	0
Barriers & market constraints	Severity of demand side barriers	1	3	2	2		0	1	1	3	0	0		1	2	2	0	0
	Severity of supply-side barriers	1	1	1	2		1	1	1	1	1	1		2	1	1	1	1
	Potential for policy / regulation	0	2	2	1		1	0	2	1	1	1		2	2	2	1	1
Deployment at scale	Applicability	2	2	3	3		3	2	2	1	2	2		1	1	-1	2	2
	Resource constraints	0	1	1	0		0	0	0	1	0	0		-1	-1	0	0	0
Technology maturity	TRL	3	2	2	1		2	2	2	1	1	1		1	1	1	1	1
	Timescales	3	3	3	2		1	2	2	1	2	2		2	2	2	2	2
Alignment with ETI objectives	Engagement opportunity	1	0	0	1		2	1	2	1	1	1		1	1	1	0	1
	Short term return	0	0	0	1		1	1	1	0	1	1		1	1	0	0	0
Benefits to UK plc	Opportunity for UK manufacturing	1	0	0	2		1	1	1	1	1	1		1	2	1	1	1
	Jobs creation	1	2	2	1		1	1	1	1	1	1		1	1	1	1	1
	Security of supply	0	1	1	0		0	0	0	0	1	1		2	2	1	0	0
	SCORE	**18**	**20**	**20**	**12**		**26**	**22**	**24**	**9**	**22**	**18**	**0**	**16**	**14**	**14**	**19**	**21**
	RANK	9	6	6	14	16	1	3	2	15	3	9	16	11	12	12	8	5

Scoring key	Very positive		3
	positive		2
	slightly positive		1
	neutral		0
	slightly negative		-1
	negative		-2