Freedom Project

Interim Report

January 2018

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1. Executive Summary

The Freedom Project is seeking to understand the potential role of multi-vector solutions in the decarbonisation of domestic heating. Based in Bridgend, South Wales, the project is investigating the consumer, network and energy system implications of hybrid heating system deployments, where domestic heating systems have the option of operating using a standard gas boiler, an air source heat pump (ASHP), or both.

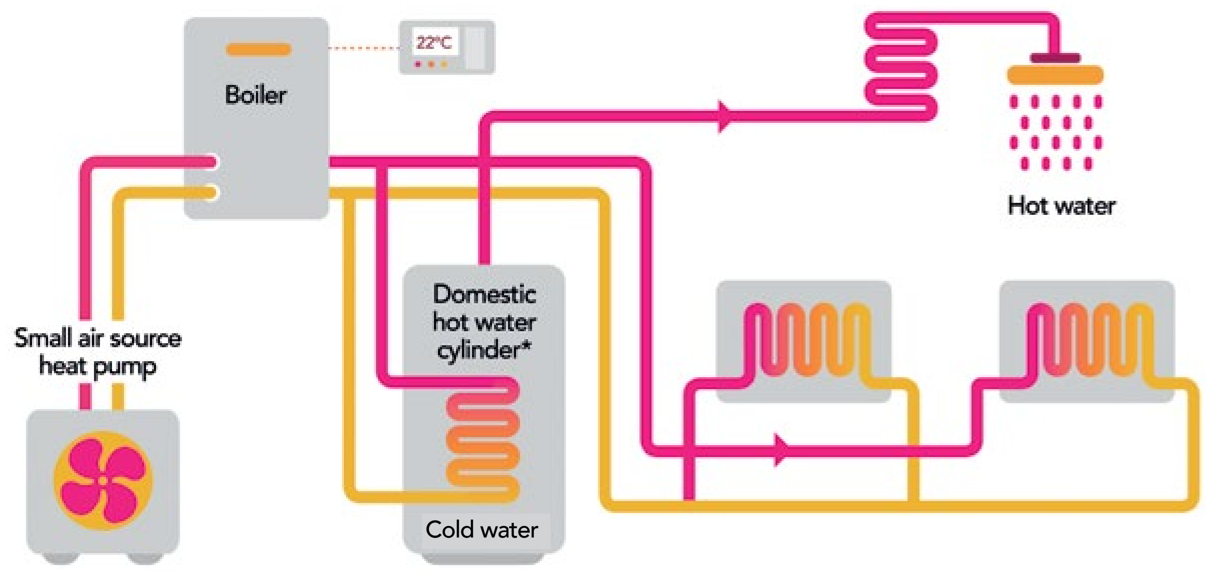


Figure 1. The hybrid system

The Freedom Project has completed 13 months of a 27-month project programme. The Project has installed 75 hybrid heating systems in a mix of private and social housing, with the focus now on the optimised controlling, monitoring and consumer feedback throughout the 2017-18 heating season.

Once the heating season has concluded the collected data will be reviewed and analysed with final reporting due in January 2019. The project has already delivered significant learnings which are expanded upon in this report:

- Imperial College's modelling of hybrid heating system adoption shows that the potential benefits accruing to the energy system as a whole are considerable. Modelling the 2030 energy system, their analysis shows that an increased annual spend of £178m on the gas system as a substitute to electricity in ASHP-only scenarios, the whole system is able to achieve gross **savings in total cost of more than £1.3bn per year.**
- Imperial College's modelling has also identified a counterintuitive carbon outcome. Conventional wisdom is that full electrification delivers a lower carbon output to hybridisation; however, this is not the case. On the coldest days when the electricity system is under greatest load, or when intermittent renewable generation is insufficient to meet demand, the additional ASHP load would need to be met by marginal increases in flexible generation sources.

Burning gas in the home at **93% efficiency** is more carbon efficient than incurring **6% electricity network transmission losses** after burning fossil fuel at these power stations:

Coal
34% efficient,
937 gCO²e/kWh

Gas Peaking OCGT
28% efficient,
651 gCO²e/kWh

Gas CCGT
48% efficient,
394 gCO²e/kWh

- The addition of renewable gases to the network, such as hydrogen blends, biomethane or BioSNG[1] significantly improves the carbon reduction for when the boiler operates.
- PassivSystems' control strategy identifies that hybrid heating systems, or any ASHP uptake, will be very difficult with current UK electricity and gas prices. Although there is some potential for exploiting tariffs like Economy 7, the government will need to take steps to make electricity relatively cheaper to progress towards decarbonisation.
- Early modelling has highlighted that conventional approaches to controlling hybrid (or bivalent) systems with a simple transition between fuels based on external temperature are likely to perform poorly compared to a fully optimised system; control systems should focus on the heating water temperature, which closely determines efficiency.
- PassivSystems' recommended control strategy for a hybrid heating system is to utilise the boiler to provide bursts of heat to warm the house up quickly, with the heat pump providing temperature maintenance and a 'base load' during periods where a fully warm house is not required.
- The project has demonstrated that it is feasible to install optimised hybrid heating systems and smart controls on three different hybrid heating systems in a range of different house types (broadly representative of UK housing stock) using the existing wet heating systems and with no in-home disruption from additional insulation measures in 35 private homes and 40 social homes.
- The project has also completed installations of three hybrid systems with a system boiler setup, three hybrid systems not on the gas grid (using Calor gas storage) and one property with a new ASHP connected to an existing boiler as a retrofitted hybrid system.
- Initial survey results show that awareness could be a barrier to hybrid heating systems uptake. Only **12% of participants** had what they considered 'good' or 'excellent' knowledge about hybrid heating systems prior to the trial. This was the same for heat pumps in general.
- Initial survey results show that hybrid heating systems were appealing to participants once they had been explained, with running cost savings viewed as the biggest advantage. Nearly **90% of respondents found the idea of hybrid heating systems appealing** to some degree and **50% said they were very appealing.**
- Initial survey results show that an overall awareness of flexibility and demand response was higher than expected. Fifty percent of people said they had good knowledge of it, which is positive considering it is not a common offering at present in the UK.

2.1 Project Overview

The Freedom Project is investigating the network, consumer and broader energy system implications of high volume deployments of hybrid heating systems. The technology, which combines domestic gas boiler and air source heat pump (ASHP) heating, can be used as fully flexible loads capable of providing significant energy system value.

Freedom = Flexible Residential Energy Efficiency, Demand Optimisation & Management

As an industry first, Distribution Network Operator (DNO), Western Power Distribution and Gas Distribution Network (GDN), Wales & West Utilities have formed a partnership and accessed their respective Network Innovation Allowances (NIA) to invest with PassivSystems to deliver the Freedom Project. To support the delivery of this two-phased project, PassivSystems has appointed project partners Imperial College, Delta-ee and City University:

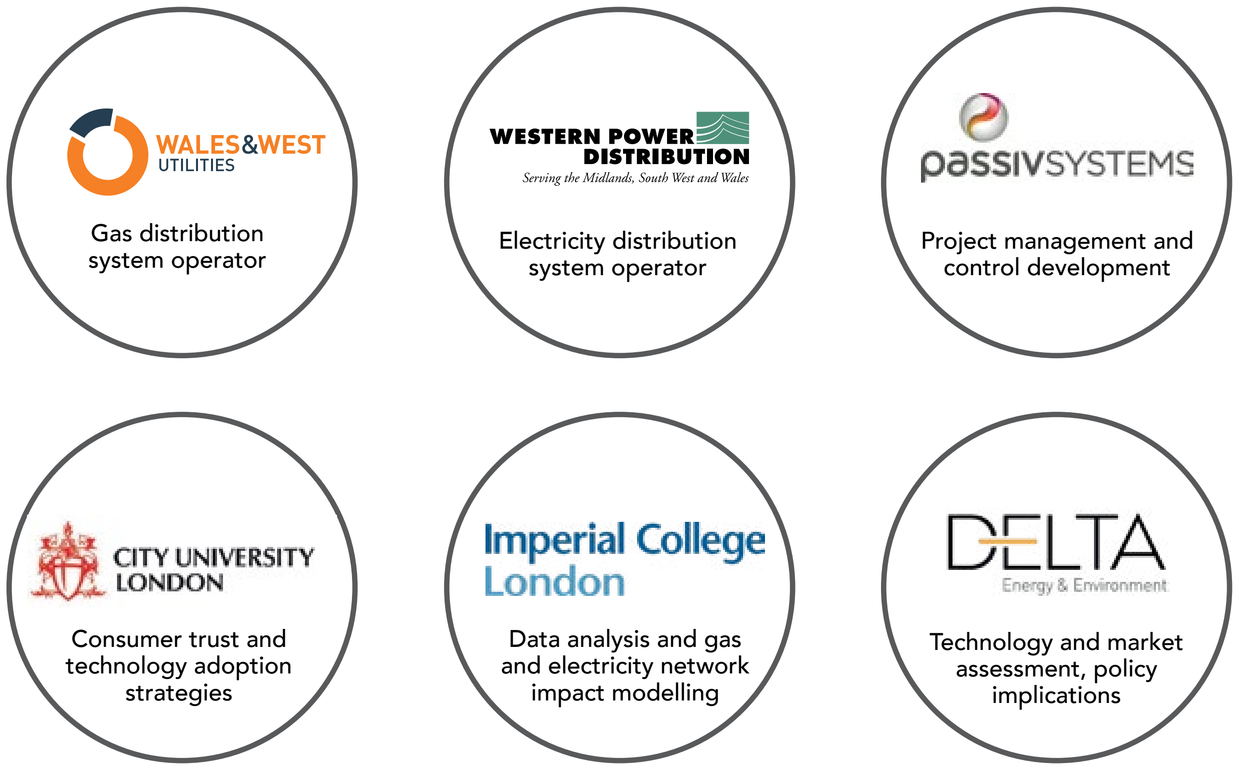


Figure 2. The project partners

Phase 1

Phase 1 of the project produced forensic models from which hypotheses of system performance, detailed market assessments, and consumer research were derived. In addition, it delivered a four-home pilot installation to assess the selected hardware, installation contractors and project customer engagement.

Phase 2

Phase 2 is currently field testing the hypotheses developed during Phase 1 in 75 homes, which are a mixture of social and private housing, in Bridgend, South Wales.

Figure 3. The Freedom Project property mix

The project partners are all experts in their fields and the project builds on market-leading controls technology developed by PassivSystems. The ambition is to provide both electricity and gas network operators with meaningful insights into the future evolution of the domestic heat sector, the impact on networks in the short and long term and steps that can be taken to best manage future network risk and opportunities arising from a proliferation of the hybridisation of heat.

For the first time, this NIA-funded project brings together the gas and electricity network operators in the field trial region and aims to provide both organisations with robust, field-tested data which can make a meaningful contribution to long-term network investment planning. The cross-sector scope makes this a unique project which aims to set the benchmark for holistic 'whole systems' projects, as articulated in Energy UK's Pathways for the GB Electricity Sector to 2030 (February 2016).

2.2 Project Objectives

1. **Use the ability of the hybrid heating system and PassivSystems controls to switch between gas and electric load to provide fuel arbitrage and highly flexible demand response services.**

2. **Demonstrate the consumer, network, carbon and energy system benefits of large-scale deployment of hybrid heating systems with aggregated demand response controls.**

3. **Gain insights into the means of balancing the interests of the consumer, supplier, and network operators when seeking to derive value from the demand flexibility.**

4. **Address all elements of the energy trilemma:**

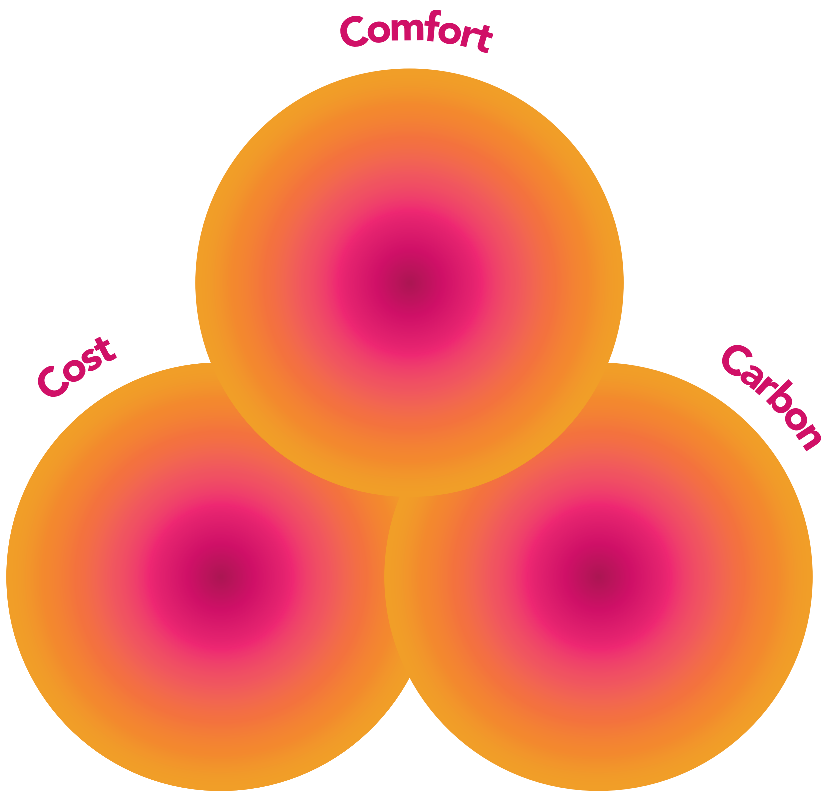


Figure 4. The energy trilemma

The project is addressing all aspects of the energy trilemma, with a specific focus on heat and the potential for hybrids to be transformational in delivering solutions that will shape future energy market dynamics. As a result of the work delivered so far in the Freedom Project, hybrid heating systems are demonstrating that they are a complementary solution across the various future of heat pathways, providing the opportunity for partial electrification combined with hydrogen in major cities and other decarbonised gas elsewhere.

The findings of the project will contribute to the challenge of reducing carbon emissions at the lowest cost impact for domestic consumers by delivering increased heating system efficiencies and a reduced unit cost from the energy supplier for energy consumed by the hybrid heating system. The project is now trialling a comprehensive range of demand -response events to demonstrate the ability to deliver electric heat while protecting energy network security. Algorithms are also being developed and refined based on actual field and market data over the duration of the project.

3.1 Gas and Electricity System Impact

The global recognition of the challenges of climate change, in particular the ambitious reductions in carbon emissions proposed by the UK Government (i.e. 80% reduction relative to 1990 levels), are driving significant changes across the energy landscape. Significant progress is being made in decarbonising electricity generation and seeking low-carbon gas alternatives.

However, in the UK, domestic heating remains largely unaffected by attempts to lower-carbon outputs, aside from the considerable progress made through increased boiler efficiency.

Gas boilers are the predominant technology for the provision of domestic space heating and hot water in the UK with a market penetration of **80% of homes**. In order to meet ambitious carbon reduction targets, our high dependency on fossil gas heating will need to reduce, with hybrids offering the flexible solution to make best use of renewable gas and electricity.

In comparison to gas boilers, electric heat pumps have significantly higher capital costs. Heat pumps may also have higher running costs compared to gas unless a seasonal performance factor of 3 or higher is achieved, which is unlikely without investment in disruptive insulation and upgrades to the heat delivery system (larger radiators, etc).

Where mains gas is not available, comparisons are somewhat more favourable. Prices for heating oil fluctuate significantly, dropping from 6.5p/kWh to 2.5p/kWh in the last two years. Meanwhile the installation of a heat pump can deliver significant efficiency (and comfort) benefits over forms of direct electric heating such as storage heaters.

The increasing penetration of renewable energy sources, together with the decommissioning of coal-fired power plants, is resulting in an increase in volatility in the electricity system, which is relying on gas as the flexible enabler to the growth of intermittent low-carbon generation sources. Additionally, the electrification of the heat and transport sectors is expected to have a further impact on the energy system demand leading to substantial investments in network reinforcement and flexible generation. In a future low-carbon electricity market, flexibility will be fundamental to ensure a cost-efficient decarbonisation of the energy sector.

Currently, due to the higher peaks of demand on the electricity network occurring **on winter days compared to summer days, the utilisation level of power system assets is about 55%.** Potential electrification of residential heat demand (associated with a much stronger seasonal swing) will further increase the peaks in demand during winter and aggravate power system utilisation levels. Thus, while significant investments in electricity network reinforcements will still be required to accommodate the increment in winter demand, during summer months the additional capacity will not be utilised. This aspect, among many others, will considerably increase the value (and need) for flexibility from end-users.

Hybrid heating systems have the potential to address these issues:

1

Peak heating and hot water demand can be delivered by the gas boiler meaning:

- a. A smaller capacity heat pump can be installed reducing capital costs.
- b. Less/no impact on winter electricity peak demand as the heat load can be shifted onto the gas boiler.
- c. The system can be optimised on carbon as well as cost, with heat load shifted onto the gas boiler if the electricity grid is carbon intensive, typically for periods without wind generation.
- d. The gas network, with its inherent storage capability, retains an important role in the energy system, offering the equivalent benefit of 210TWh of seasonal storage.

2

The household gains the ability to participate in price arbitrage, reducing running costs by aggregators taking away the complexity of when to run their heating system on gas when electricity is expensive, renewable generation is low or temperatures are very cold, and vice versa.

3

The additional flexibility provided by utilising multiple fuel sources provides further opportunities to reduce the cost of operating energy networks and for consumers to receive a share of the benefits generated.

4

Utilising green gases, which alone are insufficient to decarbonise heat, indicate there is adequate feedstock in the UK to decarbonise the gas feed to a boiler within a hybrid heating system. Cadent Gas has calculated the bioenergy feedstock availability to produce renewable gas from biomethane and BioSNG[1].

Their central estimate of 108TWh/yr by 2050 would be enough to meet approximately one-third of domestic heat demand. Their upper estimate of renewable gas potential is 183TWh/yr. Power-to-gas to produce renewable electricity generation enabled hydrogen, for blending into the gas network or to undertake biomethanation by combining with captured carbon, is being investigated but is excluded from the figures published by Cadent Gas. In addition, the potential to repurpose the gas network in some cities to distribute hydrogen from steam methane reformation for heating and cooking is also being explored by the H21[2] collaborative project, led by Northern Gas Networks, with hybrids also offering an opportunity to efficiently use this lower carbon gas.

[1] *'Review of Bioenergy Potential: Technical Report' for Cadent Gas, September 2017*

[2] *'H21 Leeds City Gate', Northern Gas Networks, Wales & West Utilities, Kiwa Gastec and Amec Foster Wheeler, December 2016*

3.2 Decarbonising Heat

Consumer Willingness and Ability to Pay

The Department of Energy & Climate Change (DECC) 2013 Heat Pathway suggested two solutions: heat pumps would replace gas central heating in suburban areas and communal heating networks could replace the individual central heating systems in urban dwellings currently served by the UK Gas Network.

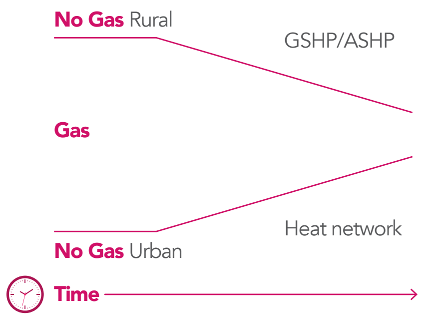


Figure 5. UK heat pathway (DECC 2013)

Wales & West Utilities commissioned research[3] into large-scale switching to an alternative heat provision from a consumer perspective to assist with understanding the investment requirements in gas networks during the 2020s and 2030s.

The research shed new light on the complex business of decarbonising heat and revealed a number of surprising results, including:

- **Initial capital cost** is the key factor that influences consumer switching behaviour.
- **80%** of consumers would not/could not afford to change to lower-carbon heat provision.
- **Very large subsidies** would be needed to change consumer preferences.

This research revealed that the proposed 2013 DECC pathways for heat decarbonisation are far more expensive than anticipated. At the time, it was suggested that the policies would save consumers money, but the economic analysis has revealed that large upfront investment is needed and that the savings may never pay back that investment. It was evident that some level of compromise is required to keep the energy trilemma balanced, i.e. decarbonising heat whilst maintaining security of supply at the lowest cost.

It was observed that some pathways did not address the issues surrounding peak demand, noting that domestic premises can consume up to 10 times the daily energy for heat compared to power. It was also observed that seasonal demand for heat swings significantly and this doesn't align with some forms of renewable generation. This study identified the need to analyse in detail the compatibility of different renewable energy options, including how seasonal peak demand could be met.

[3] 'Future of Energy & Investments in Gas Networks: Bridgend Project Summary Report', Business Navigators and Wales & West Utilities, January 2016

3.3 Modelling the Impact of Hybrid Heating Systems

To address the objectives of the Freedom Project, project partners have developed and improved their energy systems modelling to consider and optimise the operation of hybrid heating systems served by a combination of electricity and gas.

The optimal split between the two energy sources is intrinsically determined by finding the lowest-cost choice to meet the heating demand while also considering the costs in other parts of the system, such as seasonal storage, interconnection and reinforcement. This cost-optimal split will generally vary from one hourly interval to another and will be driven by the assumed price of gas as well as the endogenously driven cost of generating electricity in a given hour.

A key feature of the modelling is the capability to explicitly impose system-wide carbon emission constraints in a cost-efficient manner. Obviously, the use of gas to top up the supply of heat would have implications for the overall carbon emissions from the system, although if gas is only used during the coldest days, in response to electricity network capacity or constraint issues and in the absence of intermittent renewable generation, the overall effect on annual emissions should be relatively small. Further benefit from decarbonising the gas grid with renewable gases makes the carbon efficient performance of a hybrid heating system even more compelling, with gas demand significantly reduced but utilising the network capacity to store energy and deliver flexibility.

3.4 Integrated Energy System Simulation

A high-resolution, spatial and temporal dynamic model has been developed to enable the holistic evaluation of the changing interactions between gas and electricity networks.

As the networks continue to integrate (see **Figure 6**), variation of demand and supply on the electricity network will have immediate impacts on the gas network. For example, where more electric vehicles are charged with intermittently generated renewables, this creates larger demand swings on the electricity network, affecting demand on the gas distribution system as gas peaking plants respond to maintain capacity on the electricity network.

Modelling has been conducted to transparently assess the feasibility of how different future energy mixes would work in practice. It enables any energy scenario, current or future, to be modelled for a town, city, county or country and the results show the costs, carbon impact and any shortfall/surplus in heat and power supply. Simulations using this model can be used to find the feasibility of alternate solutions across all energy types in a more integrated way.

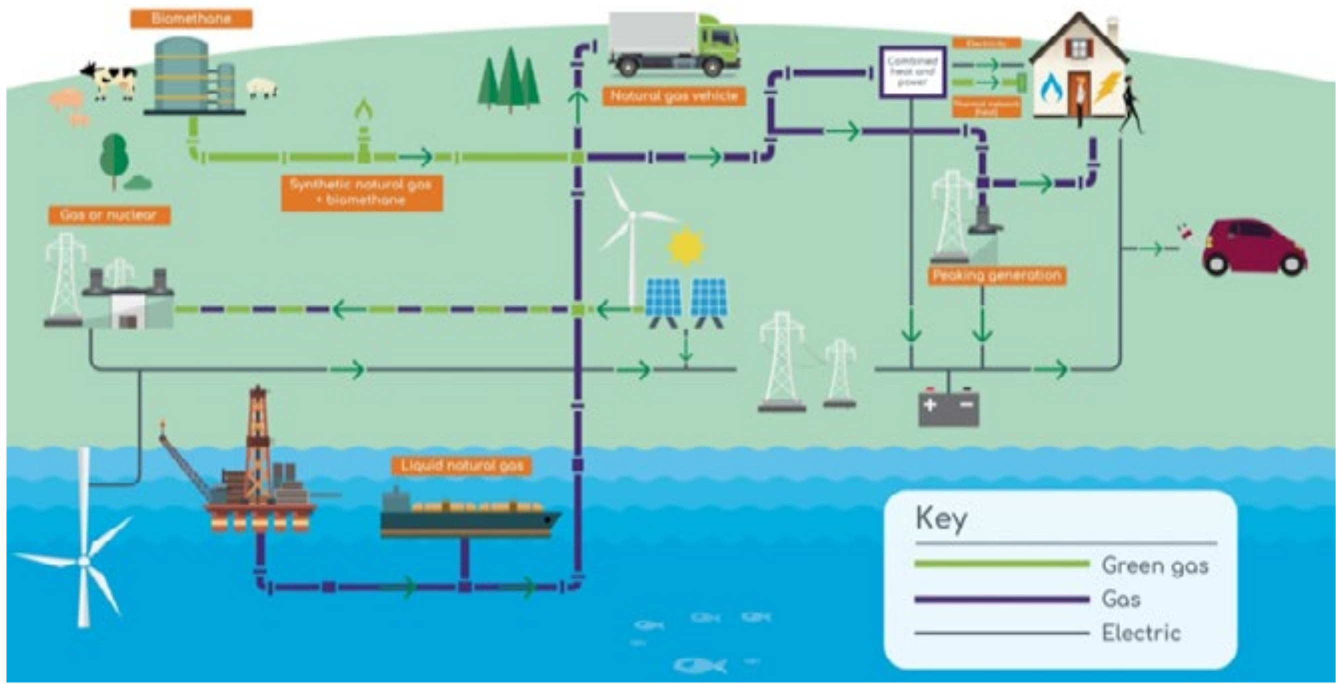


Figure 6. Energy network integration

To illustrate its use, the integrated energy model was used to evaluate proposals to create a totally renewable simulation for Cornwall[4] using a mix of:

- **50% wind**
- **25% solar**
- **25% geothermal**
- **All supported by battery storage**

Hourly heat and power demand profiles were modelled, which calculated a required **500 GWh of seasonal storage and a ~£60k** cost per household per year to deliver the proposed scenario. Biomethane gas injection subsidies were found to offer a much more cost-effective route to decarbonisation than the full electrification option explored.

In summary, the Cornwall simulation highlighted that the use of renewable energy sources in providing heating in this way requires very large seasonal storage at a cost consumers are unable to afford using the most commonly suggested storage medium of batteries.

3.5 Switching Fuel Sources on Availability of Intermittent Renewable Electricity Generation

A high-resolution, spatial and temporal dynamic model has been developed to enable the holistic evaluation of the changing interactions between gas and electricity networks.

Hybridisation of domestic heating comes into its own during the winter with limited renewable generation, for example low wind periods system in winter when wind generation is not available, when other storage or reinforcement solutions would be exorbitantly expensive and under-utilised.

The same model used to simulate a fully electrified renewable future for Cornwall was also used to simulate the future energy system in the Swansea area, due to the potential benefit of the UK's first tidal lagoon generation plant. The total heat and power demand of Swansea in the first four weeks of December 2016 was added to a projected transport demand if everybody used an electric vehicle without charging constraints, with their hourly profiles graphically presented. Peak demand in December 2016 reached 1,080 MW, and so to ensure supply of renewable electricity generation capacity could comfortably meet this demand, the UK Committee on Climate Change[5] high deployment figures for wind and solar in 2030 were generously multiplied by five and added to the projected tidal lagoon capacity to give a total supply capacity of 1,340 MW (500 MW each of wind and solar and 340 MW from tidal).

[4] *'Cornwall Energy Island: The Heat Light & Power Simulator' by Wales & West Utilities & Business Navigators, September 2016*
[5] *Climate Change Committee – Power Sector Scenarios, 5th Carbon Budget, Hypothetical 2030 Scenario, 2015*

The graph below shows the supply-demand gap due to the intermittency issues associated with the renewable generation sources.

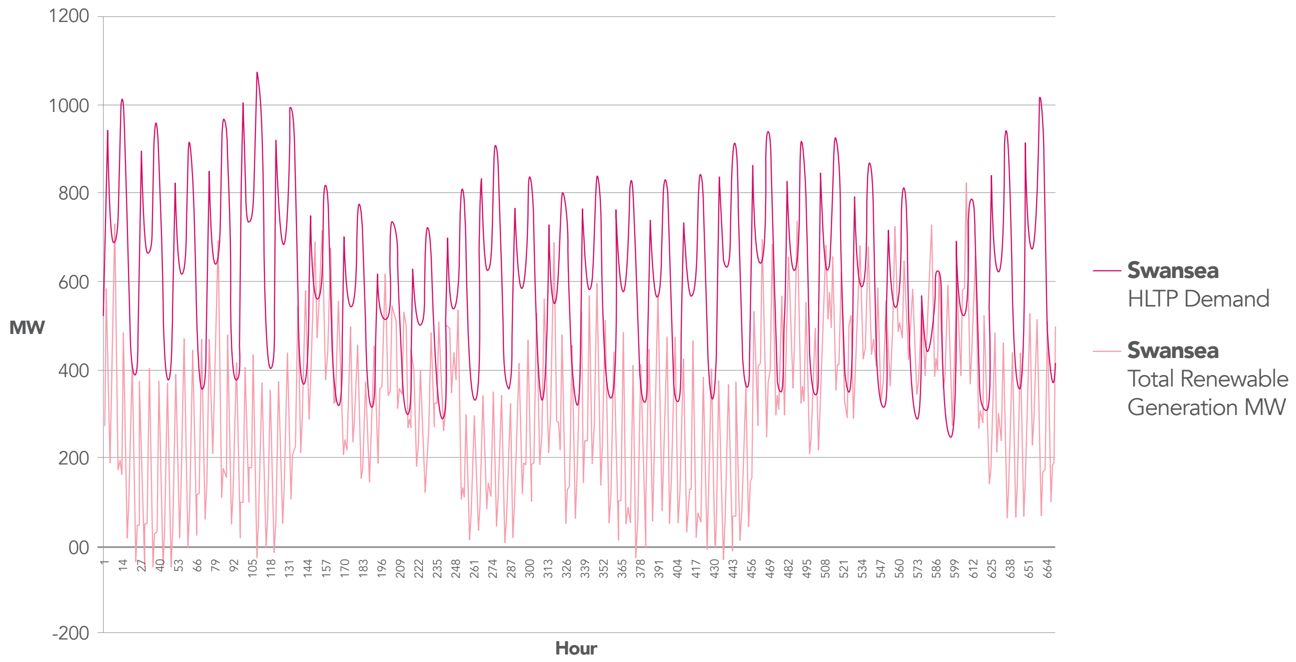


Figure 7. Swansea heat, light, power & transport supply & demand profiles, December 2030

The first week or so of December 2016 was reasonably cold at the same time that there was very little energy generated from wind and solar whilst it was a neap tide. A significant shortfall in daily supply was noted. Christmas day managed to match supply and demand in this simulation due to the annually repeated low demand on this day, milder temperatures and sustained wind. The energy supply shortfall in this 2030 Swansea simulation is 34GWh for the period 1st to 21st December.

With hybrid heating systems using low-cost renewable electricity through the heat pump in the future and delivering DSR services, the gas boiler and upstream gas network will be able to provide storage and flexibility for when the external temperatures are very cold, when there are electricity network constraints and when intermittent renewable electricity generation is unavailable.

With at least 30% of domestic heat demand able to be met by renewable gases going forward, **a total domestic heat decarbonisation pathway is emerging through a hybrid balance between two renewable energy vectors.**

3.6 Switching Fuel Sources on Electricity Network Capacity Constraints

For the purposes of understanding the capacity in the electricity network for taking on heat demand with hybrid systems in 2030, characteristics were taken from a recent Climate Change Committee (CCC) scenario with an assumed flat 100 g/kWh carbon intensity. The system in 2030 has a high penetration of variable renewables and a significant contribution from nuclear generation. The assumed gas price in the study was £53.4/MWh, which included both the cost of fuel and the cost of carbon. The carbon price assumed in 2030 was £77/t, in line with BEIS' projections used in the CCC study.

As an illustration of the hourly variation in the usage of gas and electricity by hybrid heating systems within capacity constraints, **Figure 8** shows the total demand on the system for the first week of the year, consisting of baseline demand, household appliances (SA) and electric vehicles (EV). The demand from hybrid heating systems is shown separately for electric and gas components; to make values comparable, the gas consumption by hybrid heating systems was converted to an 'equivalent' electricity consumption by applying the COP applicable to the electric part of the hybrid heating system to the heat supplied by gas.

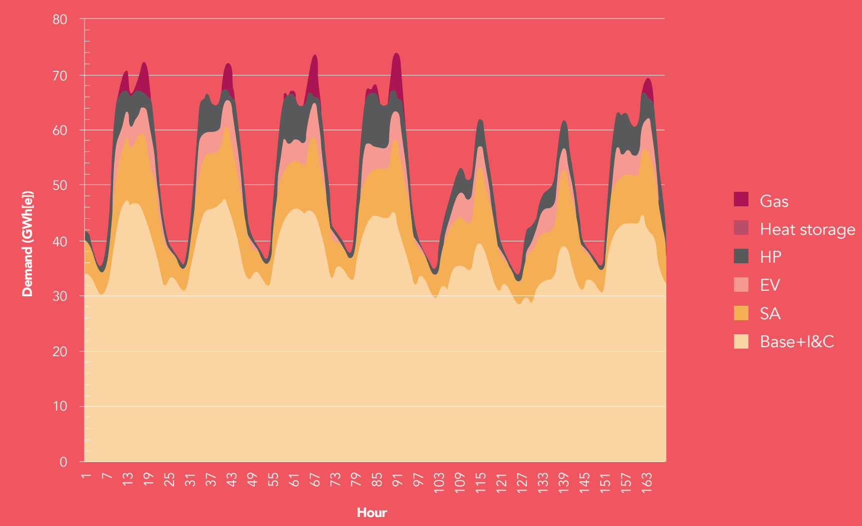


Figure 8. Electricity demand and equivalent heat pump gas demand.

It is clear from **Figure 8** that as part of a cost-efficient solution, the gas parts of hybrid heating systems are used during peak electricity demand when there isn't capacity in the electricity system to meet heat demand. This enables the gas and electricity vectors to supply the entire heat demand by load shifting to gas when the electricity system is reaching peak capacity. This hybrid flexibility results in avoided costs in relation to increasing electricity generation capacity and electricity network reinforcement when compared to the electric-only scenario, where the entire heating demand would have to be met through electricity.

Continuing the hybrid switching signals being based upon electricity network capacity, the modelling is showing that gas would be used during the evening electricity network peaks, yet not as often during the morning electricity network peaks or over weekends. This is because there is more electricity network capacity available for heat in the morning and on weekends but not during midweek evenings. **Figure 9** shows the diurnal and midweek to weekend hybrid system behaviour relating to switching on electricity network capacity constraints, with days 5 and 6 representing the weekend.

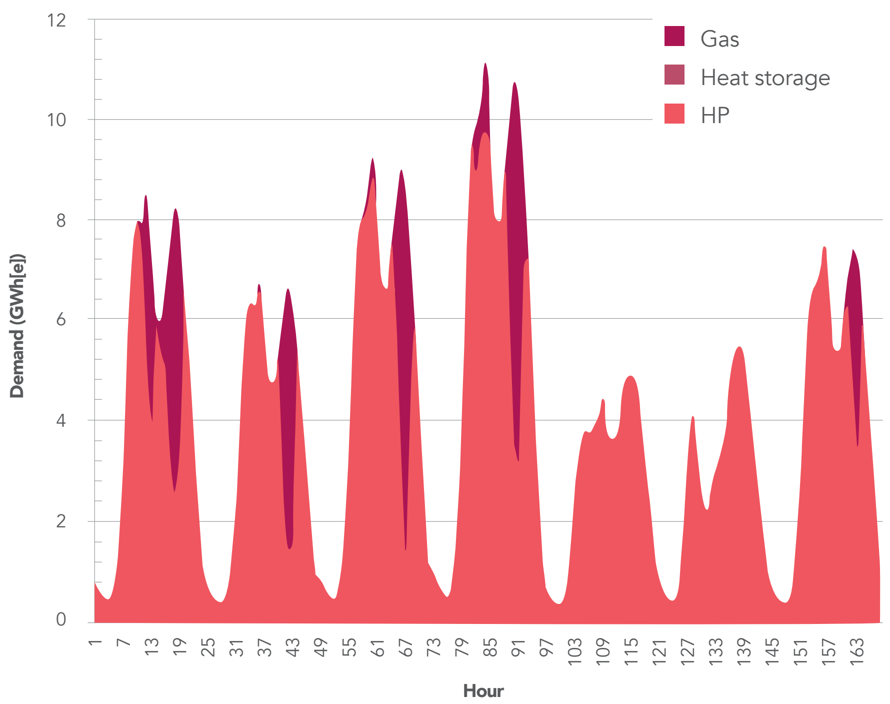


Figure 9. Hybrid heating system switching based upon electricity network capacity constraints

An Imperial College comparison of total system costs between hybrid heating systems and electric-only heat pumps enabled them to evaluate the annual system-level benefits of hybridisation of heating systems. This is illustrated by the chart in **Figure 10**, which shows the change in annual system cost if standard heat pumps are replaced by hybrid heating systems.

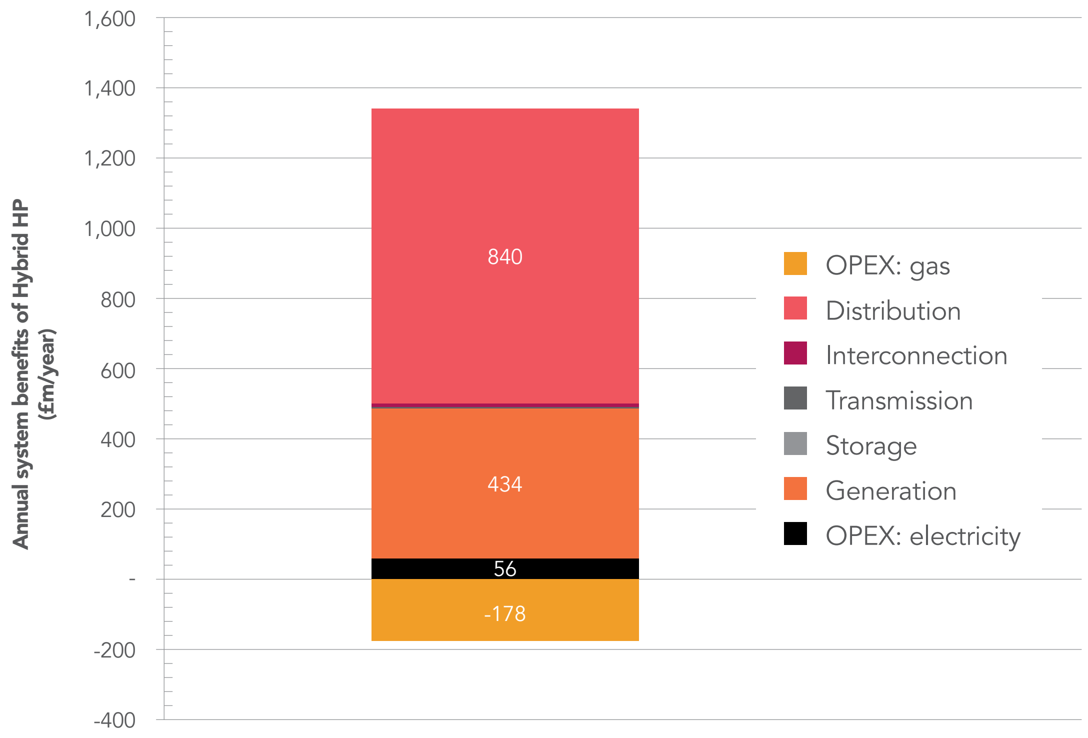


Figure 10. Imperial College modelled system-level benefits of hybrid heating systems

Imperial College identified considerable benefits accruing to the energy system as a whole:

By spending about **£178m annually** on gas to substitute electricity in hybrid heating systems during certain times of year, the system is able to **achieve gross savings in total cost of more than £1.3bn per year.**

About two-thirds of the gross benefit results from savings in electricity distribution investment cost, given that reduced electricity consumption during peaks avoids high loading and consequently reinforcement of the distribution grid. About a third of gross benefit arises from avoided investment in peak generation capacity, again driven by the ability of hybrid heating systems to reduce electricity consumption during peak load hours on the system. Finally, a small proportion of savings also comes from the operating cost savings, given that less electricity needs to be produced by the generators on the system as part of the heat pump demand is now met by gas.

The magnitude of the benefits presented here would potentially change if there were more flexible options available on the system (such as e.g. additional renewable gas and electricity storage capacities or widespread uptake of DSR). Nevertheless, this illustrates the key sources of value that the flexibility of hybrid heating systems is likely to generate.

4. Business Models for Hybrid Heating Systems

The Freedom Project is providing evidence on the role and value of flexibility that residential consumers and gas network flexibility and storage can provide to the future low-carbon heat market.

Primarily, an analysis is being carried out to identify potential services/applications that can be provided to system and network operators by hybrid heating systems while still ensuring that heat requirements (and thus end-users' comfort levels) are still met. Mainly, the flexibility associated with residential heat demand can be exploited to offer frequency response services to the system operator and even support DNOs to manage peak demand at the distribution level.

Once the optimised hybrid heating system data is collected, a series of case studies will be carried out to identify and quantify the value of individual services/applications that can be offered through the domestic heat sector.

4.1 Arbitrage Between Electricity and Gas Markets

The characteristics of a hybrid heating system allow it to operate using electricity and gas supply sources.

This aspect enables end-users to outsource to an aggregator the complexity of selecting the most appropriate energy source to meet their heat requirements based on energy supply costs, i.e. the dual fuel capability of hybrid heating systems allows end-users to benefit from arbitrage opportunities between the electricity and gas markets. Overall this means that it can ensure that their energy needs (i.e. heat requirements) are met at the lowest supply cost but fundamentally without compromising their comfort levels.

4.2 Demand-side Management Service

Demand-side management (DSM) services have been widely investigated and applied by industrial/large consumers with the objective of reducing their energy bills by providing a price-responsive demand curve.

When applied to industrial consumers, DSM considers the flexibility offered by a specific production process – i.e. the flexibility associated with over or underproduction – and thus adjust the demand for electricity based on real-time pricing while still meeting the long-term production targets. A similar method can be applied to residential heat demand by taking into consideration the potential thermal inertia of buildings and a price responsive demand curve.

In this context, the residential heat demand curve (which for the sake of clarity will be identified as 'original heat demand' throughout this section) will be subject to small adjustments in order to reduce consumers' energy bills through time arbitrage. Allowed ranges for a potential increase/decrease away from the original heat demand have been set according to three levels of DSM: 2%, 5% and 10%.

The value associated with DSM, namely the reduction on heat supply cost, should then be compared with end-users' loss in comfort levels and willingness to adjust their heat requirements. **A 10% variation in heat demand (10% DSM)** can achieve valuable reductions in heat supply cost. Note that a 10% flexibility in heat demand will have a potential effect of raising the temperature of the indoor air mass of a typical three-bedroom flat of approximately 4˚C.

The flexibility associated with hybrid dual fuel operational capabilities can further benefit consumers and other stakeholders in the electricity industry, such as electricity network operators (as detailed in the next section) and gas distribution networks who are providing the storage and flexibility available to the hybrid system.

4.3 Network Service: Supporting Integrated Distribution Networks

The full electrification of the heat industry, driven by the ambitious reductions on carbon emissions across the various energy sectors, would lead to significant changes in the electricity sector, particularly affecting electricity networks and significantly impacting consumers' bills.

In this setting, considerable electricity network reinforcements, alternative seasonal storage and wholesale insulation retrofits to existing housing stock would be necessary to accommodate the new electrified heat demand. The seasonal characteristics of demand for heat (i.e. occurring during colder months) and the increase in peaks will be significantly higher than the increase in energy demand on the reinforced electricity system, resulting in low network utilisation levels outside of peak demand periods.

In this context, the dual fuel capability of hybrid heating systems can potentially provide the necessary flexibility to defer and even avoid the need for network reinforcement without compromising the comfort levels of consumers. The ability to use gas as the primary energy source to supply the demand for heat can support network operators to reduce local electricity demand during congested periods in the network, i.e. in the event of a sudden loss of network capacity (due to a network fault or planned maintenance), heat load can shift to the gas networks and/or consumers can provide a service to the electricity network operator by reducing their demand for electricity.

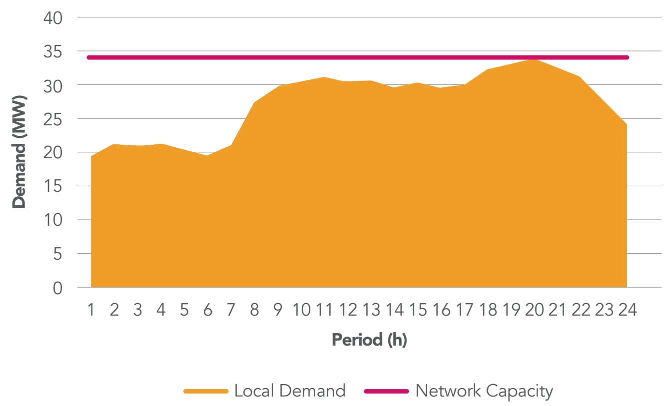


Figure 11. Local electricity demand at primary substation level and secured network capacity in a typical winter day.

Figure 11 shows the electricity demand at the primary substation level in a typical winter day and the associated secured network capacity.

As shown, during the evening hours (i.e. between 19.00 and 21.00) the primary substation demand is at its peak and is nearly overloaded. Thus, adding further to the local demand (due to the electrification of residential heat demand) will inevitably overload the distribution network and lead to necessary network reinforcements. To counter this problem, the dual fuel flexibility of the hybrid heating system can be exploited to support network operators and defer network reinforcements without compromising heating comfort levels. **Figure 12** shows the aggregated energy supply for a hybrid heating system in the same day as **Figure 11** without network support service **(a)** and considering network support service **(b)**.

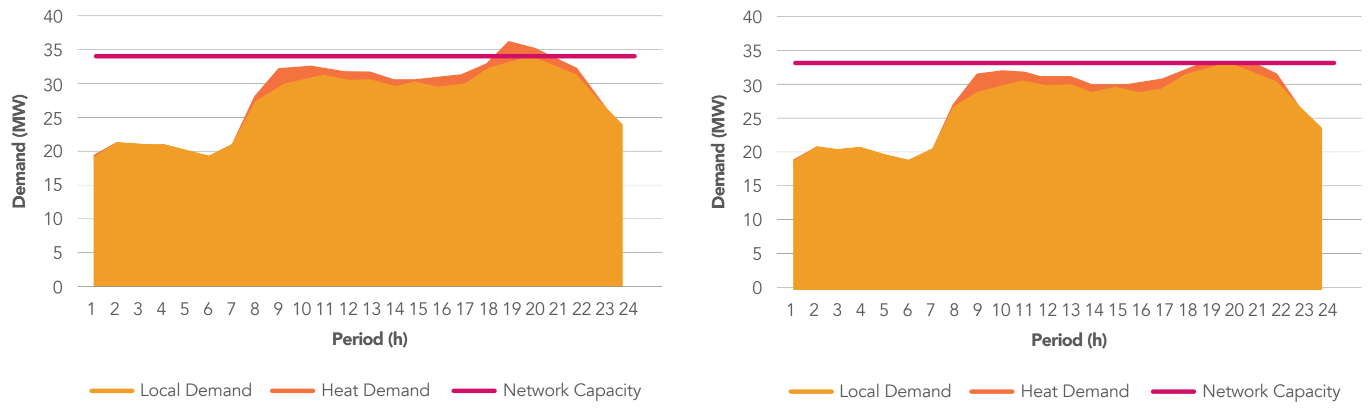


Figure 12. Local and electrified heat demand at the distribution network (a) without and (b) with network support service.

The change from electricity to gas as the energy source to supply the residential heat demand at a time of electricity network constraint may imply additional costs to end-users to maintain security of heat supply, subject to future time of use pricing ratios. Therefore, the service provided to network operators should be adequately remunerated to both compensate a potential additional cost incurred by switching to gas supply and reflect the actual benefit of deferring network reinforcements.

4.4 Frequency Response Service to the System Operator

The penetration of renewable energy sources in the electricity industry associated with the decommissioning of flexible energy sources (such as coal and oil-fired power plants) has led the system operator in GB to expand the procurement process for flexibility from gas peaking generation and also the demand side.

In this context, hybrid heating system flexibility can potentially be used to provide frequency response services to the system operator and bring additional value to the system. This capability will be assessed quantitatively in later stages of the project, as it becomes clearer from the trial phase which levels of flexibility can be realistically achieved by actual hybrid heating systems.

5.1 PassivSystems Controls

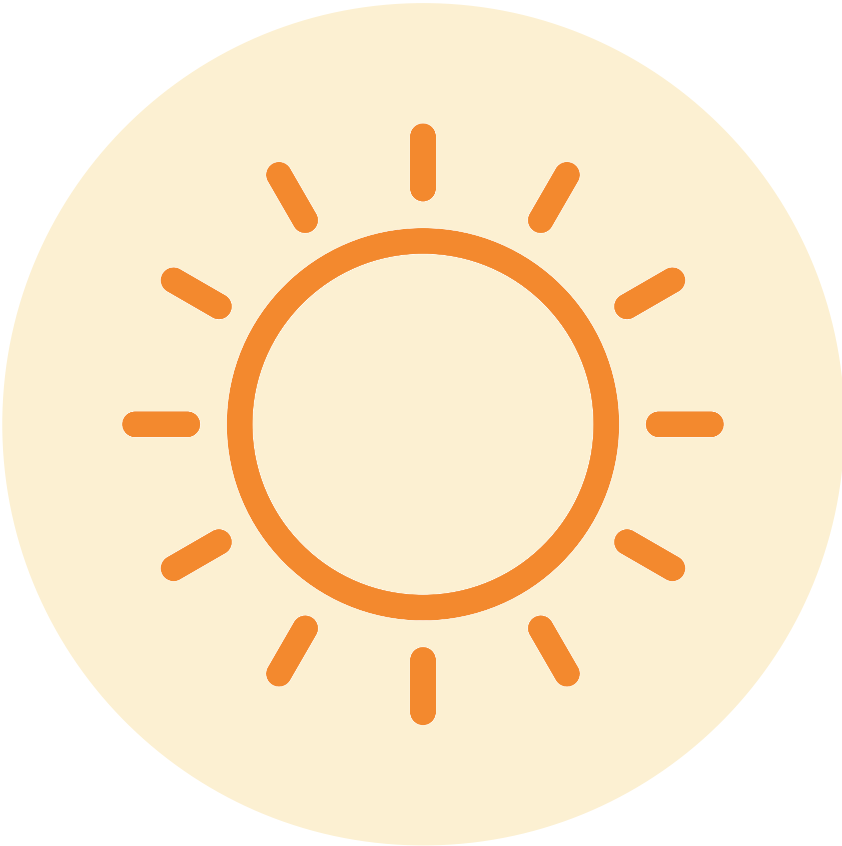
PassivSystems has developed Predictive Demand Control (PDC) technology over the last few years. The system learns the detailed thermal response of a property, and builds a physics model of the house and heating system.

Using this model, it can optimise the performance of the heating system over the upcoming day, and predict the control strategy that is required to minimise energy consumption while meeting the comfort demands of the occupiers. For example, when applied to heat pumps, PDC enables the right 'overnight setback' strategy to be chosen. Conventionally, heat pumps are controlled in one of two very different ways:

1. On a time-switch/programmer, which often results in the heat pump running for hours at an inefficiently high heating water temperature (e.g. in order to heat a house back up again in the morning)

2. On a constant weather-compensated heating water temperature, which results in unnecessary overnight heat loss (and is compounded by installers frequently choosing unnecessarily high settings)

PDC chooses exactly the right compromise between these two extremes: keeping the heat pump running gently, but ramping up slowly throughout the night using a dynamically controlled flow temperature. This allows the house to cool slightly, reducing thermal losses, while keeping the heat pump running at as low as possible a temperature. Critically, the strategy is automatically tuned to the house, so, for example, the system would choose continuous heating for a slow responding system such as underfloor heating, or turn off for some of the night if the house appears to lose heat quickly.



5.2 Demand Response with Predictive Control

As well as being able to optimise the performance of heat pumps, predictive control enables comprehensive functionality for demand management and varying energy prices: building thermal inertia can be exploited to store energy.

Demand is completely automatically shifted in order to take advantage of the lowest prices, while fitting within demand constraints and ensuring that the comfort requirements of occupants is met. Decisions are made on the basis of quantitative trade-offs between storing heat in the fabric of the building, the additional heat losses incurred, and any discomfort for the occupants.

5.3 Optimised Control of Hybrid Heating Systems

Conventional control systems for hybrid heating systems usually simply transition between electricity and gas on the basis of the current external temperature, sometimes with a region of simultaneous operation. The systems calculate the external temperature at which the heat pump produces heat at the same price as the gas boiler, due to the coefficient-of-performance (COP) dropping at lower external temperatures.

This is a natural extension of weather-compensated control, which assumes a static heat load. The Freedom Project is exploring whether there is a dynamical approach for hybrid heating systems that works better than the conventional 'external transition temperature' approach: the heating water temperature affects COP as much as the external temperature.

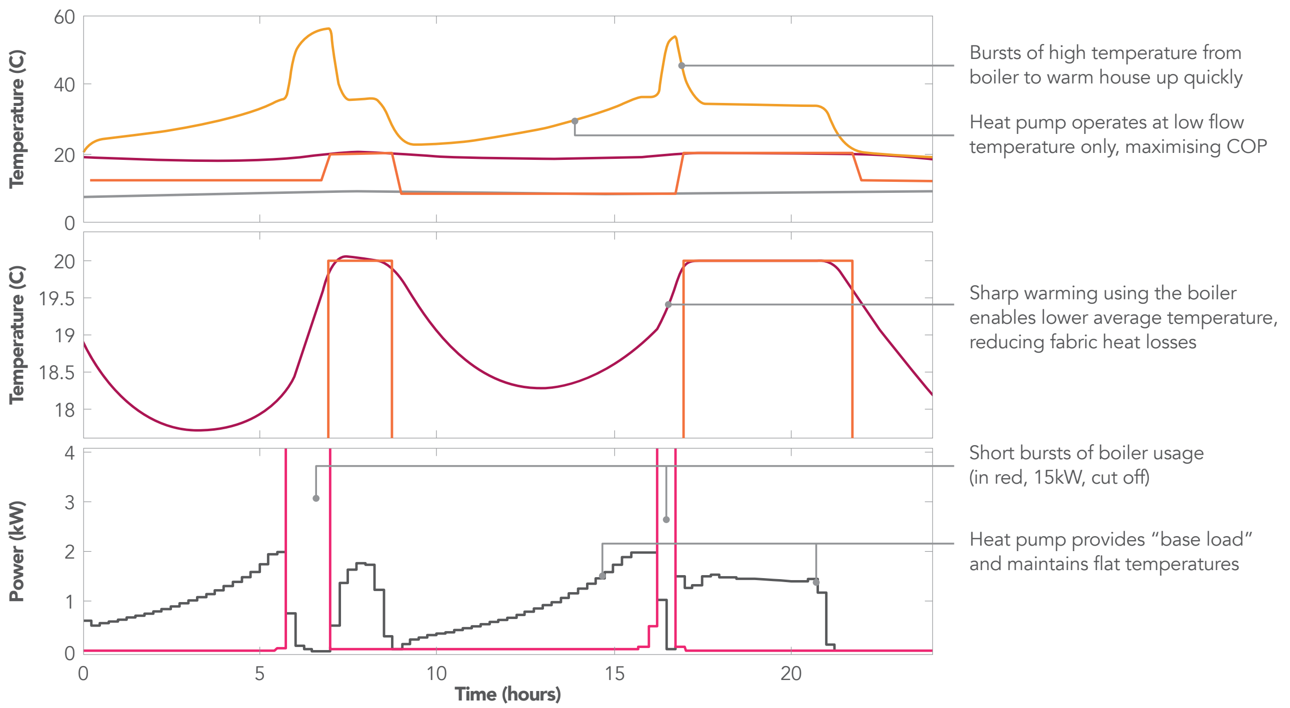


Figure 13. Graphs illustrating cost-optimised control of a hybrid system with a gas:electricity price ratio of 1:3, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom, with electricity in black and gas in red).

Figure 13 shows the fully-optimised predictive control solution for a hybrid heating system, for a scenario where electricity and gas are in close competition. Our model assumes that the heat pump and boiler simply provide alternative sources of energy to heat up the space and heat up water, without further detailed modelling of the hydraulics. We have assumed a gas:electricity price ratio of 1:3 and an empirical model for the COP of the heat pump; the predictive controller is programmed to minimise cost to the consumer.

A qualitative interpretation of the optimisation output is that the heat pump is being used to provide a baseload, keeping the house topped up with warmth with a low flow temperature, achieving a high COP; and the gas boiler provides boosts of high temperature warmth to get the house up to temperature. In warmer external conditions (not shown), the controller is able to use the heat pump on its own, and in colder conditions the boiler is needed to maintain the 20°C room temperature. In all cases the transitions are determined automatically without the need for an installer to set a transition temperature; the system just needs to know the fuel price ratio and the performance curve (COP) of the heat pump (and potentially an approximate boiler efficiency figure).

The above scenario is unfortunately not relevant for the current UK market, where the gas:electricity price ratio is closer to 1:4.5. In this scenario, the optimised controller almost never uses the heat pump (using just the gas boiler) since a COP of 4.5 is generally not achievable. So, for a realistic scenario we have considered instead an Economy 7 electricity tariff, which gives 7 hours of cheaper electricity overnight. **Figure 14** shows a fully cost-optimised solution in the presence of real-world prices (gas 3.07p/kWh, nighttime electricity 7.62p/kWh, daytime electricity 13.84p/kWh).

The behaviour is similar with the heat pump providing a baseload where its performance is worthwhile; but this does not happen during the daytime, and the boiler reheats the property on its own from cold for the evening occupied period.

It should also be noted that in both of these scenarios (and indeed all the others explored to date) there is a sharp transition between electricity and gas use, in contrast to other systems and research which includes a simultaneous operation mode with the heat pump and boiler both providing heat at the same time. Such a mode is driven by extending the conventional weather-compensated control approach, and does not take account of the possibility of dynamical water temperature.

Our results indicate that the transition between fuels should be driven by water temperature not external temperature, as this has immediate impact on system efficiency; and optimised control is proactive about providing heat in advance which has a significant effect on the control strategy. We intend to explore further whether there are benefits for simultaneous operation, whether in series (enabling the heat pump to pre-heat water) or in parallel (enabling the boiler to contribute when the heat load of the building is in excess of what the heat pump can provide).

5.4 Next Steps

Figures 13 and 14 are only two snapshots of the performance of optimised hybrid heating system for control, and as the Freedom Project progresses we are carrying out a variety of simulations covering a whole heating season, for different house models, tariff scenarios, and heating systems (comparing a hybrid heating system with an ASHP operating alone, or a boiler operating alone).

Demand profiles and load duration curves will be produced for each case and used as inputs to the whole system modelling carried out by project partners, to understand the whole energy system implications. The same energy system models will be used to investigate real-world flexibility and how, in practice, the in-house operation of the home would be affected by the requirements of the electricity and gas networks, without affecting the comfort of the occupants.

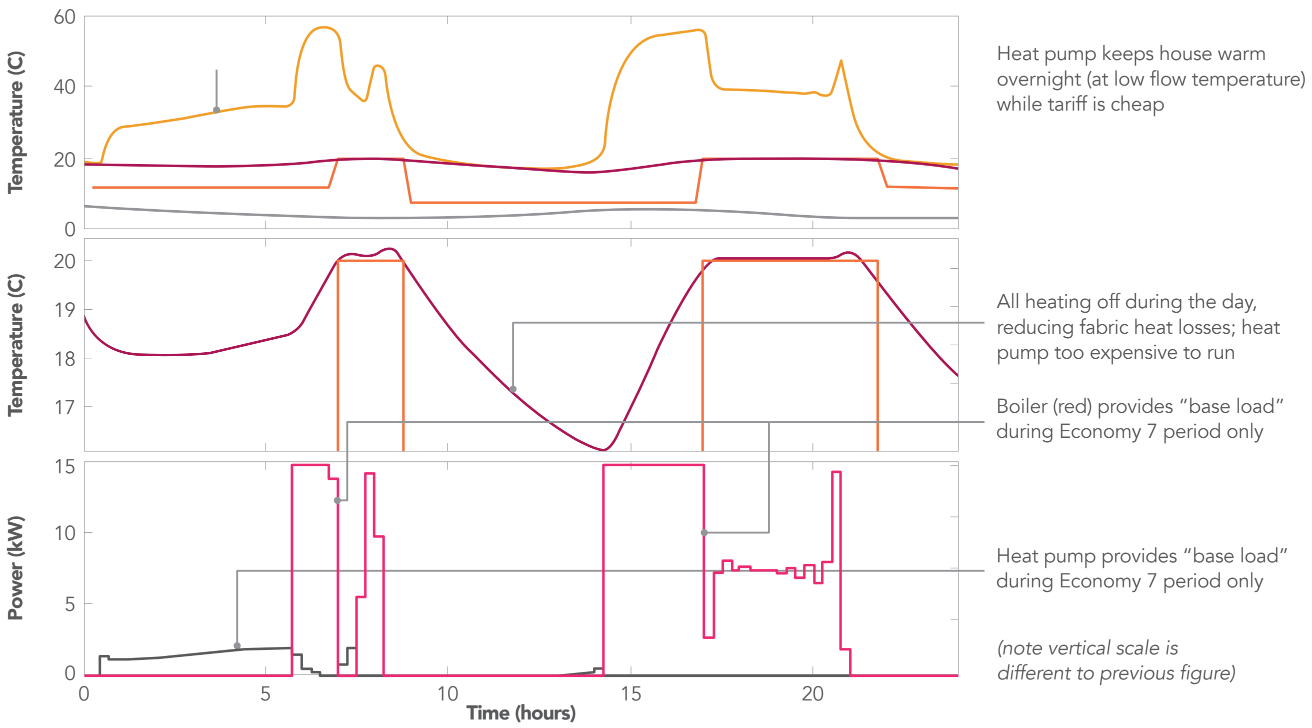


Figure 14. Graphs illustrating cost-optimised control of a hybrid system on an Economy 7 electricity and current (Oct 2016) prices, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom, with electricity in black and gas in red).

5.5 Preliminary Conclusions

Hybrid heating systems have significant potential for decarbonising UK domestic heating, including electrical heating systems, in a cost-effective manner while ensuring grid congestion is kept manageable. Smart technology will be required for coordinated control to provide the necessary level of grid flexibility, and making the systems attractive to householders by maintaining comfort levels at affordable cost. The Freedom Project is providing the first comprehensive exploration of the real value of hybrid heating systems, through a sufficiently large field trial backed up by a broad programme of research.

In this interim report, we have presented detailed plans for the project as well as some early results. Our preliminary conclusions are:

- Take-up of hybrid heating systems will be very difficult with current UK electricity prices. Although there is some potential for exploiting tariffs like Economy 7, the government will need to take steps to make electricity relatively cheaper in order to progress towards decarbonisation.
- Conventional approaches to controlling hybrid (or bivalent) systems with a simple transition between fuels based on external temperature are likely to perform poorly compared to a fully optimised system; control systems should focus on the heating water temperature, which closely determines efficiency.
- The best control strategy for a hybrid heating system is to utilise the boiler to provide bursts of heat to warm the house up quickly, with the heat pump providing temperature maintenance and a 'base load' during periods where a fully warm house is not needed. A smart system is required to implement this strategy.
- The decision to switch fuel between gas and electricity can be determined automatically based on learned thermal house properties (combined with current conditions and occupant thermal requirements), without any need to manually choose a transition temperature (which is unlikely to be optimal).

The role of a smart home energy management system (such as that provided by PassivSystems) is to interface with the smart grid and provide a realistic representation of the demand flexibility of the household. The purpose of the flexibility is firstly to ensure that local gas and electricity networks are within their operational limits, and secondly to deliver income streams from electricity markets and balancing mechanisms. It is crucial that these systems incorporate the thermal comfort requirements of house occupants, and communicate effectively to gain householders' trust, otherwise it will be difficult to gain wide-scale acceptance of smart grid-connected heating systems.

6. Field Trial Hybrid Heating System Experiments

Over the course of the Freedom Project main field trial, a number of interventions are being set to change the operation of the hybrid heating systems from their 'baseline' control strategy (minimum cost to consumer) to explore other scenarios and meet the research objectives of the project.

As a matter of course, homes are being moved back to the 'baseline' control strategy whenever possible, to avoid impact on consumer bills (as any intervention will increase consumer energy costs slightly).

The interventions being delivered include:

- **Different fuel cost ratios** (i.e. lower electricity price relative to gas) to explore future price scenarios, including hydrogen prices for potential hydrogen cities;
- **Fixed patterns** of time-varying electricity tariffs and restricted-consumption periods as a simple proxy of the smart grid representative of renewable generation intermittency;
- **'Impulse' experiments** to look at the effects of highly simultaneous fuel switching on both electricity and gas networks;
- **Forecast** electricity grid carbon intensity; and
- **Aggregated demand management** to simulate avoiding the capacity limit of an electricity subnetwork.

The approximate timeline is shown in the diagram below:

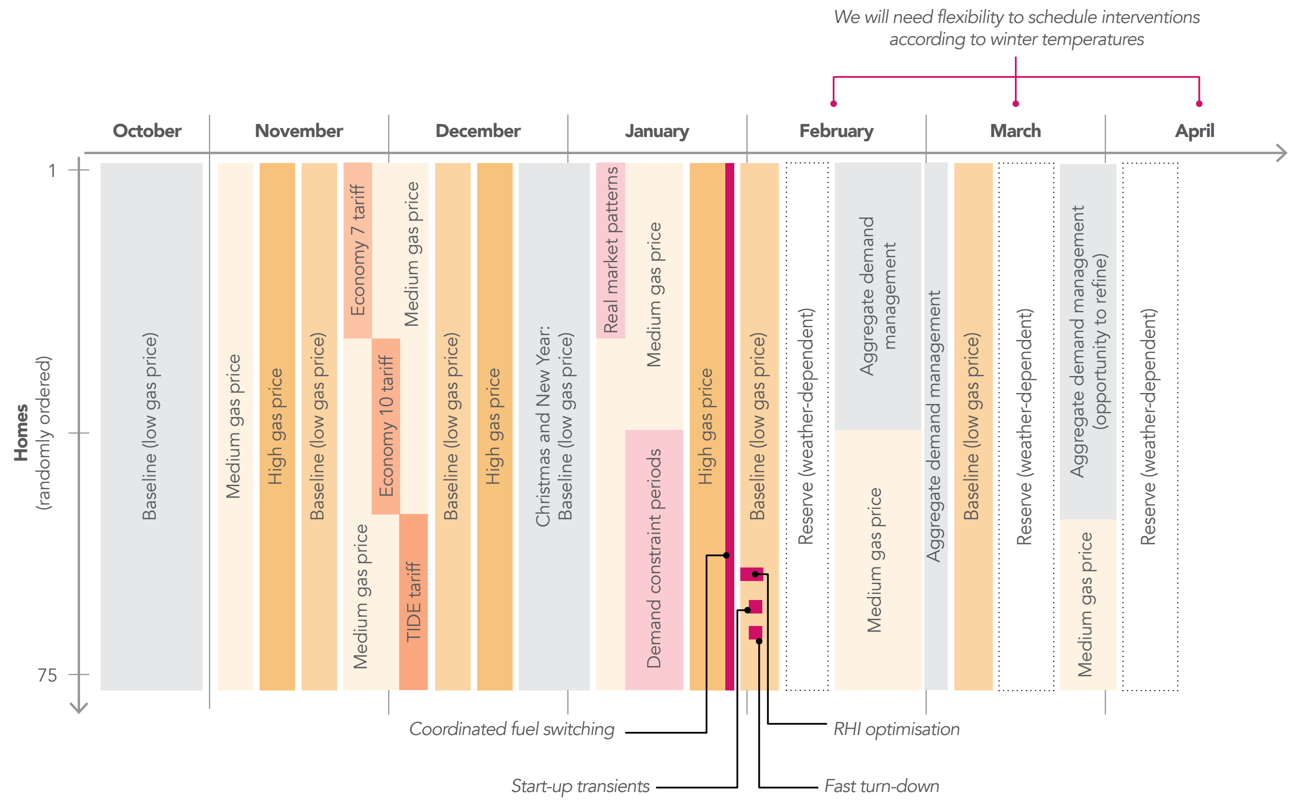


Figure 15. Intervention timeline

Note that all interventions are carried out remotely without the need to revisit properties. Wherever possible, populations of homes will be chosen completely at random from the pool of available properties (despite the visualisation above).

In the rest of this section we describe the interventions in more detail, but firstly consider consumer impact during the interventions.

6.1 Consumer Impact

COMMUNICATION

Triallists will be kept informed of the phases of the project, and told to expect that the patterns of operation of their heating systems are likely to change over the course of the winter, but they will not be provided with detailed updates on when their homes are being used in experiments. Instead, triallists will be able to see what's happening in their homes via the graphical explanations feature in their app; virtual price scenarios will be reflected here.

RUNNING COSTS

The costs to run the home heating will be increased above the baseline by the experiments (although it should be noted that running costs will still be less than prior to the trial due to the new gas boiler and PassivSystems optimised control). Triallists will also have the 'budgeting' feature in the app to help them reduce their heating costs (note that during experiments the figures will change to reflect the cost to them of the experiment if it were applied permanently).

THERMAL COMFORT

Triallists will at all times be in control of the thermal comfort via the PassivLiving app – this will be honoured at all times by the system. They will not be given any means of opting out of demand response periods in-the-moment (as these interventions will not impact their thermal comfort, as they will involve fuel switching only). However, triallists may opt out altogether if they are unhappy, and will be excluded from future experiments.

DOMESTIC HOT WATER

Production of hot water will be unaffected throughout the trial, as it is always produced by the gas boiler.

6.2 Exploring Price Ratios

A key project aim is to understand the performance and running costs of hybrid heating systems as part of future national scenarios.

This means we need to measure their operation in different **weather conditions** (so that results can be extrapolated to the whole of a winter season) and also in different **price situations** (so that results can be extrapolated to future scenarios where electricity and gas prices are different). We also need to understand the real-world effect of diversity: this has emerged from the simulation work as a key unknown, and is very important when considering the impact of the peak power consumption of a fleet of heat pumps.

To understand this, we need to determine the price scenarios we are considering, and ensure they are applied across a variety of weather conditions. The challenge is that consumers are billed for energy according to today's prices – so any change from this will increase their bills slightly – so we need to avoid homes spending too long on tariff figures far from the real ones.

Extreme cold weather is of particular interest as this is the scenario when the future electricity grid will be most stressed by heat pump load, and secondly we wish to explore the capacity limit of the heat pump: switching fuel to the gas boiler not because it's cheaper, but because the heat pump no longer can produce enough heat to keep the house warm.

There may be only one major cold snap in the winter of 2017-2018; our proposal is to suspend all other experimentation when this happens (likely January) and push a high gas price scenario to all heat pumps.

For this intervention, we will apply different price ratios for whole-week periods to all the Freedom Project homes.

- We will use gas:electricity price ratios of 0.222 (low gas price, default, representing current prices), 0.26 (intermediate gas price, matching that used for many of the simulations) and 0.33 (high gas price, the highest ratio Delta-ee predict that we're likely to see).
- A whole-week period ensures that we cover both weekday and weekend behaviours.
- Extending to all Freedom Project homes means that we can yield full diversity data (using all homes simultaneously makes the most of the sample size).
- If a particularly cold snap arises, we will prioritise this intervention and push a price ratio of 0.33. Later cold snaps will be used for other price ratios or other experiments.

6.3 Time-varying Patterns

Once we have understood the performance of hybrid heating systems in isolation (i.e. focused on the needs of each householder individually), we need to move on to understanding their demand flexibility: what happens when the wider network requires them to shift electricity demand?

This is a very broad question, and we propose tackling three different and more specific questions:

Q.1

How do demand patterns change under tariff patterns that are available today to consumers?

Q.2

How do demand patterns change if electricity costs directly reflect market variations?

Q.3

How do demand patterns change if electricity consumption has simple restrictions applied at peak periods?

6.3.1 Real-world Tariff Patterns

We propose setting homes to run for a period on the following virtual tariffs:

- **ECONOMY 7:** cheap rate 00:30GMT to 07:30GMT **55% cheaper than peak rate.**
- **ECONOMY 10:** cheap rate 00:00GMT to 05:00GMT, 13:00GMT to 16:00GMT, and 20:00GMT to 22:00GMT, **55% cheaper than peak rate.**
- **TIDE TOU TARIFF:** peak rate 16:00GMT to 19:00GMT **(208% of normal rate); cheap rate 23:00GMT to 06:00GMT (41.6% of normal rate).**

In each case we will assume gas prices to match the 'intermediate' scenario (gas:electricity price ratio of 0.26) above, taking account of the peak rate in the variable tariff scenario being higher than a normal unit rate. Although a ratio of 0.22 is representative of the real world at the moment, there will be very little electricity used in the flat tariff scenario, so we believe a ratio of 0.26 will give more insight into electricity demand flexibility. The comparison group will use a 0.26 ratio.

These scenarios are of particular interest to the gas network due to the sudden simultaneous tariff changes; we will consider the gas network consequences when analysing data from these scenarios.

6.3.2 Real Market Variations

We intend to run a scenario where day-ahead half-hourly electricity prices are used to influence heating system running.

The process will be to extract half-hourly cost values (£/MWh) for the following day after the 15:30 auction, transform these into realistic consumer prices (e.g. by adding distribution costs) that maintain significant variations, and push them to the portfolio of (~20) homes (as half-hourly electricity price variation for the next day). As previously, a second group of 20 homes will act as a comparison on flat average profiles.

6.3.3 Demand Constraint Periods

We propose imposing a simple restriction on the electricity consumption of the hybrid heating systems during the early evening peak, for example:

Consume no more than 1kW on average during the period between 5pm and 7pm

Note that the right time to choose is not necessarily the peak heat pump consumption – it should be chosen to represent the peak strain on the electricity network as a whole.

6.4 Impulse Experiments

There are a number of individual experiments we would like to carry out, which are unsuitable for extended periods of operation. These will be scheduled during the winter period; many of them require background heat pump operation so will be implemented during periods when the virtual price ratio is set higher.

The experiments planned are as followed:

START-UP TRANSIENTS
Heat pumps have an impact on the local electricity network due to current spikes at start-up and reactive power, as well as general demand.

FAST TURN-DOWN BEHAVIOUR
For grid services such as Fast Frequency Response there is a need to turn off load very quickly, perhaps even sub-second.

COORDINATED SWITCHING
The entire portfolio simultaneously switched between electricity and gas with no notice (following on from the last two experiments, but involving all homes). A few homes will be selected to have rapid electricity monitoring during this period.

RHI OPTIMISATION
Where this system is configured to maximum net cost to the consumer including RHI (Renewable Heat Incentive) income (paid at a fixed rate per unit of renewable energy consumed, as bivalent systems are metered).

6.5 Aggregate Demand Management

The final intervention will make full use of PassivSystems aggregated demand management technology, and addresses the central challenge of the Freedom Project: the scenario where many homes have moved over to heat pumps in order to decarbonise home heating, but the electricity network does not have enough capacity to meet the load.

The project's proposed solution to this problem is the hybrid heating system: when the electricity network nears its capacity, heating load is intelligently switched over to gas.

Half-hourly settlement: If time permits we will carry out a 'time-limited' variation, where the aggregated demand cap only applies to one or more half-hour periods, to emulate a scenario where an energy supplier has under-purchased electricity and wishes to reduce consumption to that level.

7. Hardware, Metering And Data Processing

Three different ASHPs were included in the trial. Each utilised the plumbing configuration recommended by the installer, and the smallest size heat pump available.

MasterTherm

BoxAir BA22i heat pump (8kW) – **43 installs.**

Samsung

EHS Mono heat pump (5kW) – **16 installs.**

Daikin

Altherma integrated hybrid heat pump (5kW) – **16 installs.**

RETROFIT:
In MasterTherm homes a Vaillant Ecotec Sustain 24kW gas boiler was installed. In Samsung homes a Worcester Bosch 30i (30kW) gas boiler was installed. In one private home a MasterTherm heat pump was added to an existing gas boiler to demonstrate retrofit feasibility.

DOMESTIC HOT WATER:
All installations had a gas combination boiler, except three installations which were system boilers with a hot water tank. In these cases, hot water was heated entirely by the gas boiler and control logic was set up to avoid running the heat pump shortly after a hot water cycle due to high temperatures.

GAS SUPPLY:
We have not captured gas price data but our assumption is that a typical gas unit price is 2.93p/kWh. Three homes (two Daikin, one Samsung) are on LPG, with an assumed price of 6.20p/kWh[6].

ELECTRICITY SUPPLY:
We have not captured electricity price data but our assumption is that a typical electricity unit price is 13.146p/kWh (flat rate). No homes are known to be on variable tariffs (such as Economy 7).

[6] *Prices retrieved from USwitch 10th October 2017 for the Bridgend area. LPG price from extralfuel.co.uk (who provide fuel for one of the householders).*

7.1 Measurement Configuration

From each home the following data points were reported:

- Energy flows through the system;
- Comfort of the householder; and
- Performance of the heating systems.

From each home the following data points were reported:

- Whole home electricity consumption via Loop Electricity Monitor (15-minute frequency)
- Whole home gas consumption where possible via Loop Gas Monitor (15-minute frequency)
- Heat pump electricity supply metered with SmartRail meter (one-minute frequency), measuring the following quantities[7]:
  - Cumulative energy consumption (kWh)
  - Instantaneous power consumption (kW)
  - Cumulative reactive energy (kVArh)
  - Instantaneous reactive power (kVAr)
  - Voltage (V)
- Sontex 440 heat meter (RHI compliant) or a Sharkey 775 (not RHI compliant) measure the output from the heat pump only (one-minute frequency), measuring the following quantities:
  - Cumulative energy (kWh)
  - Instantaneous power (kW)
  - Flow temperature (°C)
  - Return temperature (°C)
  - Cumulative volume (L)
  - Flow rate (L/hour)
- Pipe temperatures on the overall flow and return to the heating system (non-invasive sensors, reporting 0.1°C resolution on-change)
- Room temperature (0.1°C resolution on-change)
- Bedroom temperature (0.1°C resolution on-change) and humidity (hourly)

[7] *Can be remotely configured to report every few seconds in short bursts.*

7.1 Measurement configuration

These data points are indicated in the diagram below. The configuration is slightly different for Daikin units with the integrated unit with the boiler and heat pump in series.

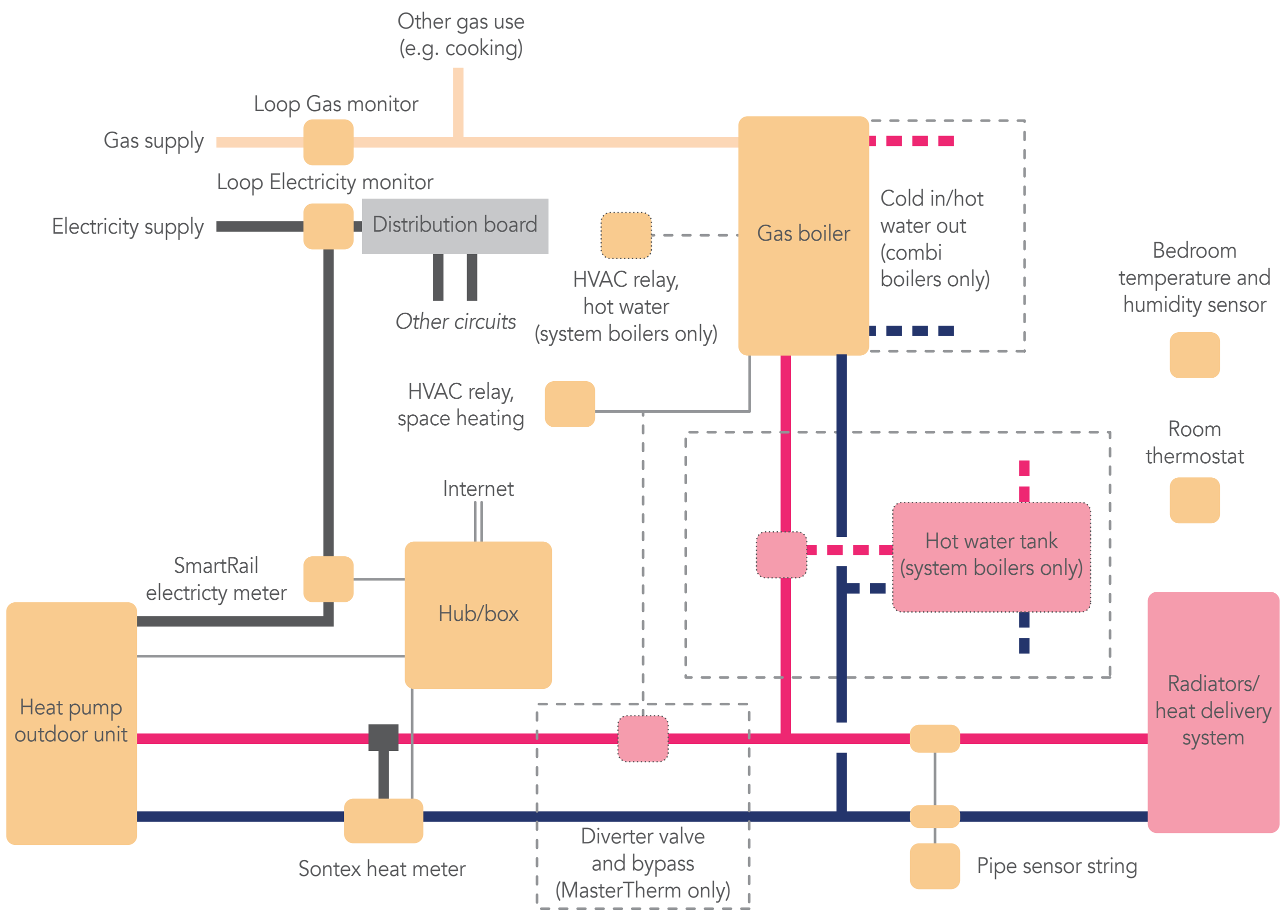


Figure 16. Meter schematic

8. The Customer Engagement Framework

One of the biggest challenges of deploying any new heating technology is getting the end-users (i.e. householders) engaged with it and trusting that the system is working properly and to their advantage (i.e. keeping them warm while saving them money).

This research stream of the Freedom Project looks at hybrid heating systems from the perspective of the consumer, (a) to ensure that they are engaged throughout the project, and (b) to ensure that the heating system user interfaces are friendly and gain consumer trust.

Delta-ee has designed a Customer Engagement Framework that includes effective communication throughout the trial, including recruitment, understanding how to control the heating system, and providing feedback to the project partners. New and enhanced user interfaces will be deployed in the 2017-18 heating season, helping householders to communicate their comfort requirements in a straightforward way, and explaining some of the counterintuitive ways in which hybrid heating systems are controlled for highest efficiency.

This will have a focus on gaining the trust of the consumers, understanding their energy consumption, and feeling in control of the system and that they are not being exploited by operators of demand response services (e.g. perhaps receiving their fair share of the income stream, or a fixed incentive).

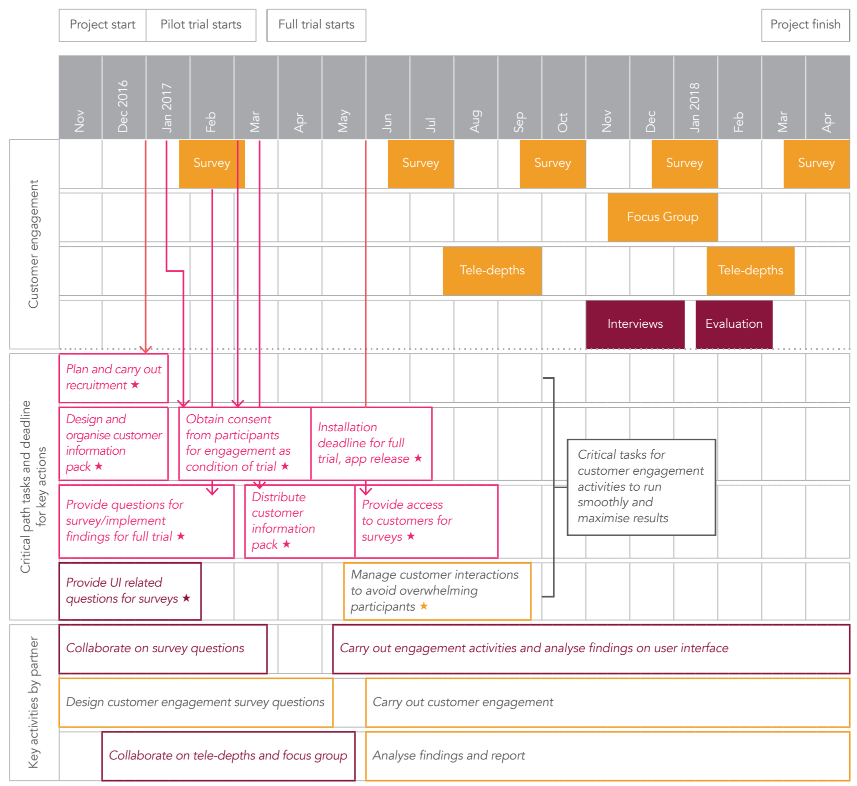


Figure 17. Customer engagement framework and engagement timeline, designed by Delta-ee

9.1 Recruitment Challenges

75

Finding 75 homes to have a hybrid heating system installed and newly designed heating controls was always going to be challenging. Through successful partnerships, events and incentives, we were able to secure 75 homes.

9.2 Registered Social Landlord Partnership

40

PassivSystems approached Wales & West Housing Association, who are one of the largest Registered Social Landlords (RSL) in Wales with 11,500 homes. They have won many awards for innovation and sustainability, and were delighted to take part in the project. Wales & West Housing Association provided 40 homes.

9.3 Private Homes

35

PassivSystems secured the remaining 35 homes through the support of Bridgend MP Madeleine Moon, Bridgend County Borough Council and working with local organisations such as Bridgend College, Ford Manufacturing, Western Power Distribution (WPD) and Sustainable Wales – these parties fully supported the project and promoted the project within Bridgend.

9.4 Information And Education

As the delivery partner of the Freedom Project, it was PassivSystems' responsibility to ensure that people and organisations of Bridgend were fully informed about the project and understood the goals and objectives.

Between February and June 2017, PassivSystems boosted the profile of the Freedom Project in Bridgend through a range of activities; presenting at local organisations and communities, hosting project workshops and conducting project question and answer sessions.

The project partners collaborated to produce customer-facing literature designed to give interested people and organisations of Bridgend an overview of the Freedom Project, a hybrid heating system and what to expect if interested in being part of the trial.

A well-thought out project overview, with a supplementary question and answer leaflet and contact details for further information ensured that interested tenant and homeowner stakeholders were informed and educated.

9.5 Incentivisation

The Freedom Project recruitment and consumer engagement activities have been a success to date as a result of the Project Partners collaborating to investigate, evaluate and implement the correct incentive strategy. The incentive strategy considered a variety of homeowner participants as the Project Partners aimed to have a mix of homes; private homeowners, social landlords and social tenants.

PassivSystems and Delta-ee have completed similar projects in the past and the following incentives have improved customer recruitment statistics and customer engagement:

- Free state-of-the-art heating system – supplied, installed and service package
- Efficient heating system
- Gas/electricity bill savings
- Cash/vouchers
- Project responsibility

It is has been important that the Project Partners continued to engage with the community and demonstrate these benefits. Highlighting to participants and demonstrating that their involvement will contribute to these ancillary benefits for Bridgend will encourage better customer engagement.

10.1 The Pilot Trial

The purpose of a four-home pilot installation in February 2017 was to assess the selected hardware, installation contractors and project customer engagement. The completed pilot trial enabled the project team to finalise the planning for the 75-home main trial installation that commenced in June 2017.

10.2 Hardware

Figure 18. Daikin installation

Figure 19. Samsung installation

Figure 20. MasterTherm installation

The assessments of the three hybrid heating systems and the installation contractors were extremely positive. This pilot trial report was reviewed by Wales & West Utilities and they recommended the use of all three hybrid heating systems as each of them offered something different.

- Samsung (5kw) heat pump and Worcester 30i boiler, a budget range hybrid heating system.
- Daikin (5kw) Altherma hybrid heat pump, a fully integrated hybrid heating system and market leader.
- MasterTherm heat pump (8kw) and Vaillant EcoTech boiler, a high-end heat pump with an internet-enabled control box and a brushless DC (BLDC) compressor with ZERO starting current.

The decision to use three different hybrid systems was an additional cost but has provided much greater project learnings.

10.3 Customer Engagement

Interviews were conducted in the post-installation phase of the pilot trial to understand and learn from the installation process and to help the full trial run more smoothly:

"Up-front information was very good – especially the presentation

"Post installation information was good in terms of manuals, but it would be useful to have a better understanding of how the heat pumps might operate and the differences without existing system

"It would be useful to leave customers with more written information prior to installation to remind them of the presentation

"Liked being able to decide where equipment would be located including pipes, cables, etc

"Issues around noise, visual impact, air flow, addressed well by the installer

"I feel very lucky to have the opportunity to have this installed for free – big incentive!

"Very happy to participate in surveys – online would be good. A financial incentive won't drive me but may help with some people

"Installers did a very good job – polite, careful of people and property including protecting carpets

"Everybody individually during the installation was very helpful, but needed to be better co-ordinated

Figure 21. Post-installation feedback from pilot trial customer interviews

The findings were positive with a free hybrid heating system acting as a strong incentive. Some teething problems were encountered but were understood by the customers and are part and parcel of a pilot trial.

10.4 Key Learnings

Following the pilot trial installations that took place in February, a review took place to identify areas that had not been considered previously, potential issues, risks, technology assessment and to gain feedback from the homeowners. The key learnings from the pilot trial are the following:

Coordination between PassivSystems and the installation contractor

Once the hybrid system installation and the meter and monitoring equipment had been installed, PassivSystems would have to enter the home and connect these items to the Passiv hub. Between the homeowner, the installation contractor and PassivSystems we had to arrange availability to do this and it took more effort/coordination than expected. In the main trial the installation contractor connected the hybrid heating system, meters and monitoring equipment straight after the hybrid heating system had been installed – this pilot trial learning allowed for the main trial to have a fluid process and minimal visits to the home.

A lack of literature pre-pilot trial

Following the survey conducted by Delta-ee it was highlighted that a lack of literature was provided. All four homes were very enthusiastic about the project and wanted to know more than we had expected.

The project team drafted detailed Freedom Project literature for the main trial and home recruitment to ensure they had a full overview of the project.

11. The Installation of 75 Hybrid Heating Systems

The 75 hybrid heating system installation work package commenced in June 2017 and was completed in early October 2017. Typically, a hybrid heating system installation was completed in two to three days and an additional day was allocated for the installation of the meter and monitoring equipment.

The installation plan was designed to start slowly and initially only installing MasterTherm hybrid heating system units, this was to ensure that any potential installation issues would be highlighted and could be addressed. Once confident of installing multiple units of the MasterTherm unit we initiated an identical process with the Daikin unit and eventually the same exercise with the Samsung unit.

PassivSystems ensured that all installations complied with Construction Design Management 2015 regulations, this included: a pre-construction information pack, construction phase plan and appropriate pre-construction meetings. Since the installations commenced, PassivSystems has had weekly reviews with all sub-contractors and our RSL partner, Wales & West Housing Association (WWHA).

At the end of each installation, a PassivSystems representative demonstrated to the tenant/homeowner the PassivLiving app and answered any questions about the app or project.

PassivSystems has demonstrated that it is feasible to install optimised hybrid heating systems and smart controls on **three different hybrid heating systems in 35 private homes and 40 social homes.**

PassivSystems has demonstrated retrofitting 75 hybrid heating systems to existing home wet systems, including; three hybrid systems with a system boiler setup, three hybrid systems not on the gas grid and using Calor gas and an ASHP retrofitted to an existing boiler to become a hybrid heating system.

12. Pre-Main Trial Customer Findings

Survey 1 was the pre-installation survey, with the questions focused on perceptions to hybrids and demand-response pre-trial, as well as expectations for the hybrid heating system.

Out of the 50 responses to the pre-trial survey it has been clear that there is a challenge around encouraging uptake of hybrid heating systems. Participants in this trial show similar characteristics to other customer research on a larger scale:

- Customers are overwhelmingly positive about their existing heating system; they will therefore not automatically see the value in an alternative technology.
- There is low awareness to alternatives to their current system, both of heat pumps in general and specifically hybrid heating systems.
- However, as found in Delta-ee customer research over a number of years, appeal is positive once the technology is explained, highlighting the significant potential to engage customers with this technology.
- Overall only 13% of customers were dissatisfied with their existing heating system and a huge 70% would recommend their existing heating system to a friend or family member
- Customers prioritise peace of mind and ease of use and 80% of our sample rated their current systems highly for this. Reliability was also important and highly rated.
- There is room for improvement around running costs – 50% of respondents stated these were 'neither good nor bad' – and potentially around controls, although a majority still found these easy to use.
- Only 12% found their current controls difficult to use, but this could be because, surprisingly, 40% already have a smartphone app to control their system. After this, manual control was preferred.

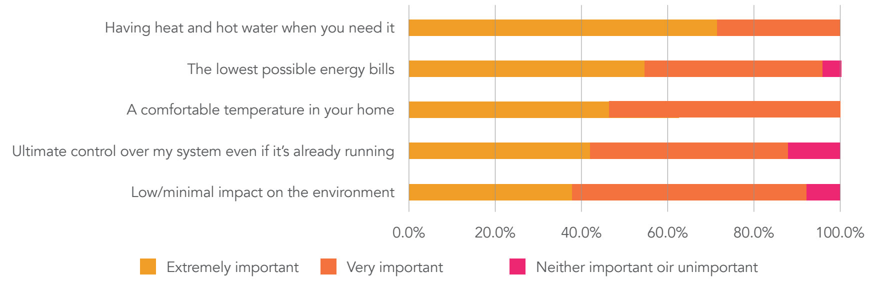


Figure 22. What is important for the customer?

Customers prioritise reliability, low bills and comfort above other factors – but they are all important to them:

Overall these results indicate that awareness could be a barrier to hybrid heating system uptake. Positively, appeal is high for all of the potential benefits of hybrid heating systems – but if customers do not know a technology option is available to them they cannot invest. Unsurprisingly, running cost savings are the biggest customer driver, but having a product for free and using a combination of fuel types also rated highly.

Twelve per cent of participants had what they considered good or excellent knowledge about hybrid heating systems prior to the trial, this was the same for heat pumps in general. Hybrid heating systems were appealing to participants once explained, with running cost savings viewed as the biggest advantage. Nearly 90% of respondents found the idea of hybrid heating system appealing to some degree and 50% said they were very appealing. The reason for this is largely the promise of lower energy bills, but all other motivators we questioned also showed strong appeal.

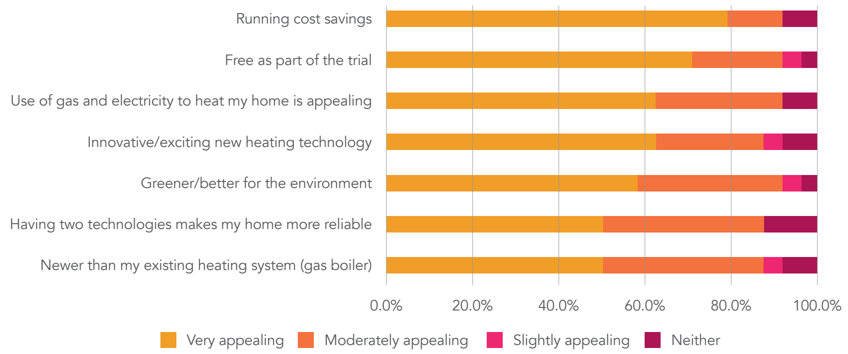


Figure 23. The reasons for considering a hybrid heating system.

Overall awareness of flexibility and demand response was higher than we might have expected. Fifty per cent of people said they had good knowledge of it, which is positive considering it is not a common offering at present in the UK. The majority of participants were not overly concerned about having a hybrid heating system installed, which shows that during the trial the systems were explained well to customers. This is also reflected in the fact zero respondents felt they did not understand the technology enough. However, for those that had some concerns, it was to do with reliability, running costs and the availability of installers.

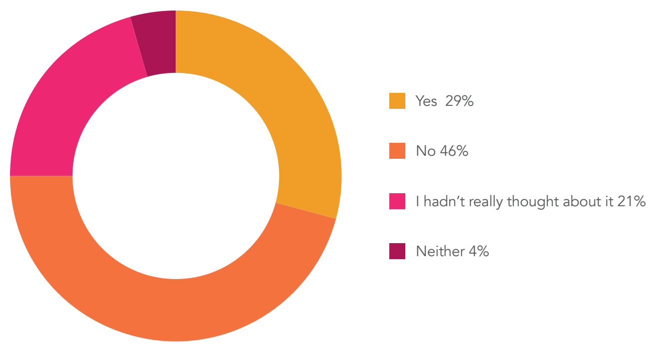


Figure 24. Concerns about hybrid heating systems

13. Summary

The Freedom Project has developed and tested algorithms for optimised hybrid heating system controls. The project team has developed methodologies for assessing the impact of hybrid heating systems on electricity distribution planning and gas network operation, listing the required data inputs and the produced outputs, and providing explanatory case studies on typical UK electricity and gas networks. The methodologies are currently being tested in the main field trial.

CONTROLS: HIGH-LEVEL DESIGN

The project partners have collaborated to produce the use case specification; process flows and the high-level design for the hybrid heating system control. PassivSystems has designed a control approach that incorporates fuel switching into existing load shifting approaches and has designed the interface into the hybrid unit and coordinates with the PassivSystems control the on-board control functions.

CONSUMER INTERFACE/HEAT PUMP INTERFACE DESIGN

Working with City University, PassivSystems has produced a detailed design, development and unit-testing of the user interface, including the guidance of City University best practice and research outcomes, smart meter tariff and consumption information.

MARKET INTEGRATION STRATEGIES, MARKET OPTIMISATION AND MARKET PROJECTIONS

Imperial College, Delta-ee and PassivSystems have developed models of value optimisation strategies against real market data; analysis of future market opportunities and current trends; updated control parameters; and analysis of new business opportunities arising for network operators from the emergence of hybrid-heating systems.

CONSUMER ENGAGEMENT AND DESIGN

PassivSystems has worked closely with Delta-ee to develop a suitable 'customer touch point plan' on how we engage with consumers. City University was closely involved and will be involved in a number of workshops throughout the 2017-18 heating season with consumers. We have assessed the likely perception of hybrid heating systems and identified how network operators can work with customers to promote uptake where desirable. This work has included new primary research into customers with Delta-ee's customer panel, focused research with the hybrid heating system trial customers, and used existing Delta-ee research from their Heat Insights and Heat Pump Research Services.

CUSTOMER RECRUITMENT AND PILOT INSTALLATIONS

The Freedom Project has delivered a four-pilot home trial installation, which supported the development of the documentation to support the main 75-home trial, review customer engagement and data analysis.

MEASUREMENT SPECIFICATION

PassivSystems has produced the metrics and measurement regime for the main 75-home trial. The Freedom Project now presents an early-stage methodology for assessing the business case for deployment of hybrid heating systems, has listed the required data inputs and the produced outputs, and is providing explanatory case studies in the context of the UK energy system.

75-HOME RECRUITMENT AND INSTALLATION

PassivSystems has successfully recruited 75 homes, installed 75 hybrid heating systems and is following the 'customer touch point plan' to ensure the triallists are regularly engaged with and educated about the Freedom Project.

CONTROL DEVELOPMENT AND TESTING

The Freedom Project is demonstrating a detailed design, development and unit testing of the PassivSystems hub hybrid control, demand forecasting, demand dispatch, service level monitoring algorithms and the hardware connection between the hub and the hybrid heating system. The first phase of the development of the consumer hybrid heating controls interface is complete.

Next steps

CONTROL DEVELOPMENT AND TESTING

In January 2018, PassivSystems will update the hybrid heating controls to provide budgeting features that will enable the triallists to determine a heating set point regime. Testing will include the creation of simulation scenarios to validate different use cases.

City University will conduct research into consumer trust, associated interface adaptations and delivery of heating budget data to consumers so that users will be able to specify a set point or budget to determine thermostat settings.

AGGREGATION PLATFORM

PassivSystems is developing and unit-testing a server level aggregation platform of individual home hub demand forecasts, demand response planning and demand response execution. This innovation will create portfolio level demand forecast and intelligent load shifting.

SYSTEM MODELLING UPDATE

Imperial College and Wales & West Utilities will update their modelling with the optimised hybrid heating systems trial data. The trial data will be used to assess the impact of optimised hybrid heating systems on electricity distribution planning and gas network operation, listing the required data inputs and the produced outputs, and providing explanatory case studies on typical UK electricity and gas networks.

MARKET INTEGRATION STRATEGIES, MARKET OPTIMISATION AND MARKET PROJECTIONS UPDATE

Imperial College, Delta-ee and PassivSystems will input the trial optimised hybrid heating systems data into the models of value optimisation strategies against real market data; analysis of future market opportunities and current trends; updated control parameters; and analysis of new business opportunities arising for network operators from the emergence of hybrid heating systems.

REPORTING

The Freedom Project team will produce an academic research publication; presentation material for academic and industry conferences; and a White Paper with market, regulatory and policy recommendations for realising the value of flexible hybrid heating systems.

Freedom Project