Early results from the FREEDOM project: fully-optimised hybrid heat pumps providing demand flexibility

Edwin Carter[a]*, Oliver Lancaster, [b] Faithful Chanda[c]

[a]PassivSystems Ltd, Benyon House, Newbury Business Park, London Road, Newbury, RG14 2PZ, UK
[b]*Wales & West Utilities Ltd,Wales & West House,Spooner Close, Celtic Springs, Coedkernew, Newport, NP10 8FZ, UK*
[c]*Western Power Distribution plc,Pegasus Business Park, Castle Donington,Derbyshire, DE74 2TU, UK*

Abstract

The FREEDOM project is a trial of smart control technology for hybrid heat pumps. Allowing a heating system to switch between gas and electric load provides greater customer value, a route towards decarbonisation, and complete flexibility on the electrical load for demand-side management, but no existing hybrid heat pumps are controlled in a fully optimised way that balances the needs of the consumer and the energy networks.

FREEDOM is a UK project partnering Western Power Distribution, Wales & West Utilities, PassivSystems, Delta-EE, City University and Imperial College London. 75 hybrid heat pumps will be installed and controlled using PassivSystems' predictive demand control technology to optimise their performance and maintain occupant thermal comfort. The project will explore advanced strategies for exploiting demand flexibility to create new value propositions and manage peak load. Householder trust is a prerequisite for the success of new technologies and business models; trialists will be provided with tools to understand the operation of the hybrid heat pump and manage their heating bills.

There have been few large real-world trials of hybrid heat pumps to date, and we believe that this is the first in the world to include fully optimised control with predictive demand-side management and proactive consumer engagement. We will present detailed plans for the project and early results from modelling work.

Keywords:hybrid heat pump, hybrid boiler, demand response, electricity distribution, gas distribution

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1. Introduction

The FREEDOM† project[1] was instigated by two UK distribution network operators to better understand if hybrid heat pumps are technically capable, affordable and attractive to consumers as a solution for heating homes sustainably. We believe the project will be the most comprehensive study of hybrid heat pumps to date, including the first sizable field trial of smart hybrid heat pumps with full demand flexibility, and hope to demonstrate their unique capability at addressing the Energy Trilemma (carbon, cost, and security of supply).

In the context of this paper, a hybrid heat pump is a combination of an electrically-powered air source heat pump (ASHP) with a gas boiler, both of which can contribute to space heating. Hybrid heat pumps offer an attractive route towards decarbonising domestic heating, because they enable the utilization of renewably-generated electricity but without the problem of the coldest days of the year, where the electricity grid would

* Corresponding author. Tel.: +44 1635 525050.
E-mail address: edwin.carter@passivsystems.com.
† Flexible Residential Energy Efficiency Demand Optimisation and Management

have to cope with significantly increased demand [2]: in this scenario they can switch to using gas. The gas network can in the long term transition to become a large energy buffer, with an increased percentage of renewably-generated gases as the consumption volume decreases. Security of supply is also achieved, as the hybrid heat pumps can stabilize the electricity grid and react to constraints through demand side response, with the gas switch enabling complete flexibility. Economically, hybrid heat pumps are also potentially more affordable than a standalone ASHP, as lower capacity units can be used, and radiators and building fabric do not necessarily have to be upgraded; and smart grid connectivity opens the door to additional revenue streams though balancing mechanisms and electricity market services, that can help pay back the capital costs.

However, hybrid heat pumps are not widely deployed to date and their likely impact is not well understood. Smart technology will be required to ensure that they operate in the most effective manner for both the householder and the wider energy grids, and there are a number of real-world compromises that need to be made in an intelligent way (for example, between the requirements of local and national grids, different grid balancing mechanisms, and the householder's thermal comfort requirements). The FREEDOM project seeks to explore all these questions through a comprehensive research programme and field trial.

The FREEDOM project is headed by Wales & West Utilities (WWU)[3] and Western Power Distribution (WPD)[4], partnering with PassivSystems[5], Imperial College London[6], Delta-ee[7] and City University[8]. The first part of the project in late 2016 is a research phase, involving simulations of hybrid heat pumps and control strategies, looking into the whole energy system picture and the benefits of demand flexibility, with a strong focus on consumer engagement. Four hybrid heat pumps will be installed as a pilot trial in early 2017, aimed at verifying early assumptions. The second phase involves the installation of 71 hybrid heat pumps (trial total 75) in Bridgend, South Wales with fully-optimised controls for winter 2017-2018, and a series of experiments to characterize real-world demand flexibility and acceptability to householders.

In this paper we describe in more detail the planned research to be carried out in the FREEDOM project, and give some early results from the simulation work on the characteristics of optimised hybrid heat pump control.

2. FREEDOM project overview

2.1. Project partners

Wales & West Utilities (WWU) owns and operates the gas distribution network across Wales and the South West of England.

Western Power Distribution (WPD) owns and operates the electricity distribution network across the Midlands, South West and South Wales.

PassivSystems is a leading provider of home energy services, with a particular focus on demand management for domestic heating systems (encompassing district heating as well as heat pumps). PassivSystems has previously developed unique Predictive Demand Control (PDC) technology which optimises the performance of heat pumps, a cloud platform for aggregated demand management, and easy -to-use remote heating controls for householders. Together these comprise a state-of-the-art "smart heat pump" platform for exploring the capabilities of hybrid systems.

Imperial College (Control and Power research group) bring extensive experience in modelling and analysis of future low carbon power systems, including assessment of the role and value of demand side and storage technologies across local and national networks.

City University (Centre for Human-Computer Interaction Design) has a research focus on user interactions with intelligent and smart systems, with a particular interest in communicating system behaviour and the impact on consumer trust.

Delta-ee is a consultancy that helps clients navigate the transformation of the energy system, bringing particular expertise in market analysis, customer insight, technology assessment, and strategy development.

2.2. Project goals

The top level aim of the FREEDOM project is to understand the overall value proposition of wide scale hybrid heat pump deployment. This encompasses the perspective of a number of different stakeholders:

- **The government**, which needs to find an affordable path for the decarbonisation of domestic heating while maintaining security of supply (i.e. tackle the energy trilemma);

- **The electricity and gas networks**, which may be impacted by changes in load and demand patterns, but are also interested in cost-effective alternatives to electricity network reinforcements, and the pivotal role the gas network can play in decarbonising heat using hybrid systems (e.g. facilitating green gas solutions);
- **The householder** who is being provided with heat: they need to achieve the thermal comfort levels they need, at an attractive price point, with the confidence that the system is working in their best interests;
- **Potential providers of novel service propositions**, who need to understand the business case for new service models, such as a hybrid heat pump coupled with demand response services, or contracts for heat and comfort provision.

These broad aims lead us to a set of specific research questions, for example:

- What are the real-world running costs of a properly-optimised hybrid heat pump?
- What income could be realistically extracted from electricity markets and balancing mechanisms?
- What novel business models could be supported to finance hybrid heat pumps?
- How can the impact on gas and electricity networks be minimized?
- How can the technology be made attractive to consumers and fully gain their trust?
- How can hybrid heat pumps contribute to government objectives such as decarbonising UK domestic heat?

The Energy Trilemma (affordability, security of supply, and sustainability) forms an important theme across these research questions.

The first phase of the project involves several different research streams to help answer these questions, which are described in the next section.

2.3. Research streams

2.3.1. Modelling and simulation of hybrid heat pumps

The project involves a number of modelling activities from contrasting angles, which are used to provide broad insight into the hybrid heat pump proposition, determine the direction of the field trial, and extrapolate the results of the field trial.

- PassivSystems are developing high resolution (minute-by-minute) simulations of houses with hybrid heat pumps and other heating systems. This will enable load profiles and load duration curves to be calculated for a variety of scenarios, within the thermal comfort requirements of occupants. An important output will be the impact of fully optimised control of hybrid heat pumps, and how that compares with conventionally controlled units, or a heat pump or boiler on its own.
- Imperial College will tackle the modelling from the perspective of the whole energy network, and provide insight on the way of operating a hybrid heat pump that is most beneficial for the electricity and gas networks as a whole.
- Delta-ee will extrapolate the results of PassivSystems' and Imperial's modelling to understand the impact across representative house types and national scenarios, combining it with intelligence about likely uptake and real world costs, in order to understand the feasibility of large-scale deployment.

2.3.2. Market integration and load flexibility

The central technical challenge of the FREEDOM project is determining how the load flexibility of a hybrid heat pump can be exploited to generate income from electricity market mechanisms, at the same time as (a) ensuring that occupant satisfaction is not compromised and (b) ensuring that the impact on the local gas and electricity grids is acceptable (given national objectives which may come into conflict). The flexibility arises from both fuel switching and also utilizing building thermal inertia to store heat.

The project will explore a range of potential commercial drivers for demand management, including settlement risk, electricity market arbitrage, balancing mechanisms, the capacity market, constraint management, and gas network investment. The aim will be understand potential income and new business models for hybrid heat pumps in realistic scenarios where account is taken of conflicts between different offerings, the physical limitations of buildings, and the acceptability to the householders.

2.3.3. Design of field trial and physical deployments

At this stage the project is starting to plan the field trials. We will consider three scenarios:

- What can be achieved in a small pilot trial (winter 2016-2017);
- What is required for the main pilot trial (winter 2017-2018) in order to yield meaningful results; and
- What would be required for large scale deployment of hybrid heat pumps in the future.

In each of these scenarios we will consider aspects of the specification:

- The **physical configuration** of the heating system: detailed specification of the heat pump and boiler units, relative sizing (kW) of the two units (see also [9]), how the hybrid unit is plumbed together, and how domestic hot water is stored/produced;
- What **measurements** will be taken during the trial to monitor the units: metering of gas, electricity, and heat consumption, and what temperature are measured throughout the home and heating system;
- What **choice of experiments** will be carried out to explore the real-world demand flexibility of the hybrid heat pumps (such as tariff patterns and demand shaping tasks).

2.3.4. Consumer engagement and user interfaces

Probably the biggest challenge 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 heat pumps 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.

This will include 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 trial, helping householders to communicate their comfort requirements in a straightforward way, and explaining some of the counter-intuitive ways in which heat pumps are controlled for highest efficiency. This will have a particular 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).

3. Results

3.1. Predictive control technology for heat pumps

PassivSystems have 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 minimize energy consumption while meeting the comfort demands of the occupiers.

As an example, 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 (see Figure 1). 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.

The building simulation model used for Figure 1 and subsequent figures is designed to be the simplest representation of realistic dynamics of a domestic building. Four thermal blocks are used to represent the room temperature, heating water temperature, and wall masses, with the heating system supplying energy to the heating water. Thermal comfort is ensured by penalizing the discomfort of not meeting set point (magenta line in Figure 1) in the optimization calculation. Coefficients of the model can be learned on-line using Bayesian inference, enabling the system to automatically characterize the ability of a building to store energy in its fabric.

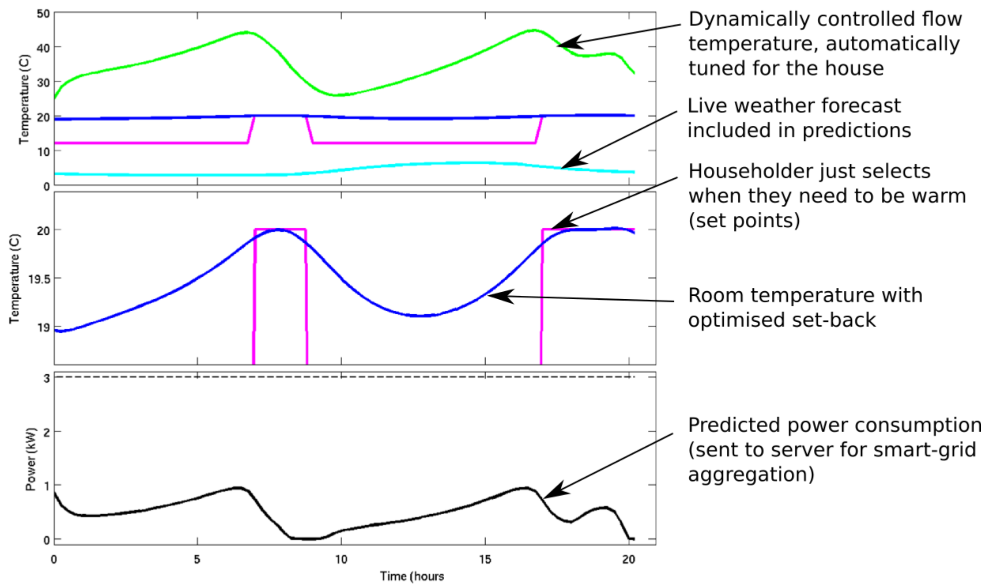

Fig. 1. Graphs illustrating optimised control of an air source heat pump using Passiv PDC, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom).

3.2. 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. Figure 2 shows an example of optimised control of a heat pump in the presence of an “Economy 10” electricity tariff and a scheduled demand constraint at peak hours. Economy 10 was chosen as a tariff with current (albeit limited) real-world availability; several spread-out periods of cheaper electricity (typically 0000-0500, 1300-1600 and 2000-2200) enable lower running costs for a heat pump in the UK.

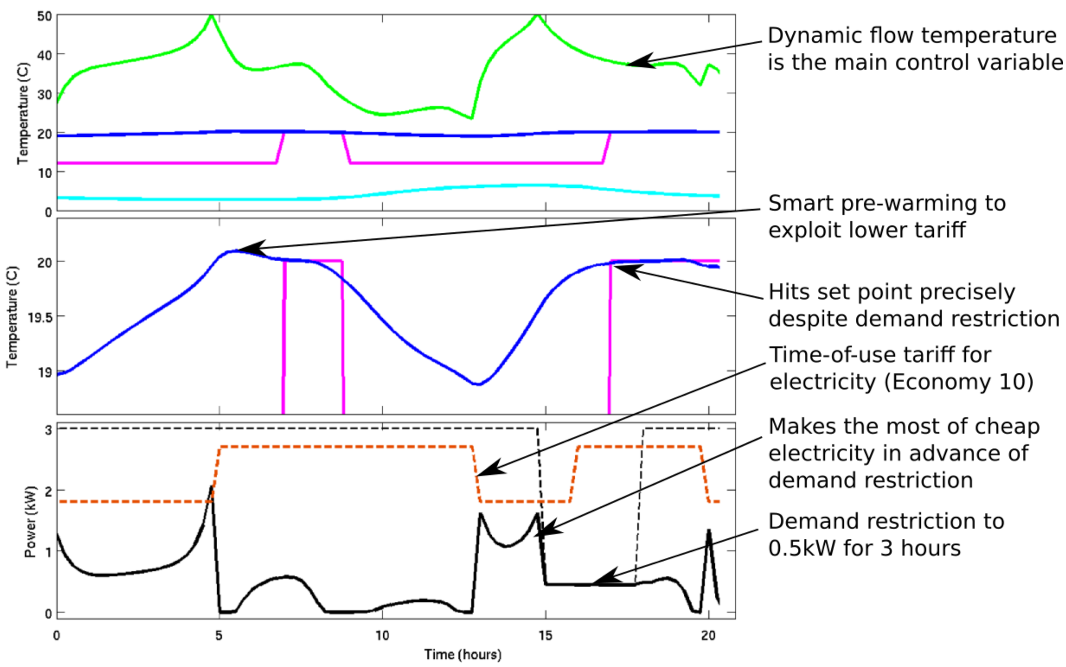

Fig. 2. Graphs illustrating cost-optimised control of a heat pump with an Economy 10 electricity tariff and an advance demand restriction during peak hours, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom).

The demand restriction example here forms part of PassivSystems demand response platform that provides facilities for aggregated demand response planning: finding out how much demand can be reduced or increased on a portfolio of homes during a period – without impacting occupant comfort. This enables a central control system (i.e. virtual power plant) to push down requests to the portfolio of homes in the knowledge of the resulting demand profile, and provide higher level layers such as demand shaping (which PassivSystems has demonstrated recently on heat networks).

3.3. Optimised control of hybrid heat pumps

Conventional control systems for hybrid heat pumps usually simply transition between electricity and gas on the basis of the current external temperature, sometimes with a region of simultaneous operation [10]. 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 first step in the FREEDOM project is to explore whether there is a dynamical approach for hybrid heat pumps that works better than the conventional "external transition temperature" approach: the heating water temperature affects COP as much as the external temperature.

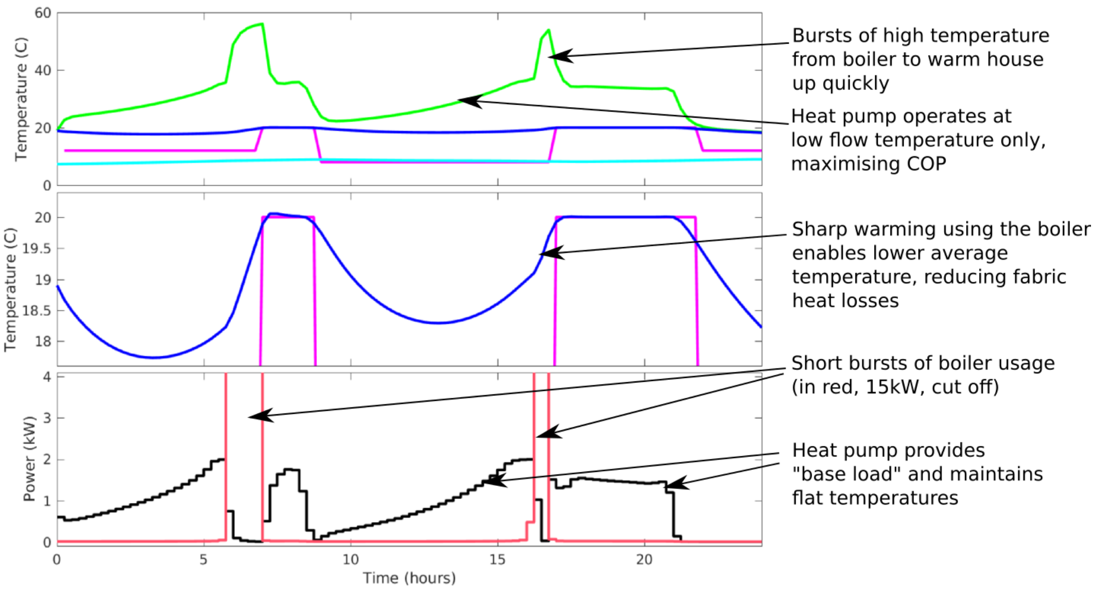

Fig. 3. Graphs illustrating cost-optimised control of a hybrid heat pump with a gas:electricity price ratio of 1:3, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom, with electricity in black and gas in red).

Figure 3 shows the fully-optimised predictive control solution for a hybrid heat pump,‡ 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 heating 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[11]; the predictive controller is programmed to minimize cost to the consumer. A qualitative interpretation of the optimization 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 20C 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 4 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 behavior 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 we have explored to date) there is a sharp transition between electricity and gas use, in contrast to other systems[12] and research[9,10] which include a simultaneous operation mode with the heat pump and boiler both providing power 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

‡ Note that the results in Figures 3 and 4 are for a different modelled house than Figures 1 and 2, so are not directly comparable.

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).

3.4. Next steps

Figures 3 and 4 are only two snapshots of the performance of optimised hybrid heat pump control, and as the FREEDOM project progresses we expect to have carried out a variety of simulations covering a whole year, for different house models, tariff scenarios, and heating systems (comparing a hybrid heat pump with an air source heat pump operating alone, or a boiler operating alone). We will produce demand profiles and load duration curves for each case, and use these as inputs to the whole system modelling carried out by Imperial College, to connect with what is required from the perspective of the grid as a whole. At the next phase, we will use the same models to investigate real-world flexibility and how in practice the in-house operation of the house would be affected by the requirements of the electricity and gas networks, without affecting the comfort of the occupants.

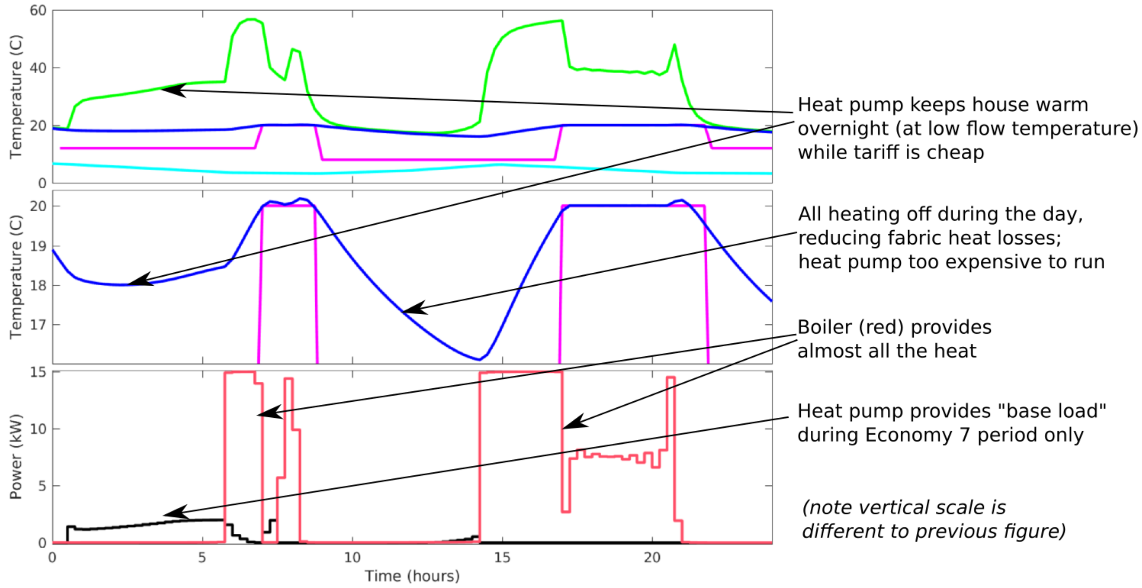

Fig. 4. Graphs illustrating cost-optimised control of a hybrid heat pump on an Economy 7 electricity and current (Oct 2016) prices, showing day-ahead predictions of heating water temperature (top), room temperature (middle), and power consumption (bottom, with electricity in black and gas in red).

4. Preliminary conclusions

Hybrid heat pumps have significant potential for decarbonising UK domestic heating 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 expects to provide the first comprehensive exploration of the real value of hybrid heat pumps, through a sufficiently large field trial backed up by a broad programme of research.

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

- Take-up of hybrid heat pumps 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 heat pump is to utilize 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. To implement this strategy requires a smart system.
- 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).

It is important to note that these are subjective conclusions from a small number of early simulations. We hope to have more extensive, quantitative results by the time of the IEA Heat Pump Conference in May 2017.

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.

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