# MADE

## MULTI-ASSET DEMAND EXECUTION

## **FINAL** REPORT

passivSYSTEMS

WESTERN POWER
DISTRIBUTION
*Serving the Midlands, South West and Wales*

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# 1 PROJECT PARTNER FOREWORD

**Greener, cheaper domestic energy – WPD customers benefit from flexibility services with Time-of-Use (ToU) from the Network Innovation project, Multi-Asset Demand Execution (MADE). The project has demonstrated that the coordination of domestic Low Carbon Technologies (LCTs) can create significant value for homeowners, local and national electricity systems.**

The commitment to Net Zero emissions by 2050 is a significant positive step by UK Government, and Western Power Distribution (WPD) is working hard to ensure we can support its delivery.

Net Zero by 2050 will require domestic homes to transition away from fossil fuel to electric vehicles and heating, however, this transition adds complexity. LCTs, such as electric vehicles (EVs), hybrid heating systems and heat pumps will add additional, potentially unpredictable electrical load onto the distribution network, making it tougher to manage and plan. Aware of this, WPD is investigating opportunities to use the flexibility from the LCTs to manage the network more effectively and enable cost savings for customers.

In collaboration with domestic energy flexibility specialists PassivSystems, WPD's MADE project, a £1.6m Network Innovation Allowance (NIA) project investigates the network, consumer and broader energy system implications of high-volume deployments of the combination of LCTs, including generation and storage.

The project explored the feasibility of controlling and aggregating multiple LCTs (EV, hybrid heating system, battery storage and solar PV) through a single consumer device by optimising to ToU tariffs and other market signals, with the aim to reduce network peaks, unlock value from energy markets and reduce consumers bills.

**Decarbonisation of the electricity supply is expected to rely on two main pillars:**

- Rapid increase in low-carbon generation, primarily delivered through expanding variable renewable energy sources (wind and solar) that have recently seen significant cost reduction, and;

- Electrification of large segments of heat and transport sectors.

These factors will lead to increased flexibility requirement, delivered among other means by increased uptake of domestic flexibility and energy storage, to ensure the system can efficiently maintain secure and stable operation in a lower carbon system.

Domestic flexibility has the ability to adjust generation or consumption in the presence of constraints or contingencies in order to maintain a secure system operation, which will be the key enabler of the necessary transformation to a cost-effective low-carbon electricity system.

There are several flexibility resource options available including highly flexible thermal generation, energy storage, Demand-Side Response (DSR) and cross-border interconnection to other systems. Quantitative evidence from previous NIA projects strongly suggests that tapping into residential flexibility sources could unlock significant value for the system to support the decarbonisation of energy supply.

"As we transition to a low carbon future, the requirements of our domestic customers will shift dramatically. We have already seen the large-scale deployment of PV systems and need to be ready for a world where customers' transportation and heating requirements may also be met through our network.

This is a huge transition and MADE is one of the many projects helping us to understand how we can lead the way and ensure we hit our Net Zero targets.

Through our extensive innovation programme, we have already built a good understanding of the potential value of the smart control of assets. Both our Electric Nation and Freedom projects showed huge value that could be achieved and are influencing how we look to plan future networks. By shifting load away from peak times, we can use the network more efficiently, deferring potentially costly and inconvenient network reinforcement.

Despite the great learning to date, we need to keep on learning. To hit Net Zero, homes will need to start adopting multiple LCTs and we want to understand how they might interact. What are the benefits for customers, and for our networks of coordinating control? Do you unlock more value than more basic segregated control?

This is what the MADE project is trying to understand. What benefit is there and how do we unlock it?"

**Matt Watson**
Innovation and Low Carbon Networks Engineer
Western Power Distribution

"2020 has tested the UK's energy system to some of the most extreme network conditions in modern times. We have seen Britain go without coal-fired power generation for its longest stretch since the Industrial Revolution, 90 mph winds creating 100+ hours of negative prices and the significant impact of COVID-19 on energy demand forecasts.

Combined with the urgency to meet Net Zero emissions by 2050, which includes the need to decarbonise domestic transport and heat, the UK's electricity system is having to evolve, and fast.

Spring 2020 saw record-breaking renewable generation with significant demand changes as a result of COVID-19, highlighting the need for a more agile, flexible system in order to shape a cheaper and greener energy future. This forced the GB electricity system to implement short-term measures to avoid system faults, which has included allowing embedded generation to be cut from the grid and paying for renewables (wind and solar) to be turned off. Long term, such measures are unsustainable.

Over the next three decades the UK's electricity system will become more unpredictable. COVID-19 responses have highlighted how flexible technologies can help manage the grid, bolster long-term renewable energy penetration and reduce system costs that will ultimately lower customer bills.

Domestic flexibility solutions have the ability to import and store energy during periods where electrical demand is low and exporting any local generation or stored energy during peak periods, typically these are often linked with periods of generation from renewable sources like solar and wind.

Responding to generation and network requirements enables demand to become much more agile and dynamic as opposed to static, creating carbon savings, customer savings and commercial opportunities for a smarter, decentralised grid that is powered fully by renewable energy.

Flexibility controls and platforms such as PassivSystems have the ability to connect and aggregate multiple Low Carbon Technologies (LCTs) within a domestic home. Once a signal is received, these flexibility controls reduce pressure on the grid at peak times while lowering energy costs and carbon for customers.

The MADE project has identified opportunities to support Net Zero and the GB electricity system transition by investing in the UK's workforce, low carbon technology incentives and enhanced engagement between the distribution networks and domestic homes."

**Tom Veli**
Professional Services Manager
PassivSystems

# 2 EXECUTIVE SUMMARY

**The MADE project has set out to explore the impact of multiple LCTs in the home on the electricity distribution network, and the initial potential for reducing this impact by coordinating the assets.**

All scenarios for the transition to 2050 decarbonisation goals show that a large proportion of UK homes with a combination of hybrid heat pumps for space heating, solar PV panels generating electricity to use at home and export to the grid, a battery system installed to store the solar generation and take advantage of cheap grid electricity generated from renewables, and an electric car which can be charged at home. The project aims to replicate this combination of technologies for the first time as a deployment which is coordinated within the home to make the most of the combined flexibility, and also can be orchestrated between homes to offer grid services and honour local grid constraints.

Following the analysis of data collected during the project, this report presents the findings, learnings and benefits of PassivSystems coordinated control.

**Aggregated, optimised low carbon technologies**

- Predictive controls that can optimise and coordinate asset behaviour play a key role in delivering best value from the assets to the consumer, as well as negotiating patterns of behaviour desired by the local and national electricity grid. The greater the level of coordination between the low carbon assets, the greater the savings in consumer electricity costs.

- Time-varying tariffs can offer significant running cost benefits to consumers with MADE assets, particularly where the battery and heat pump can be coordinated to store energy in the right balance between the battery and the thermal fabric of the building, and making the right decisions about waiting for available PV generation.

- Even slight variations in tariff can introduce demand peaks, for example due to batteries delivering arbitrage. These peaks can easily be mitigated by a smart control system, at only a small incremental cost to the householder, as long as the provision of cheap electricity is not significantly reduced.

- Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

### Consumer benefits from smartly coordinated LCTs

- Domestic flexibility provides a notable value opportunity. The modelling by Everoze showed possible savings of up to £260 p.a. per household under best conditions. These are, however, very dependent on asset usage and geographic location. Additionally, domestic flexibility offers material peak load shifting potential for the DSO. Modelling based on half-hourly data indicates a reduction of between 35-40% in peak loads on the network compared to the Baseline Case.

### Local network benefits from aggregated, reactive LCTs

- Analysis by Imperial College has shown that there is significant potential for coordinated control to deliver distribution network cost savings across different voltage levels and asset types, which can reach £200m to £500m of avoided annualised reinforcement cost by 2035. These add to the savings enabled by smart asset control and help to offset some of the increased reinforcement spend needed to accommodate the significant load increase on the network.

- In collaboration with PassivSystems, Everoze has identified that distribution networks can utilise the MADE concept by limiting loads to 33% of the 14kW fuse limit at a property level without compromising household consumption behaviour and savings that can be achieved (based on half-hourly average loads). There is a notable potential for using residential consumers to manage peak loads on the network.

- The MADE concept offers material peak load shifting potential for the distribution network of between 35 and 40% reduction in peak loads on the network compared to optimised low carbon technologies optimised, but in silo operation (based on half-hourly data).

### Whole-system network benefits from peak load shifting

- Whole-system case studies run by Imperial College demonstrate that there are opportunities to deliver significant cost savings by utilising distributed residential flexibility based on the MADE concept. The opportunities for cost savings increase with the level of uptake of the MADE flexible solution. In the 2035 horizon, the net benefits of MADE (including the cost of enabling residential flexibility) could reach between £500m and £2.1bn per year, through allowing the electricity system to achieve the carbon target more cost-effectively, while at the same time reducing the need for high volumes of peaking generation capacity and distribution network reinforcements.

- The same modelling by Imperial College quantified marginal system benefits per customer. These show the high level of net benefit created by early adopters of the MADE concept. However, as the system becomes more flexible the marginal value of more flexibility decreases. Near 100% penetration net benefits drop to close to zero. This suggests that the opportunities to add value to the system are offset by the cost of implementing MADE functionality at very high uptake levels.

# 3 DOMESTIC HOME DECARBONISATION: CHALLENGES AND OPPORTUNITIES

**Energy use within domestic homes will play a significant role in achieving Net Zero. This will include the electrification of heat, power and transport and is likely to have multiple low carbon technology assets installed.**

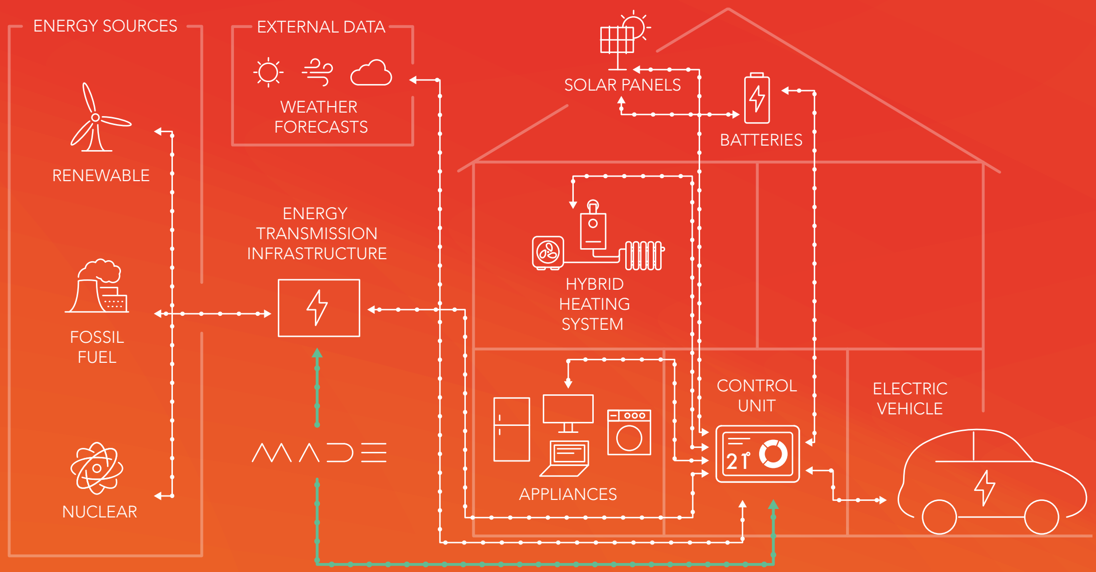
## 3.1 THE DEPLOYMENT OF LOW CARBON TECHNOLOGIES WILL GROW RAPIDLY OUT TO 2050

**Strong growth in the sales of all low carbon technologies is expected in the medium to long-term.**

The following section draws predominantly from the National Grid Future Energy Scenarios (FES) and supplemented with research from Western Power Distribution and Delta-ee. Under almost any scenario the number of air source heat pumps and hybrid heating systems installed in UK homes will be well into the millions by 2030. The uptake of EVs will also be rapid from the late 2020s in to the early 2030s with over 10 million on the roads by the mid 2030s in all scenarios.

Domestic solar PV installations will also see a significant increase with anywhere from 2 to 5 times more installations than today by 2050.

Understanding how to optimise these technologies in mature market conditions will be essential to maximise value and limit network and system impacts.



# 3.2 LOW CARBON TECHNOLOGY UPTAKE

**As the UK adapts to meet its carbon targets, the number of each type of LCT is expected to increase dramatically.**

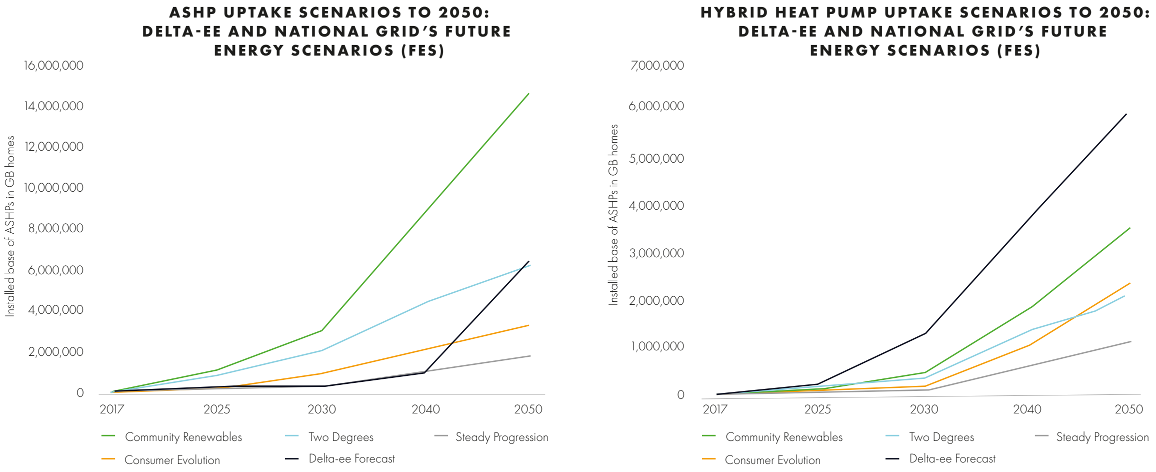
## 3.2.1 3 MILLION AIR-SOURCE HEAT PUMPS, 1 MILLION HYBRID HEAT PUMPS BY 2030

**The forecasted uptake of heat and hybrid heat pumps depend on predictions of the regulatory and economic environment. Uptake will be boosted by stronger building regulations on permitted heating technologies or minimum efficiency standards. For example:**

- UK Government announcing end of fossil fuel heating in new build homes
- Consultation on electrification of off-gas homes

The current subsidies for low carbon heating technologies are due to stop in 2021. Without replacement, heat pumps remain a far more expensive technology compared to gas boilers and we are likely to see a reduction in uptake of heat pumps.

If gas prices increase and/or electricity prices decrease, heat pumps become more favourable. We see no indication of a major change in prices out to 2025. Electricity price decreases may be via greater availability of ToU tariffs; with the right control and storage, heat pumps could be powered by cheap off-peak electricity.


ASHP UPTAKE SCENARIOS TO 2050: DELTA-EE AND NATIONAL GRID'S FUTURE ENERGY SCENARIOS (FES)

HYBRID HEAT PUMP UPTAKE SCENARIOS TO 2050: DELTA-EE AND NATIONAL GRID'S FUTURE ENERGY SCENARIOS (FES)

**Figure 1** – Delta-EE and National Grid (FES) heat pump and hybrid heat pump uptake scenarios.

### 3.2.2 9 MILLION ELECTRIC VEHICLES BY 2030

**The uptake of electric cars in the future will depend on the proportion of cars that are electric and how many households have a car.**

Future predictions are that electric vehicles will replace petrol and diesel internal combustion engine cars. This is shown in all four of National Grid's FES scenarios. This transition to electric cars will be a combination of:

- Policy push: The UK Government announced "it will end the sale of all new conventional petrol and diesel cars …by 2030" and the Scottish Government committed to "remove the need for petrol and diesel cars and vans on Scotland's roads by 2032". The Mayor of London is tightening restrictions in central London in ultra-low emission zones
- Industry leading the way: All major car makers have announced plans to make their cars electric. Some are planning to release electric versions of all of their cars while others have said they are going to develop a new range of electric vehicles.

National Grid's Future Energy Scenarios (FES) predict the total number of cars to remain fairly constant, with differences in when mass adoption occurs.

**Figure 2** – National Grid (FES) pure electric and hybrid vehicle scenarios.

Some predict car ownership will continue to increase due to increasing population estimations and reduced cost to buy a car, in particular with the increasing popularity of car leasing options. However, many are predicting that private car ownership will decrease due to mobility shifting to car sharing, demand-responsive private hire car providers (such as Uber and Lyft) and greater availability of fully automated cars after 2030, especially in cities. Neither of these overall trends are featured strongly in the zero-growth approach of the National Grid Future Energy Scenarios (FES).

The number of domestic charging points is likely to be limited to the estimated two-thirds of dwellings who have access to a garage or other off-street parking (data for England, ref: English Housing Survey 2010). This would be 16 million dwellings across the UK.

### 3.2.3 8 MILLION HOMES WITH SOLAR PV BY 2030

**Solar PV continues to grow in all scenarios out to 2050, but the pace of growth varies between scenarios. Despite new applications for Feed-in Tariffs ending in 2019, domestic solar capacity is expected to continue to grow. This growth is driven by falling cost of solar technology, and advances in technology in both efficiency and materials solar PV can be embedded into. Fastest growth is expected where there is co-location with storage, allowing for greater self-consumption.**

In all FES, there is a step up in growth which is the point of cost parity – where solar generation is cost effective. The scenarios vary in when this will occur (2020 in Community Renewables to early 2030s in Steady Progress and Consumer Evolution) and it will depend on business models available which promote solar PV installation. The rapid uptake in the Community Renewables scenario is based on expected take up of business models combining solar PV and storage.

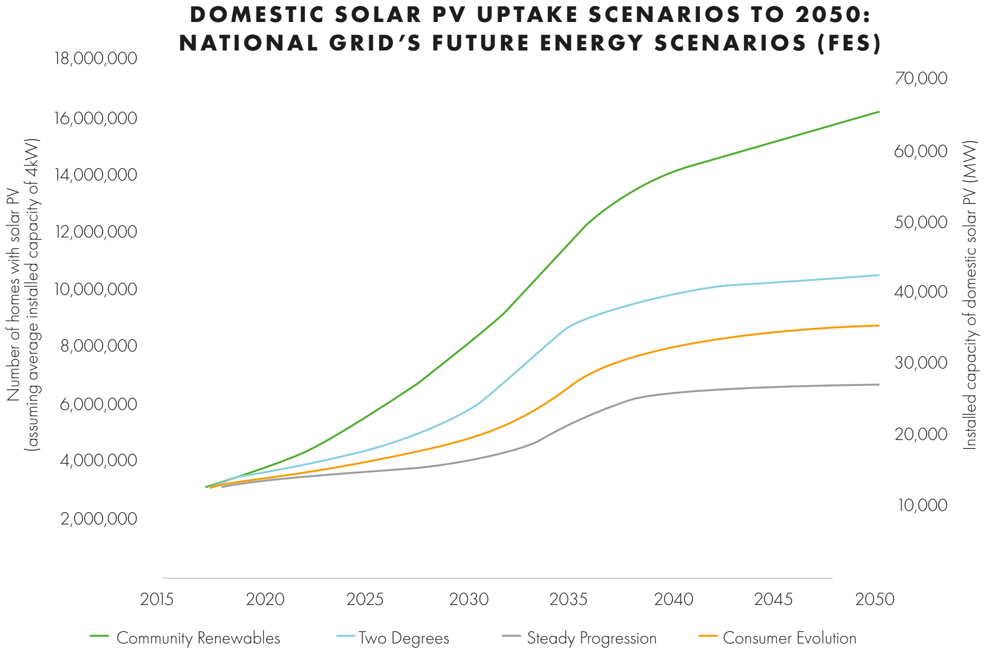

DOMESTIC SOLAR PV UPTAKE SCENARIOS TO 2050: NATIONAL GRID'S FUTURE ENERGY SCENARIOS (FES)

**Figure 3** – National Grid domestic solar PV uptake scenarios.

### 3.2.4 DOMESTIC BATTERY UPTAKE FORECASTS

UK residential storage market installed base is currently 16,300 units (61.5MWh), and could reach anywhere from 300,000 – 1,000,000 units by 2050.

Short-term growth is uncertain following the termination of the UK Government’s Feed-in Tariff (FiT) subsidy for small-scale generation.

Self-consumption will become a key driver for PV customers. While the proportion of PV systems including storage will increase, opportunities to upsell storage will reduce as the PV market shrinks.

Innovative business models are creating additional value streams for storage in the UK. Climbing electricity prices, especially during peak demand, coupled with real-time electricity prices will be the main driver of growth in the market post 2025. This will make the economics of self-consumption more attractive.

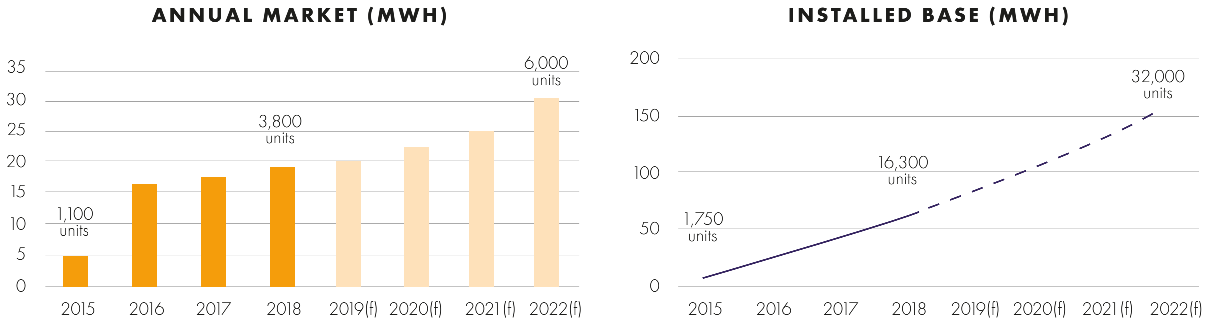


**Figure 4** – Delta-EE, Research Services: Annual domestic storage uptake.

### 3.2.5 LCT FORECAST SUMMARY

There will be a rapid uptake of low carbon technologies, under almost any scenario, starting from the late 2020s into the early 2030s.

Starting from the mid 2020s, there will be a significant shift in the way homes are heated and the fuels used for transport. Under all scenarios, even the most conservative, by 2050: over 99% of cars on the road will be EVs, there will be over 3 million heat pumps installed in UK homes, and there will be over 6.5 million domestic PV installations.

The number of domestic battery storage installations will grow as well, alongside the rise in solar PV installations. This presents an opportunity for homeowners to self-consume the energy they generate. The rapid rise in the installed base of the above technologies will result in a substantial rise in the demand for electricity.

Domestic PV combined with storage as well as smart charging may present an opportunity to reduce impacts on the grid. There is also a role for hybrid heating systems to help reduce the load on the grid at peak times by shifting heating demand from the electricity grid to the gas grid.

There are a lot of uncertainties, for example, around the role hydrogen will play and if the necessary government incentives are put in place. However, it is certain that the electricity grid will play an increasingly important role in the future of the energy system as a pathway to decarbonisation. Demand and export of electricity at the household level (low voltage network) is set to grow immensely in the medium to long term.

## 3.3 SECTION SUMMARY

**Increased electrification of heating and mobility combined with decentralised generation and storage will require optimisation to limit network impacts. The demands and exports from the rapid increase in domestic low carbon technologies will place significant additional strain on the electricity networks through increased peak loads. Low-Voltage (LV) network modelling by Delta-EE has shown that the deployment of these technologies will result in serious impacts on the low voltage network once more than approximately 30% of high demand homes on a feeder adopt these technologies in a non-optimised manner.**

In many cases, optimisation of household energy demand and export based on current electricity market price signals will reduce the load on the network. At technology penetration levels of less than 50%, optimisation at the household level using existing price signals reduces occurrences of feeders being overloaded.

Beyond this point, price signals will need to be altered to incentivise behaviour and load shifting, and increase diversity, which is beneficial to networks. The proportion of high electrical demand customers with EVs used for commuting versus the number of half-hourly periods per year the low voltage network limit is breached.

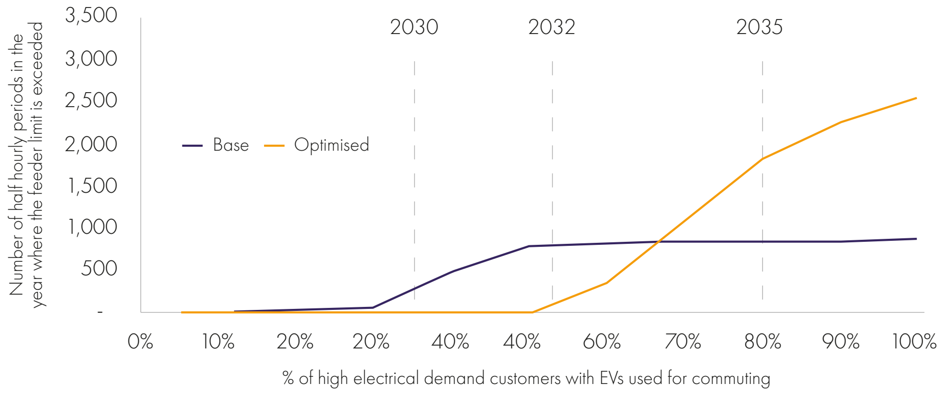


**Figure 5** – Feeder overload from optimised charging.

# 4

# OVERVIEW

## 4.1 PROJECT OVERVIEW

**The MADE project is a £1.6m innovation project investigating the network, consumer and broader energy system implications of high volume deployments of the combination of LCTs, including generation and storage.**

WPD in collaboration with domestic energy flexibility experts PassivSystems has formed a project consortium with Everoze, Delta-EE, and Imperial College to deliver this ambitious project. The project consortium are experts in their fields, their roles are summarised below:

### Western Power Distribution

- Distribution network requirements;
- Innovation strategy and leadership;
- Future low carbon technology planning and requirements;
- Flexibility platform design and drivers;
- Network intervention insight.

### PassivSystems

- Project delivery;
- Project and field trial design;
- Home energy management system;
- Customer engagement, insight and interfaces;
- Domestic flexibility services;
- Home and LCT energy data;
- LCT controls;
- LCT control strategies.

### Everoze

- Micro-economic energy modelling at domestic level;
- Inclusion of DSO services;
- Flexibility services;
- LCT data and analysis;
- Due diligence.

### Imperial College London

- Whole-system assessment on the future GB electricity systems;
- Local distribution network modelling;
- DSO and ESO conflicts and synergies;
- Consumer propositions.

### Delta-EE

- Market research;
- Customer research;
- Distribution network modelling;
- Business models;
- Commercial propositions;
- Consumer propositions.

The MADE project has investigated the implications of utilising multiple energy assets within a home, to better understand the feasibility of managing and aggregating these energy assets affordably to reduce network demand and minimise the requirement for network reinforcement. The low carbon technologies considered under this project are:

- Hybrid Heating Pump (HHP) consisting of an electrically-powered heat pump (either air source or ground source) together with a fossil-fuel boiler (oil or gas), which together provide the heating and hot water requirements of the home;
- Electric Vehicle (EV);
- Electric Vehicle charge point;
- Solar Photovoltaic (PV) panels;
- Domestic Batteries.

## 4.2 PROJECT METHODOLOGY AND TIMELINE

**The project was designed and delivered under six workstreams to produce a series of outputs.**

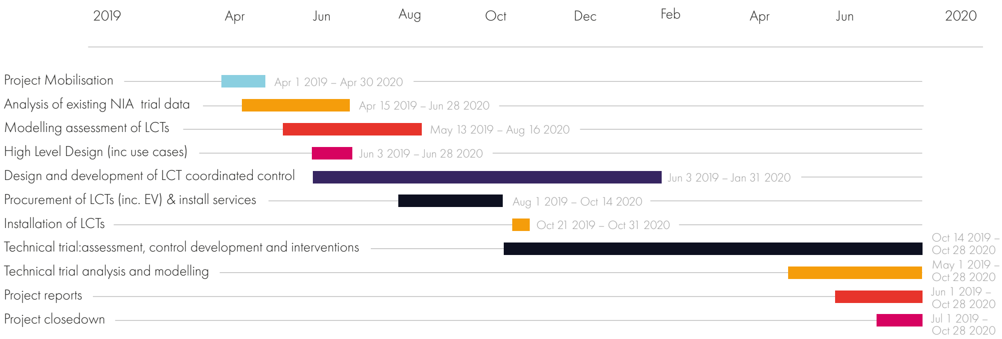


**Figure 6** – MADE project timeline.

These were split into two general phases:

1. The first focused on delivering modelling work that evaluated the feasibility and benefits of multi-asset coordination at a household, feeder and whole-system level, alongside customer engagement work.
2. The second focused on a technical trial, with five homes having PassivSystems multi-asset control, an HHP, EV with smart charge point and PV with storage to trial the proposed demand flexibility services. The results of this trial were then used to refine the analysis from Phase 1.

This report will focus on the field trial and validation, followed by in-depth analysis at the domestic home and whole energy system, followed by recommendations (including business models).

### 4.2.1 PHASE 1: DESKTOP ANALYSIS, NETWORK MODELLING AND IMPACT ASSESSMENT

**The project consortium conducted analysis of data from the following Western Power Distribution NIA projects:**

- The Electric Nation project which looked at smart charging of electric vehicles;
- The SoLa Bristol project which looked at integrating battery storage with PV panels;
- The FREEDOM project which looked at hybrid heating systems.

These projects investigated in isolation the individual LCT assets that the MADE project is combining together. The starting point of the MADE project was to understand the following from each of these projects:

- LCT behaviour and consumer behaviour;
- LCT performance, technology assessment and potential available electricity flexibility;
- Local and national electricity distribution network impact;
- Supplier tariffs (e.g. flat, ToU and max demand tariffs).

The analysis enabled PassivSystems to develop a series of home-level energy demand profiles which considered an optimal control solution for coordinating a hybrid heating system, a smart electric vehicle charging, battery storage and solar PV based on technology capability, customer type and the impact on the local and national network.

Energy-system modelling experts Imperial College, Delta-EE and Everoze then processed the profiles into their models to understand the impact at the domestic home, local and national GB network of coordinated control and creating a baseline.

**The full Western Power Distribution NIA project data analysis report is available on the MADE page of the WPD website.**

### 4.2.2 PHASE 2: 5-HOME TECHNOLOGY TRIAL (BETWEEN OCTOBER 2019 AND OCTOBER 2020)

**The field trial methodology was structured to carry out the necessary interventions and gather the required monitoring data over the course of the project, so that the project consortium could carry out analysis and answer the following questions:**

- How does real-world overall household demand shape (and balance between the assets) change depending on ToU tariffs, level of asset coordination, and over the seasons?
- What happens to the peak demand as we move between each scenario?
- How can the demand shape be influenced by interventions?
- The final key research area was to understand the interactions between smart EV charging and the user of the EV.

Controlling multiple assets in a coordinated way on behalf of consumers is challenging as there are multiple trade-offs and decisions to be made. PassivSystems optimisation technology aims to solves this challenge in a quantitative way; at the core of the physical deployment there is a PassivSystems Hub which runs optimisation algorithms to control the LCTs, as well as gathered monitoring data to send to the PassivSystems servers.

The project utilised PassivSystems' existing Whole Home Energy Management (WHEM) platform, with the addition of new components for integration with assets that are new for this project. The project has considered a number of influencing factors simultaneously:

- ToU energy supply tariffs;
- Asset coordination for in-home energy efficiency;
- Seasonality;
- Commercial flexibility services.

## 4.3 PROJECT OBJECTIVES

**Based on the lessons learned from previous WPD Network Innovation trials (Freedom, Electric Nation and SoLa Bristol), the project consortium produced the following objectives for the MADE project:**

- Design and build a microeconomic model for domestic multi-asset, multi-vector flexibility for GB today. The model identifies different customer types, linked to flexibility service stacks (including DSO services e.g. Flexible Power) and quantifies the financial value per customer type;
- Understand how the combined operation of residential solar PV generation, hybrid heat pump systems and smart EV charging may provide benefits to the consumer;
- Assess the whole-energy system benefits (including network infrastructure) and carbon benefits of large-scale deployment of the MADE concept;
- Consider conflicts and synergies between local DSO and ESO services objectives, in the context of the flexibility enabled by the MADE concept;
- Estimate consumer benefits of the MADE concept and inform the design of the market framework that would enable consumer to access the revenues that reflect the benefits delivered;
- Validate the modelled learning by completing the 5-home, 12-month technology trial over a heating season.

# 5

# COORDINATED LOW CARBON TECHNOLOGY CONTROL DESIGNED BY **PASSIVSYSTEMS**

**PassivSystems has designed and developed Predictive Demand Control (PDC) technology, which takes into account a number of factors, including:**

- Householder comfort requirements and EV usage requirements;
- ToU electricity tariff;
- Relative fuel cost of heat pump and boiler;
- Heat pump performance and efficiency in this particular house;
- Thermal response and physics of the building;
- Weather forecasts (temperature and irradiation);
- Incidental solar gains on the house;
- Predicted PV generation;
- Battery round-trip efficiency.

Using this PDC, it optimises the performance a domestic home's LCTs over the upcoming day and predicts the control strategy that is required to minimise energy consumption while meeting the requirements of the occupiers at the lowest possible cost.

## 5.1 **PASSIVSYSTEMS PDC TECHNOLOGY:** SMART CHARGING OF ELECTRIC VEHICLES

**When applied to smart charging of electric vehicles, PDC implements an agile charging strategy.**

The homeowner plugs in their EV, sets its charging requirement (battery percentage and completion time); the PDC will consider a number of factors (including local grid requirements, tariff type, generation and weather) to produce a charging strategy. PDC will charge the EV to meet the homeowner requirements, this will be done by deferring charging to avoid peak times (including pausing), kWh turn up and turn down requirement and avoiding secondary peaks. PDC prioritises the homeowner requirements over all other external factors.

Conventionally, homeowners have to manually set their EV charge requirement and can only apply a fixed time to commence charging.

## 5.2 **PASSIVSYSTEMS PDC TECHNOLOGY:** HEAT

**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.

## 5.3 SMART, OPTIMISED HYBRID HEATING SYSTEMS

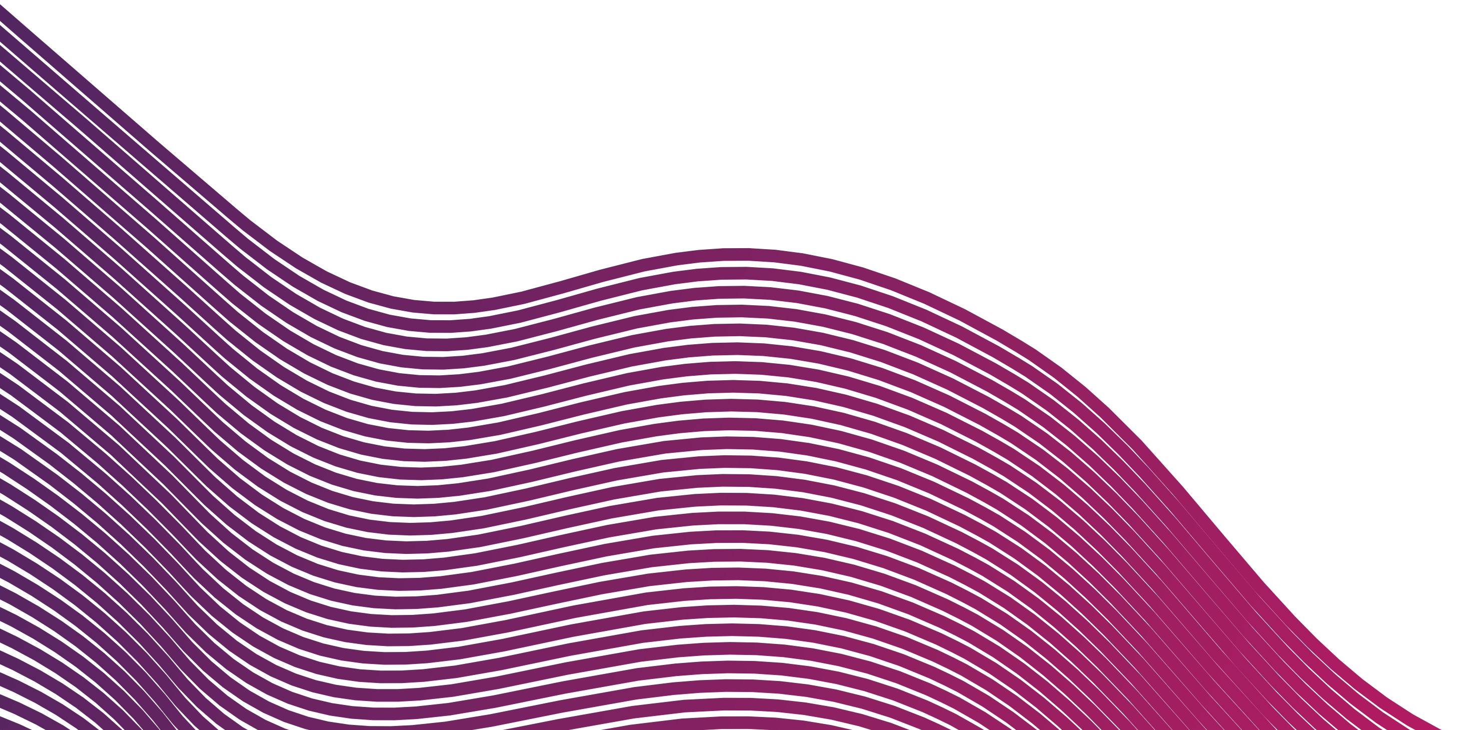
**Conventional control systems for hybrid heating systems usually simply transition between electricity and gas on the basis of the current external temperature, sometimes with a temperature range of simultaneous operation. The systems calculate the external temperature at which the heat pump produces 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 MADE project used a dynamic control 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.

## 5.4 DEMAND RESPONSE WITH PREDICTIVE CONTROL

**As well as being able to optimise the performance of LCTs, predictive control enables comprehensive functionality for demand management and varying energy prices.**

Building thermal inertia can be exploited to store energy. Demand is 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.



# 5.5 MADE TECHNICAL TRIAL: COORDINATED LCT CONTROL

**The low carbon technologies were controlled (where included in coordination) by PassivSystems' smart control system:**

- Householders had a smartphone App with which they specify their thermal comfort requirements (set points and schedule, which drives heat pump operation). The App also enables them to specify their EV preferences (when they next need to use it and the amount of charge required);
- Machine learning algorithms determine the thermal properties of the home and heating system and build a building physics model that it can use to explore the consequences of different strategies;
- Predictive optimisation algorithms determine the best operational strategy for the assets. These algorithms run every 15 minutes and look 24-48 hours into the future to evaluate the running cost of different controls strategies, mathematically solving for the optimal one.
- Control algorithms make real-time decisions to send commands to each asset:
  - Boiler operation.
  - Heat pump operation and demand level (target flow temperature).
  - Battery operation mode (automatic charge from PV generation, automatic discharge to meet overall household demand, or charge/discharge at specific rate). This implicitly includes the ability to suppress PV generation due to the "hybrid" battery.
  - EV charge point power limit.

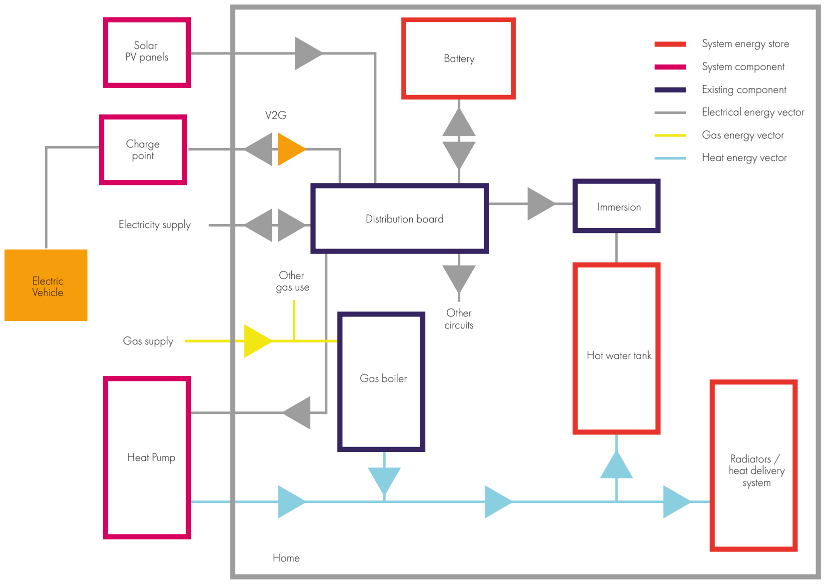


**Figure 7** – MADE system schematic.

Predictive control is a key enabling technology for inter-asset coordination and this sophisticated approach allows many trade-offs to be made correctly, and sometimes surprising interactions between the different assets to be instructed to give the best outcome (details are presented in Section 7 of the report).

# 6 THE TECHNICAL FIELD TRIAL DESIGN

## 6.1 TECHNICAL TRIAL DEPLOYMENT

**The MADE project consisted of a small field trial of the technologies, with a parallel stream of modelling work that aimed to extrapolate to the wider population of homes and assess the value of flexibility, together with a stream of customer engagement work.**

**The key aims of the technical trial were to:**

- Improve understanding of the real world complexities of installing hybrid heat pumps, solar PV panels, batteries and electric vehicle (EV) chargers in homes together with the smart technology required to coordinate their operation;
- Demonstrate how coordinated control can be executed effectively within a real home and understand the benefits to the consumer;
- Collect data which can be used to validate the modelling results produced as part of the project.

**The technical trial was designed to answer the following research questions:**

- How does real-world overall household demand shape (and balance between the assets) change depending on ToU tariffs, level of asset coordination, and over the seasons?
- What happens to the peak demand as we move between each scenario?
- How can the demand shape be influenced by interventions?

## 6.2 DEPLOYMENT SUMMARY

**The MADE field trial involved five homes, each of which had all four low-carbon assets. Table 2 provides details of the installations in each of these homes. Four of the heat pumps (and one EV) were pre-existing, reducing the need to install new assets under MADE.**

| Home | Heat pump | Fossil boiler | PV array | Battery | EV Charger | EV |
|---|---|---|---|---|---|---|
| **1** | 5kW Samsung ASHP | LPG Combi | 4.41kWp | Sonnen hybrid 5kWh | New Motion 32A | Nissan Leaf 30kWh |
| **2** | 8kW MasterTherm ASHP | Gas system boiler | 3.46kWp | Sonnen hybrid 5kWh | Alfen 32A | Hyundai Kona 64kWh |
| **3** | 22kW MasterTherm GSHP | Oil system boiler | 4.41kWp | Sonnen hybrid 5kWh | New Motion32A | Nissan Leaf 40kWh |
| **4** | 9 kW Samsung ASHP | LPG system boiler | 3.78kWp | Sonnen hybrid 5kWh | New Motion32A | Tesla Model 3 75kWh |
| **5** | 9 kW Samsung ASHP | Oil system boiler | 4.41kWp | Sonnen hybrid 5kWh | Alfen 32A | Nissan Leaf 40kWh |

**Table 2** – Summary of the installations in the field trial homes.

Notes:

- **Hybrid heat pumps** consist of a legacy fossil fuel boiler supplemented by a heat pump, with their interaction controlled by a smart control system (see below). The system was configured to maximise heat pump utilisation wherever possible, in order to emulate a future decarbonised energy system.
- **Hot water provision** is from the fossil fuel boiler until the end of Phase 4 of the trial. From Phase 5 domestic hot water production was generated using a combination of a hybrid heat pump and/or smart immersion switch.
- **Hybrid batteries** The Sonnen batteries were "hybrid" units which meant that there was a direct DC connection to the battery from the PV panels, utilising a shared inverter for PV export or battery discharge. As a consequence, PV generation is controllable (downwards) as the battery inverter can have its power limited.

The five field trial homes have been mapped to the customer types used in the Everoze modelling (within Section 9 of the report), as shown in Table 3. This has aided the validation of Everoze's modelling work performed using the technical trial data outputs.

| Home | Customer type | EV transport pattern | Notes |
|---|---|---|---|
| **1** | High thermal and electrical demand | Commuter | Two adults and two children. Long commutes. |
| **2** | High thermal and electrical demand | Commuter | Two adults and two children. Local commutes. |
| **3** | High thermal and electrical demand | Parent | Two adults and two young children. Light usage for school run and local transport. |
| **4** | Medium thermal and electrical demand | Commuter | Two adults. Long weekly commute. |
| **5** | Medium thermal and electrical demand | Commuter | Two adults and one child. Local commutes. |

**Table 3** – Mapping field trial homes to customer types using in MADE modelling.

## 6.3 FIELD TRIAL DESIGN

**The field trial was divided up into four phases, as outlined in Figure 8 which shows a summary of the trial plan.**

These four phases are as follows:

**Phase 1:** Baseline

The focus was on gathering baseline data about household and asset electrical demand with the assets largely uncoordinated and hoped to capture some of the problematic scenarios caused by assets operating independently and synchronising their activities on tariff transitions.

**Phase 2:** In-home asset coordination

This phase involved automatic coordination of the operation of the hybrid heat pump with the battery and solar generation. It also included integrated control of the EV charge point (although largely manually driven).

**Phase 3:** Full coordination including EV

This phase involved fully optimised integration of the EV charge point along with the other assets.

**Phase 4:** Summertime

The last phase of the project explores the transition of the multi-asset system through late spring into summer as the availability of solar PV generation starts to dominate the picture.

The project aimed to explore a number of contrasting dimensions simultaneously:

- ToU tariffs: which provide the first level of demand shaping through a straightforward mechanism which exists in today's market and rewards the consumer directly. Testing involved three tariff patterns:

    a) flat rate tariffs, set at 14p/kwh as a baseline,

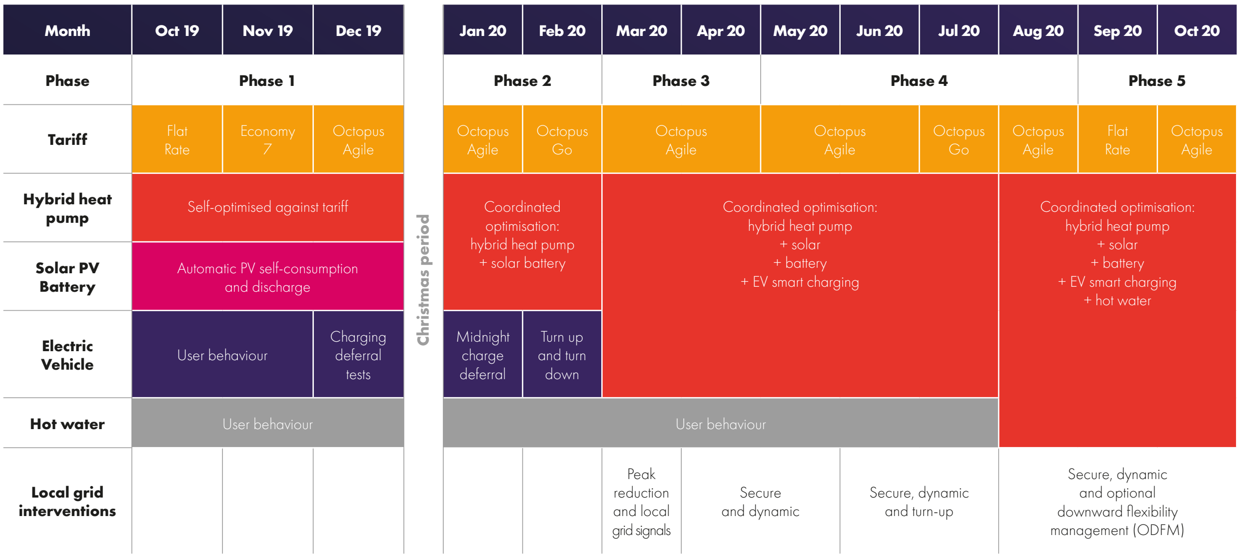
    b) cheap night-time tariffs like Octopus Go, an electricity tariff designed with EV users in mind. It offers an off-peak unit price of 5p/kWh between 12:30am and 4:30am, with a peak unit price of between 13-14p/kWh (13.8p/kWh for the MADE trial) outside of these hours, and

    c) Octopus Agile, an electricity tariff with half-hourly varying energy prices, calculated from wholesale prices and the peak early-evening DUoS charges, and updated daily (day-ahead prices published the evening before). This captures the major national-scale and distribution-scale drivers which captures the major national-scale and distribution-scale drivers.

- **Level of asset** coordination: as the project progressed, the number of assets with operation coordinated by optimisation algorithms was increased.

- **Seasonality:** the interplay of the assets changes significantly over the seasons: in winter, heating is dominant over PV generation, but vice versa in summer.

- **Interventions:** to explore the flexibility of the system to respond to local network needs.



| Month | Oct 19 | Nov 19 | Dec 19 | Christmas period | Jan 20 | Feb 20 | Mar 20 | Apr 20 | May 20 | Jun 20 | Jul 20 | Aug 20 | Sep 20 | Oct 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | Phase 1 | | | | Phase 2 | | Phase 3 | | Phase 4 | | | | Phase 5 | |
| Tariff | Flat Rate | Economy 7 | Octopus Agile | | Octopus Agile | Octopus Go | Octopus Agile | | Octopus Agile | | Octopus Go | Octopus Agile | Flat Rate | Octopus Agile |
| Hybrid heat pump | Self-optimised against tariff | | | | Coordinated optimisation: hybrid heat pump + solar battery | | Coordinated optimisation: hybrid heat pump + solar + battery + EV smart charging | | | | | Coordinated optimisation: hybrid heat pump + solar + battery + EV smart charging + hot water | | |
| Solar PV Battery | Automatic PV self-consumption and discharge | | | | | | | | | | | | | |
| Electric Vehicle | User behaviour | | Charging deferral tests | | Midnight charge deferral | Turn up and turn down | | | | | | | | |
| Hot water | User behaviour | | | | User behaviour | | | | | | | | | |
| Local grid interventions | | | | | | | Peak reduction and local grid signals | Secure and dynamic | | Secure, dynamic and turn-up | | Secure, dynamic and optional downward flexibility management (ODFM) | | |

**Figure 8** – Field trial intervention plan overview.

## 6.4 COVID-19 IMPACT

**It is worth noting that the COVID-19 pandemic hit during Phase 3 of the field trial. This caused some disruption to the trial, particularly due to significantly reduced EV use during national lockdown. As a result, some of the interventions planned during this phase of the field trial were delayed, and so some of the key examples of fully coordinated control were conducted in Phase 5.**

## 6.5 DETAILED FIELD TRIAL DESIGN

**The full technical field trial design report is available on the MADE page of the WPD website.**

# 7

# FIELD TRIAL ANALYSIS

**This section of the report presents the results obtained from the field trial, across the various project phases. The results presented in this section include both specific examples of control on a particular home, in addition to average behaviour over a longer time period for all homes under various control strategies and tariffs. This allows for key benefits of coordination and control to be observed on a single home level, whilst also providing a more encompassing overview of typical behaviour under a particular tariff and control strategy.**

Progress through the phases shows the increasing levels of benefits as the number of assets being coordinated increases: initially just the heat pump, then adding the battery, then adding the EV. There is also an inevitable change with the seasons as the trial progresses through 2020 from winter through to summer.

Due to the limited scale of the trial, the focus of this section is anecdotal real world examples that illustrate key behavioural characteristics, together with combining the results from all five homes to get as far as possible towards representative diversity.

Note that throughout the trial:

- In order to represent a future scenario with significant decarbonisation of heat, we assumed that the hybrid heat pumps were incentivised to use the heat pump as much as possible. Within the smart optimisation system, this was represented as a high (boiler) fossil-fuel price configuration
- A key aspect of the project was to explore different ToU tariffs, but it was not feasible to install smart meters and actually switch tariffs within project timescales. Therefore, all electricity tariffs used throughout the trial were applied 'virtually' – in that the systems were configured to operate the assets to minimise cost under the tariff, but the pilot householders were not actually paying for electricity according to the ToU tariff. This meant we would not expect consumers to try to move other electricity usage (appliances) to cheap times, and so – for project purposes – we regard all electricity usage other than the four low-carbon assets as non-flexible (fixed baseload).

## 7.1 PHASE 1: BASELINE OPERATION

**Phase 1 of the trial focused on gathering baseline data regarding the household and asset demand. During this phase, the energy assets within the home were largely uncoordinated. The control strategy for each asset during the baseline phase was as follows:**

**Hybrid heat pump** – use was optimised against the tariff, but with no awareness of solar, battery availability or EV demand;

**Battery** – controlled by Sonnen's internal "automatic" control algorithm which charges the battery when there is excess solar and discharges when there is net demand from the home. The battery will therefore react to heat pump consumption, but cannot distinguish this from another household demand;

**EV** – during this phase, no EV optimisation was performed. The charge point was used as and when the householder decided to charge.

During this phase, homes were optimised to two different tariffs:

- Flat Tariff
- Octopus Agile

It should be noted that, in line with the control strategy outlined above, during this section of the report the term "controllable load" refers to heat pump load only, since this was the only asset load which could be altered by the control strategy during Phase 1 of the field trial.

### 7.1.1 FLAT TARIFF

Phase 1 commenced with homes on a flat tariff, with an electricity price of 14p/kWh. Figure 9 below shows typical baseline operation for a MADE home on a flat tariff. The following can be observed from this figure:

- Thermal comfort is maintained throughout the day. Both the heat pump and boiler are used to meet heat demand, with the heat pump utilised over the majority of the day with support from the boiler when required.
- There is negligible solar in December. Thus, the battery is not utilised at all (as all PV generation is consumed during the day by the heat pump and other appliances).
- There is high electricity demand from the home during the early evening. This is largely driven by the occurrence of an EV charge session, with the heat pump also operating during this time.

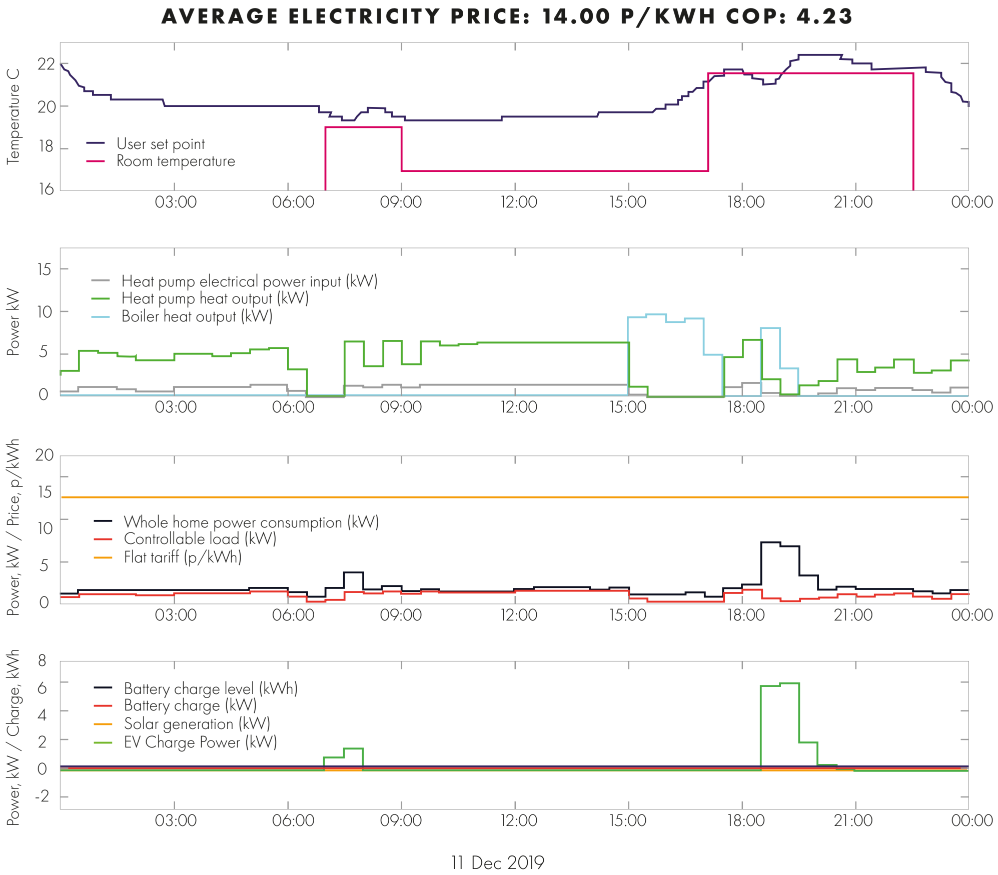


**Figure 9** – Baseline operation on flat tariff (Home 5, 11/12/2019).

Figure 10 below shows the average daily whole home power import profile over a one week period whilst on a flat tariff for all five MADE homes. The following can be observed from the figure:

- As would be expected for typical households, the electricity demand is highest during the early evening.
- The controllable load, which during this phase of the project consists of heat pump load only, is reasonably consistent throughout the day. This is as expected when optimising against a flat tariff, since heating cost will be the same at any time of day, therefore the home will simply be heated as and when required.

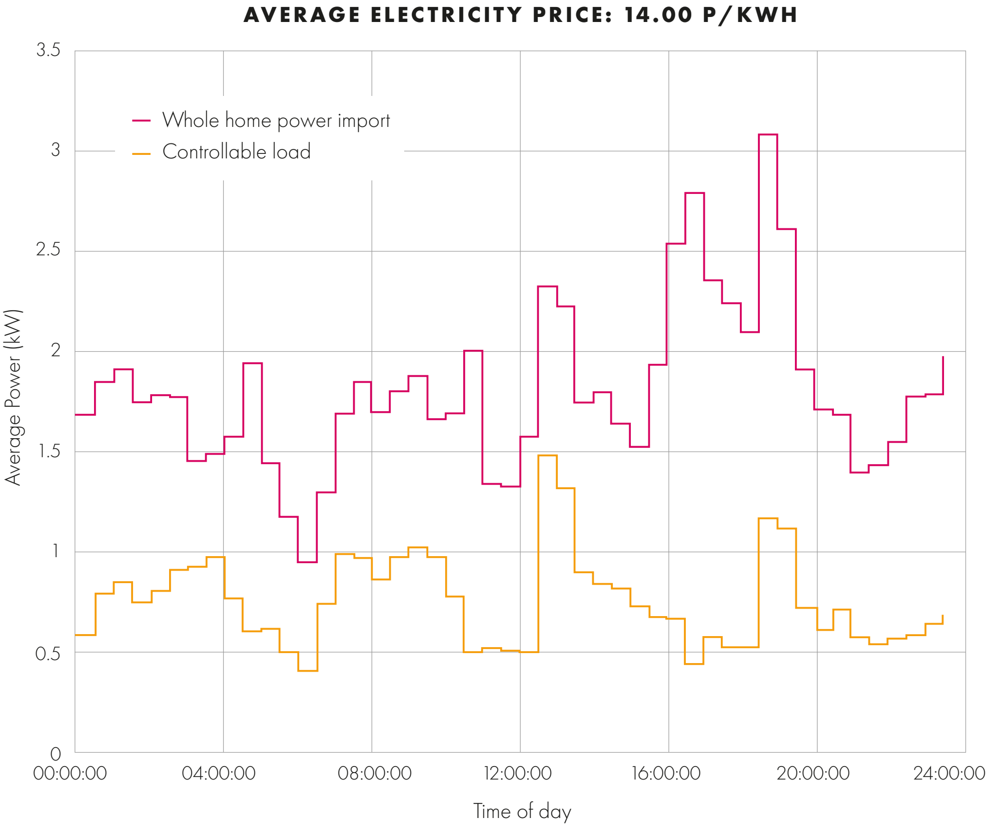


**Figure 10** – Average load profiles for baseline operation on flat tariff (All homes, 09/12/2019 – 15/12/2019). Controllable load is just the heat pump in this case. Whole home power import = import from (/export to) the grid.

### 7.1.2 AGILE TARIFF

During Phase 1 of the trial, homes were then moved to the Octopus Agile tariff. This section of the trial is the closest comparison to Everoze's baseline modelling case, with the tariff varying at half-hourly intervals and asset optimisation generally aligned with baseline modelling assumptions, as outlined above. The key difference here is that, under this phase of the field trial, EV charging was not controlled.

Figure 11 below shows typical baseline operation for a MADE home on the Octopus Agile tariff. The following can be observed from this figure:

- Thermal comfort is maintained throughout the day. The heat pump is primarily used to meet heat demand, with some support from the boiler when required during the peak Agile tariff period.
- There is negligible solar in December, so the battery is not utilised at all since it is being controlled simplistically. Within this control mode the battery is not able to take advantage of the varying electricity price.
- There is high electricity demand from the home during the early evening. This is largely driven by the occurrence of an EV charge session during this time.
- In total, there was around 8kWh of import during the peak period (16:00 – 19:00) with an average electricity price of 24.25p/kWh during this period. Nearly 5kWh of this import was due to EV demand, and around 3kWh was down to baseload import. The cost of this 5kWh of EV charge could have been notably reduced through utilisation of EV control, moving this charge outside of the peak period where the average electricity price was 7.67p/kWh, or by coordinating EV charging and battery use. Additionally, baseload costs could also be reduced if the battery were utilised to exploit the time-varying prices. Both of these features are demonstrated later in the project.

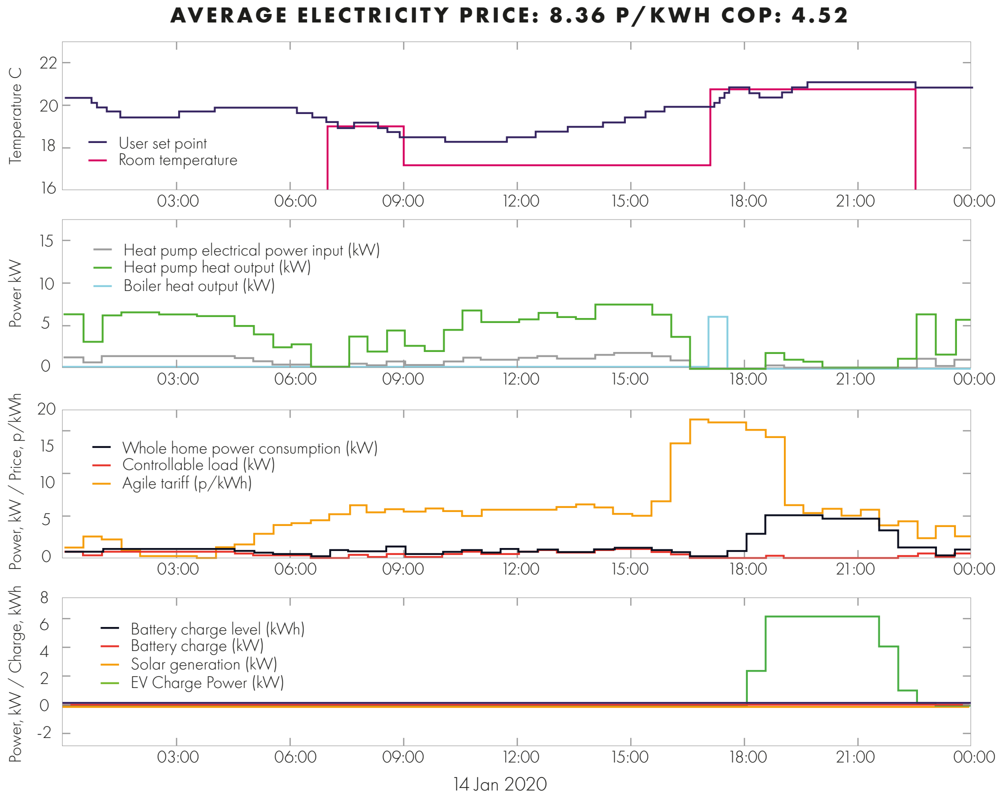


**Figure 11** – Baseline operation on Octopus Agile tariff (Home 5, 14/01/2020).

Figure 12 below shows the average daily whole home power import profile over a one week period whilst on the Octopus Agile tariff for all five MADE homes. The following can be observed from the figure:

- As previously, electricity demand peaks during the early evening.
- The controllable load has been reduced during the evening peak period (counterfactual Figure 9 for behaviour on a flat tariff), in line with the particular example shown in Figure 11. The average heat pump energy consumption between 16:00 – 19:00 has been reduced from 1.96kWh when on a flat tariff to 0.44kWh (reduced by 78%) on the Octopus Agile tariff.
- There is a sudden drop in the average controllable load at 16:00 when the peak Agile tariff period begins, with high demand immediately before. This is due to heat pump operation being optimised against the Agile tariff, with optimisation taking both comfort and cost into account, and thus in general avoiding this expensive period where possible.
- The average electricity price on the Agile tariff was 9.96p/kWh compared to 14p/kWh on a flat tariff during the same phase (a saving of 29%).
    - Some savings are due to the Agile pricing alone, but even more savings are possible from the optimisation of the heat pump asset. We can assess this by comparing with the scenario in Figure 9 where the heat pump was not optimised for Agile; if the householder had in fact been on the Octopus Agile tariff over this time period, the average electricity price would have been 11.94p/kWh, a saving of only 15%.

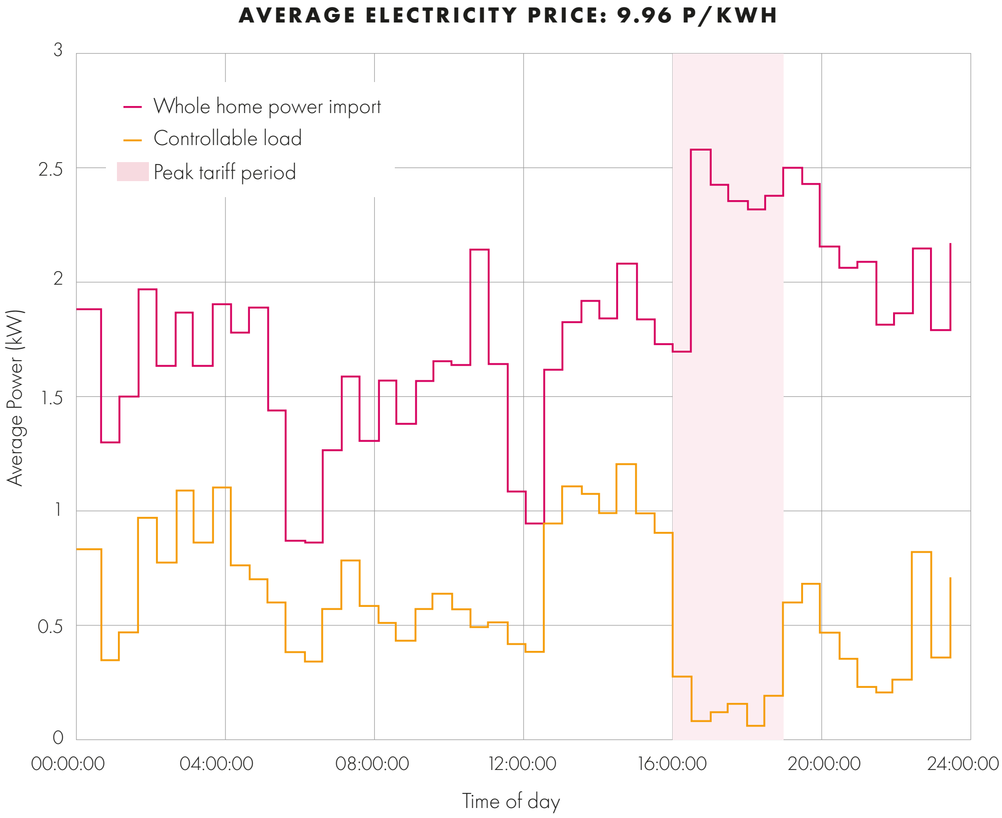


**Figure 12** – Average load profiles for baseline operation on Octopus Agile tariff (All homes, 10/01/2020 – 16/01/2020). Controllable load is just the heat pump in this phase. Whole home power import = import from (/export to) the grid.

## 7.2 PHASE 2: ASSET COORDINATION – HYBRID HEAT PUMP, BATTERY AND SOLAR

**Phase 2 of the trial involved automatic coordination of the operation of the hybrid heat pump with the battery and solar generation. We were also able to demonstrate the effect of EV charges being shifted to cheap tariff periods on individual occasions.**

The control strategy for each asset during Phase 2 was as follows:

**Hybrid heat pump** – use was optimised against the tariff, coordinated with solar generation and battery availability, but no awareness of EV demand

**Battery** – controlled via a combination of PassivSystems' battery control algorithm and Sonnen's internal "automatic" control algorithm, with PassivSystems' algorithm deciding when to switch between control strategies. During this phase, the battery was optimised against the tariff, coordinated with both solar generation and hybrid heat pump use as well as baseload electricity demand. This enabled load shifting through pre-charging the battery during cheap tariff periods

**EV** – during this phase, any EV control was manually driven. Vehicles typically charged as soon as they were plugged in, however, integration with the EV charge points was being tested and this was used to demonstrate delaying EV charges

At different times during this phase, homes were optimised to two tariffs:

- Octopus Go
- Octopus Agile

It should be noted that, in line with the control strategy outlined above, during this section of the report the term "controllable load" refers to the heat pump and battery assets (only).

### 7.2.1 OCTOPUS GO TARIFF

Figure 13 shows typical operation under the coordinated control strategy implemented in Phase 2 of the trial, against the Octopus Go tariff. The following can be observed from the figure:

- The home is pre-heated with cheap electricity during the off-peak tariff period. Thermal comfort is maintained and met entirely by the heat pump over the window shown.
- One battery cycle per day is observed. The battery charges over the cheap tariff period and then discharges following the return to the peak tariff rate.
- Minimal solar generation is available in February, so this does not influence asset operation patterns.
- There is high household consumption during the cheap tariff periods, with heat pump use and battery charging maximised during this time. The average price of electricity paid over this three day window was 10.48p/kWh (a saving of 25% over a flat rate of 14p/kWh).

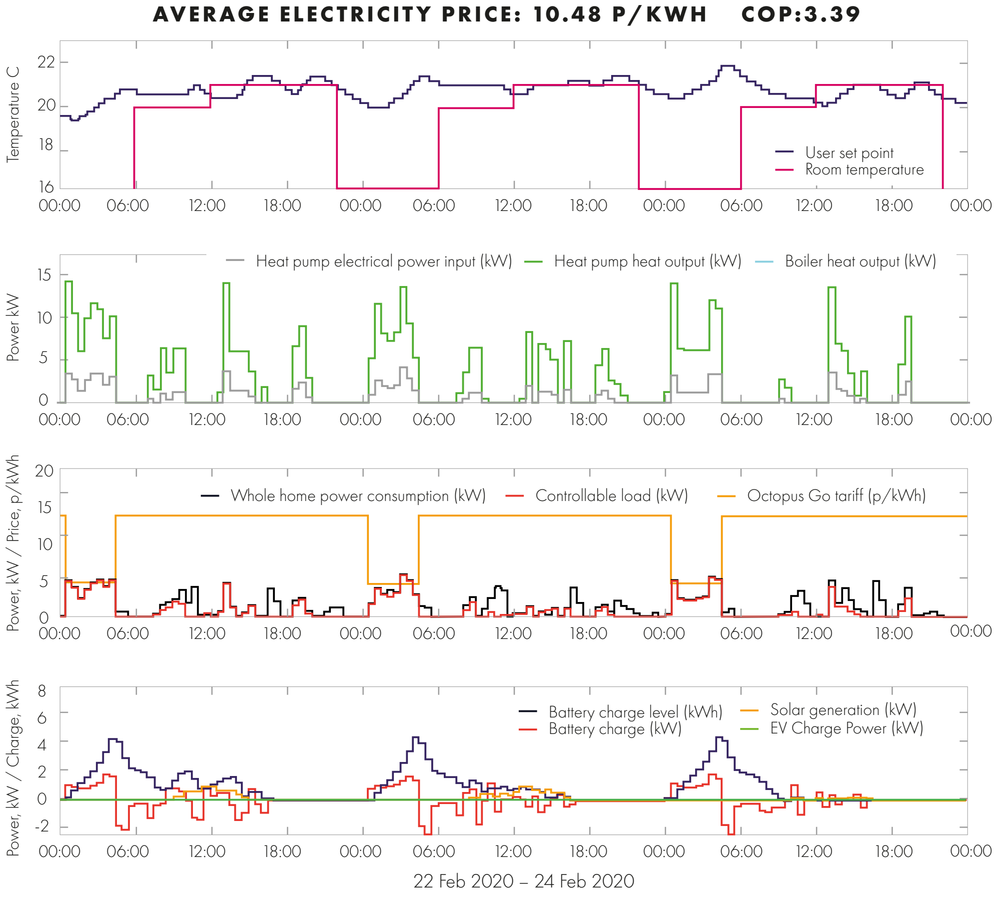


**Figure 13** – Coordinated control on the Octopus Go tariff (Home 03, 22/02/2020 – 24/02/2020).

Figure 14 shows the average daily whole home power import profile over a one week period whilst on the Octopus Go tariff for all five MADE homes. The following can be observed from the figure:

- In line with the particular example shown in Figure 13, electricity demand is notably highest during the cheap period between 00:30 and 04:30 on the Octopus Go tariff. This is driven by both the heat pump and battery taking advantage of the cheap electricity price.
- The average controllable load is negative between 04:30 – 07:30 (i.e. immediately after the cheap rate period) as the battery discharges to meet both household and heat pump demand.
- The average electricity price on the Octopus Go tariff over the one week period considered below was 11.20p/kWh (a 20% saving compared to a flat rate of 14p/kWh).

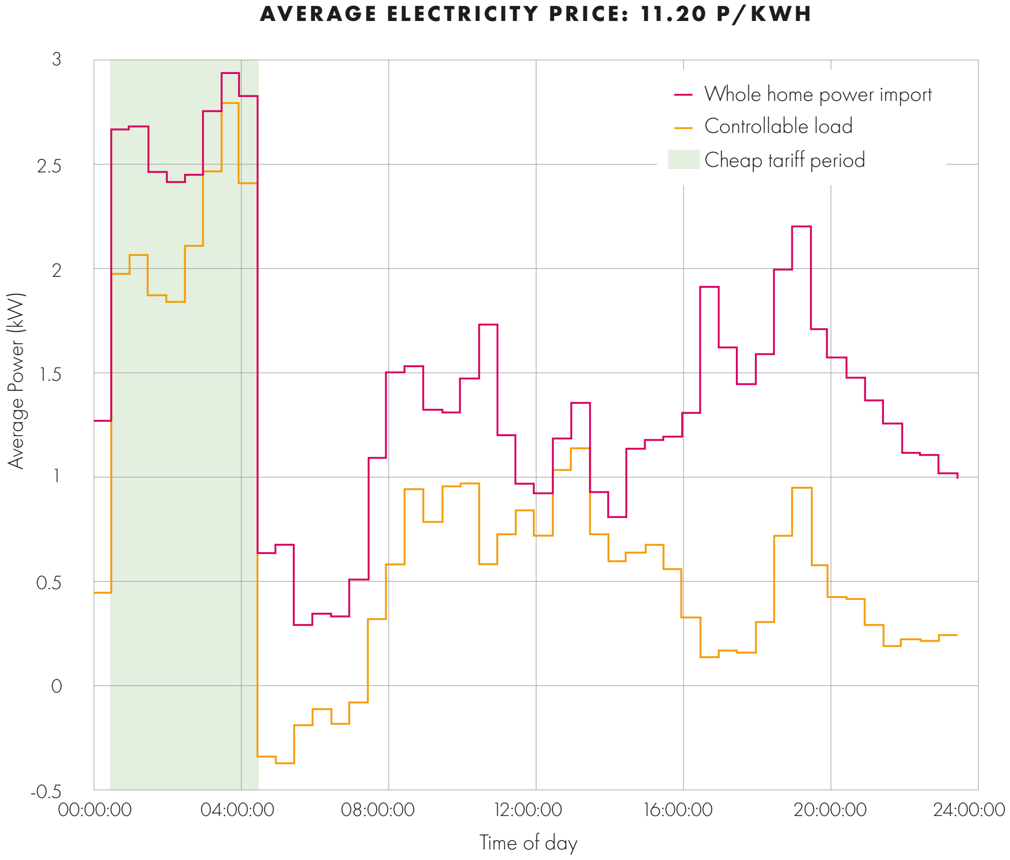


**Figure 14** – Average load profiles for Phase 2 operation on Octopus Go tariff (All homes, 18/02/2020 – 27/02/2020, note that three days' worth of data were excluded from this range due to interventions which significantly affected the demand profile).

# 7.3 AGILE TARIFF

**Figure 15 shows typical operation under the coordinated control strategy implemented in Phase 2 of the trial, against the Octopus Agile tariff. The following can be observed from the figure:**

The control strategy for each asset during Phase 3 was as follows:

- The home is pre-heated with cheap electricity during the off-peak tariff period. Thermal comfort is maintained and met mainly by the heat pump over the window shown, with support from the boiler only required to meet short notice requests for heat where the householder has manually changed their set point.
- Two battery cycles per day are observed. The first cycle involves the battery charging up with very cheap overnight electricity which is then discharged over the late morning. The second cycle occurs in order to avoid peak electricity prices. The battery charges up prior to the peak Agile tariff period (typically 16:00 – 19:00), and discharges during this expensive period. This observation of two battery cycles per day is an interesting project learning given that most domestic batteries are currently designed with an expectation of one battery cycle per day. Battery arbitrage can also be observed, particularly overnight on the 10th February, where the battery exploits varying electricity prices, charging when cheap and discharging to meet home consumption when expensive.
- Household consumption is reduced almost entirely during the Agile peak tariff period (typically 16:00 – 19:00). The average price of electricity paid over this three day window was 5.46p/kWh.

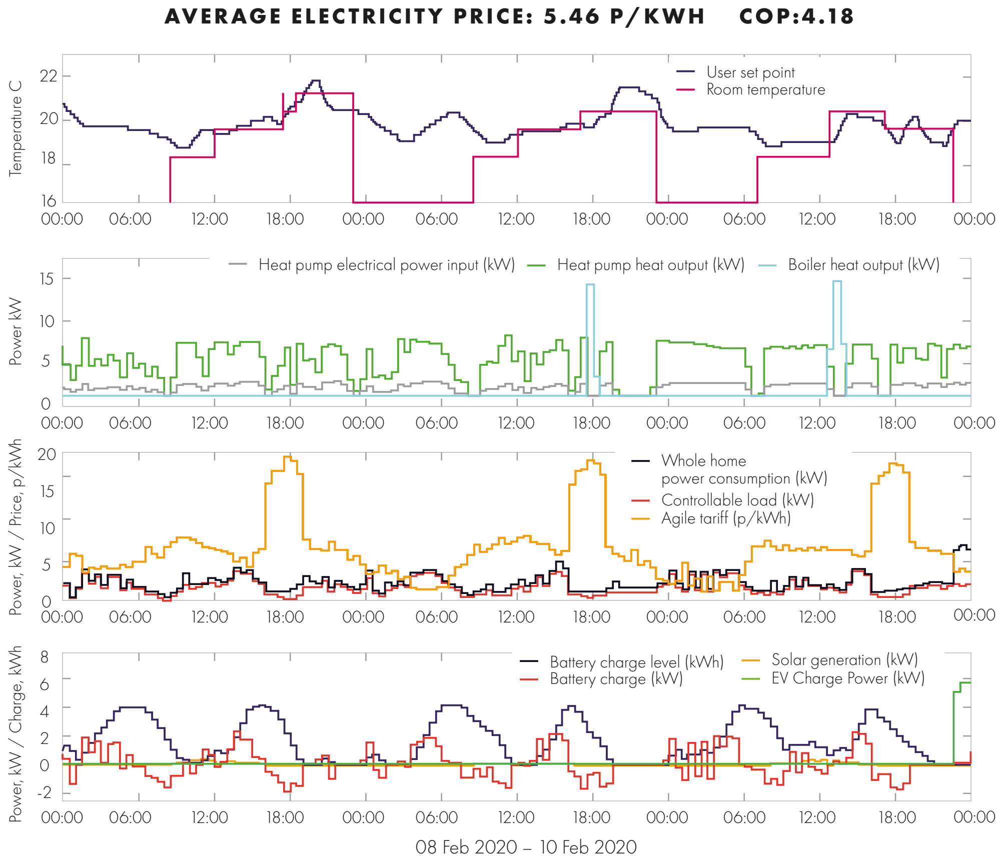


**Figure 15** – Coordinated control on the Octopus Agile tariff (Home 05, 08/02/2020 – 10/02/2020).

Figure 16 below shows the average daily whole home power import profile over a one week period whilst on the Octopus Agile tariff for all five MADE homes. The following can be observed from the figure:

- Controllable load is very low (negative) between 16:00 – 19:00, aligning with the time period where the Agile tariff price is typically particularly high. Here the battery is discharging in order to reduce import required over the peak Agile tariff period. This is in line with the particular example shown in Figure 15 above.
- Controllable load is generally highest overnight, where the Agile price is typically very low. Fluctuations in controllable load are observed during this period, with the system taking full advantage of fluctuating Agile prices.
- A demand peak can be observed prior to 16:00, where both the heat pumps and batteries are preparing to minimise grid import required over the peak Agile tariff period. Again, this is in line with the example shown in Figure 15.
- The average electricity price on the Octopus Agile tariff over the one week period considered below was 7.08p/kWh. This is compared to an average electricity price of 9.96p/kWh on the Octopus Agile tariff under Phase 1 of the field trial.

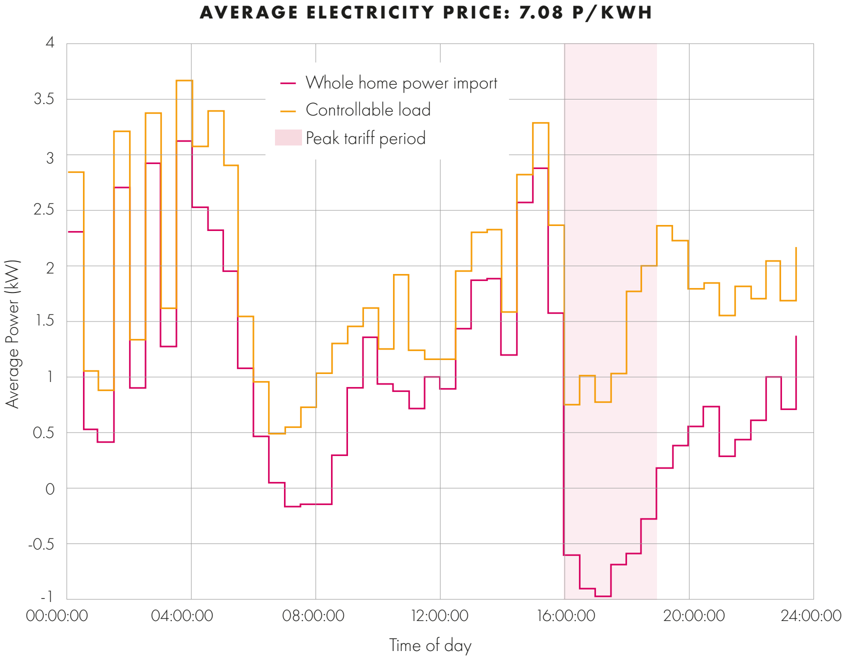


**Figure 16** – Average load profiles for Phase 2 operation on Octopus Agile tariff (All homes, 07/02/2020 – 13/02/2020). Controllable load is the combination of heat pump and battery in this case. Whole home power import = import from (/export to) the grid.

## 7.4 PHASE 3: FULL COORDINATION INCLUDING EV

**Phase 3 of the trial moved to full coordination of all assets considered under MADE, including the EV charge point.**

The control strategy for each asset during phase three was as follows:

**Hybrid heat pump** – use was optimised against the tariff, coordinated with solar generation and battery availability as well as EV demand. The hybrid heat pump controls were configured with a high price for the fossil fuel boiler in order to reflect the future scenario of substantial decarbonisation, which enabled a high proportion of the heat demand to be provided by the heat pump

**Battery** – the battery was optimised against the tariff, coordinated with solar generation and hybrid heat pump use as well as EV and baseload electricity demand. Where possible, the system utilised Sonnen's internal control mode for matching demand on a minute-by-minute basis, overriding when excess charging or discharging was required. This enabled load shifting through pre-charging the battery during cheap tariff periods

**EV** – during this phase, EV charging control was fully automated. Charging was controlled using PassivSystems' EV control algorithm, based on user information inputted via the PassivSystems app. Upon plugging in, EV users were asked to enter the current state of charge of their vehicle, the desired state of charge, and the time they required it to be charged by. Based on this information, the EV was then charged at the most beneficial time within the flexibility given (i.e. ensuring it was recharged when required), coordinated with all other energy assets in the home to minimise consumer costs whilst also honouring any constraints that may be in place

During this phase, homes were optimised to two different tariffs:

- Octopus Go
- Octopus Agile

It should be noted that, in line with the control strategy outlined above, during this section of the report the term "controllable load" refers to heat pump, battery and EV load.

### 7.4.1 OCTOPUS GO TARIFF

Figure 17 shows typical operation under the coordinated control strategy implemented in Phase 3 of the trial, against the Octopus Go tariff. The following can be observed from the figure:

- There is high demand during the cheap overnight tariff periods with the battery, and EV where plugged in, charging during this time.

- The battery undergoes a full charge during the cheap overnight tariff period. The battery then discharges over the course of the day, with some excess solar stored in the battery where available.

- Room temperature is well maintained, with a minimum of 17.7°C and a maximum of 18.6°C across the period shown in the Figure. There is little demand for heating, and heat pump demand is partially met by the battery which was charged during the cheap overnight and times of excess solar. Due to high external temperatures in June and thus little demand for heat, no heating occurs during the cheap overnight period; however, during a winter scenario the heat pump would be expected to make use of the cheap rate in addition to the battery and EV.

- The EV is plugged in at 16:00 on day one, with the user requesting full charge by 06:30 the following morning. It should be noted that the maximum charge rate for this particular EV is 3.6kW. Since the battery is empty upon the EV being plugged in, charging is delayed until the cheap overnight tariff period where the EV then begins to charge at full rate. However, the EV cannot draw sufficient charge to meet the user's request in this period alone, therefore some charging must take place after the cheap tariff period as well. Coordination between the EV and the battery has enabled the power supplied by the domestic battery (previously charged on the cheap rate) to the EV to be maximised: the EV charge rate was reduced to match the battery power capacity between 05:00 and 06:30 (with the confidence from the predictive control that a fully charged EV would still be achieved). Thus, this allows the home to stay virtually off-grid whilst the EV charge session completes, reducing the cost of charging the EV.

- The EV is plugged in at 15:00 on day two, with the user requesting full charge by 06:30 the following morning again. Day two has a greater amount of solar generation, and thus the battery still holds a fair amount of charge during the early evening (whereas it was empty on day one). Thus, EV charging can commence in advance of the cheap overnight tariff period, freeing up space in the battery so that it can charge a greater amount during the cheap overnight period. Once the tariff becomes cheap, the EV power is increased to full rate and by the end of this period the EV is essentially fully charged. As the EV charging is de-rated towards the end of the charge session, a small amount of power is drawn outside of the cheap tariff period. Again, the battery discharges to match the EV power in order to prevent the need to import electricity at the higher rate.

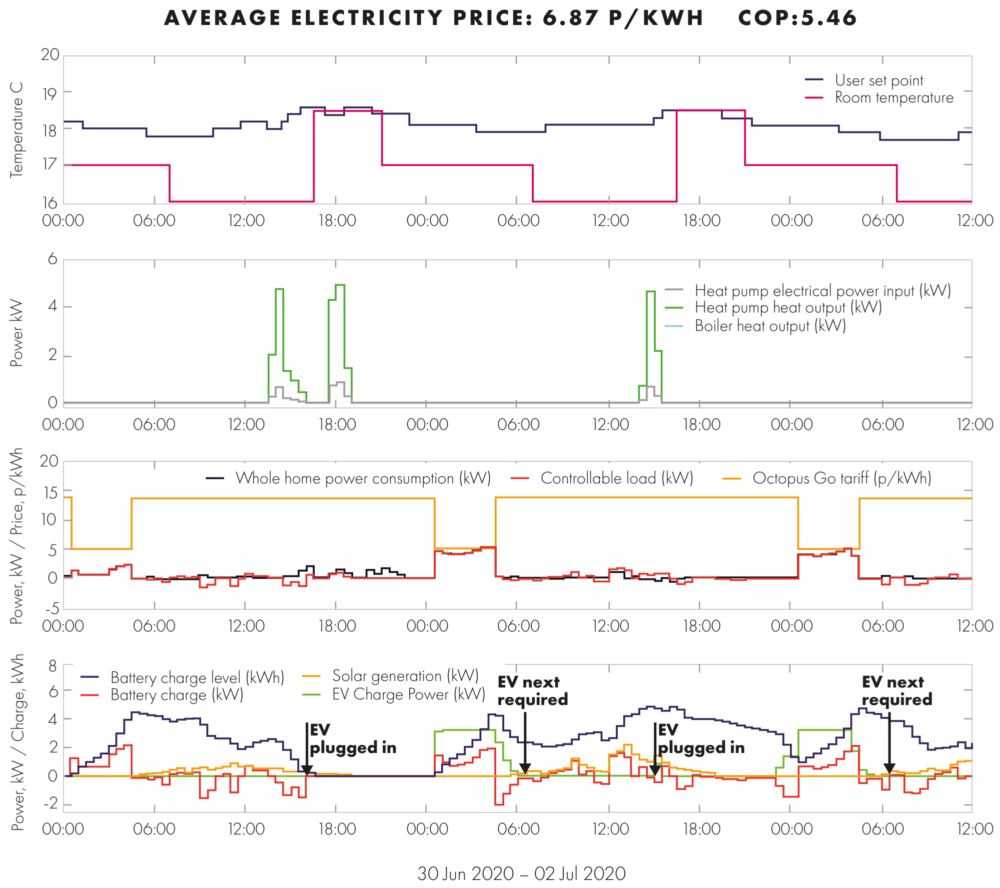


**Figure 17** – Fully coordinated control on the Octopus Go tariff (Home 1, 30/06/2020 – 01/07/2020).

### 7.4.2 AGILE TARIFF

Figure 18 below shows typical operation under the coordinated control strategy implemented in Phase 3 of the trial, against the Octopus Agile tariff.

The following can be observed from the figure:

- Room temperature is well maintained, with a minimum of 17.7°C and a maximum of 18.9°C across the two day period. For reference, the average external temperature was 15.3°C over this same period, with a high of 19.0°C and a low of 13.3°C.
  - On day one the home is sufficiently heated in advance of the evening set point due to a high external temperature and high solar irradiance, and thus no additional heating is required. After the evening Agile peak tariff period, the heat pump kicks in to ensure that thermal comfort is maintained for the duration of the evening.
  - Day two is less sunny with a lower external temperature, therefore the heat pump is used to bring the home up to the evening set point, with the bulk of this heating executed when the tariff is at 1.197p/kWh. Additional heating is required during the Agile peak tariff period; however, the required power is provided mainly by excess solar generation with some support from the battery when required to ensure the home remains off grid during this expensive tariff period.

- The EV is plugged in at 21:30 on day one, with the user requesting full charge by 06:30 the following morning. The maximum charge rate for this particular EV is 3.6kW.
- There is still some battery charge available when the EV is plugged in. As a result, the EV charges at a reduced rate in the first half hour interval to match the amount that the domestic battery can discharge, since the tariff is relatively expensive here compared to the rest of the night at 7.5p/kWh.
- Overnight the battery charges up during cheaper tariff periods and discharges during the more expensive tariff periods to offset EV charging, in order to maximise the consumption of cheap electricity.
- At 05:30 the EV reaches full charge in advance of the end time (a buffer is allowed due to the fact the true state of charge of the vehicle is not known). This is a good example of EV charging being delayed as late as possible to make use of cheap tariff periods while being confident that sufficient charge is being delivered.
- On day one the battery charges from excess solar generation, and discharges to meet excess household consumption.
- On day two there is not as much solar and there is higher demand from other uncontrollable loads within the home, therefore the battery discharges during the day. The battery then charges using electricity imported from the grid between 13:30 – 15:00 when the electricity price is between 1.1 – 2.1p/kWh to enable the home to be kept off grid overnight when the electricity price is notably higher.

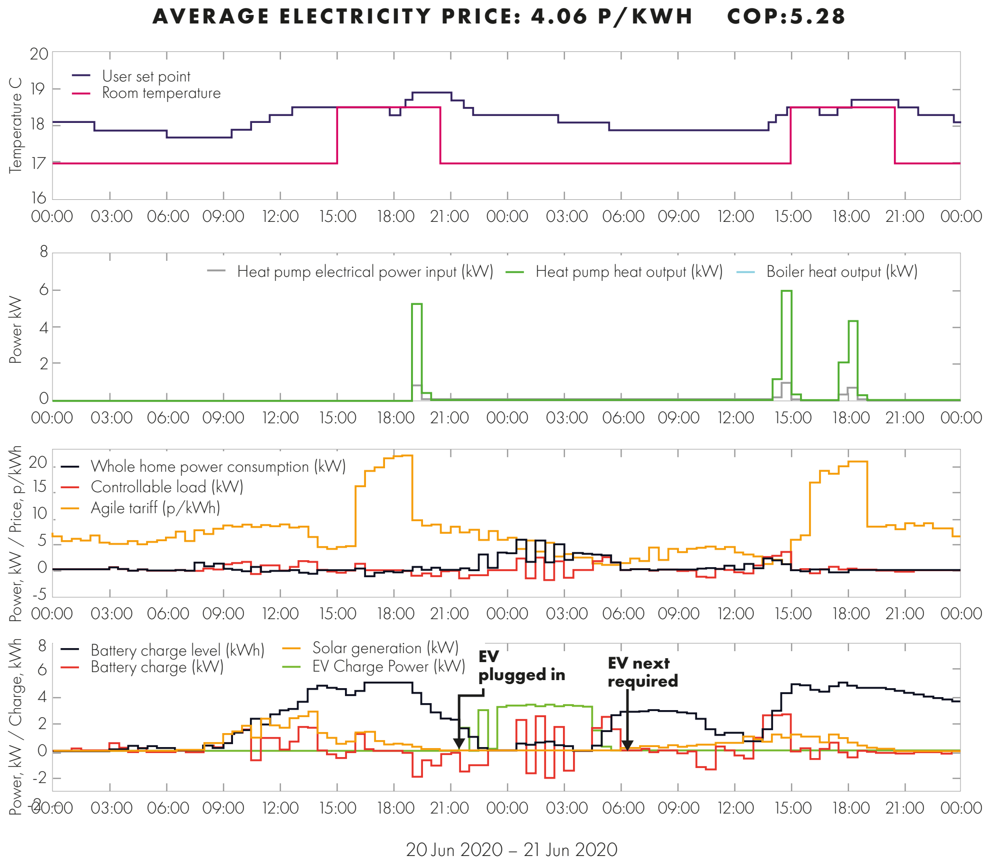


**Figure 18** – Fully coordinated control on the Octopus Agile tariff (Home 01, 20/06/2020 – 21/06/2020).

Figure 19 below shows an example of coordinated control where EV charging was optimised to match solar generation, as well as a trade-off made against time-varying Octopus Agile pricing.

The following can be observed from the figure:

- No heating was required on this day.
- The EV was plugged in at 10:40 with a full charge requested by 16:00 the same day.
  - At the start of the charge session, the EV charges at a reduced rate which closely matches solar generation, providing a nice example of asset coordination. The battery provides an active role as well, dynamically compensating for the variations in solar generation and household load.
  - Towards the end of the charge session, electricity is required from the grid in addition to the solar generation in order to charge the EV to the required level. This is primarily done during cheaper tariff periods, with the battery also charging during these periods before discharging during the more expensive periods, demonstrating coordination again.
  - The EV is fully charged by 16:00, as required. The battery charges prior to 16:00 in order to (successfully) keep the home off grid during the Agile peak tariff period.

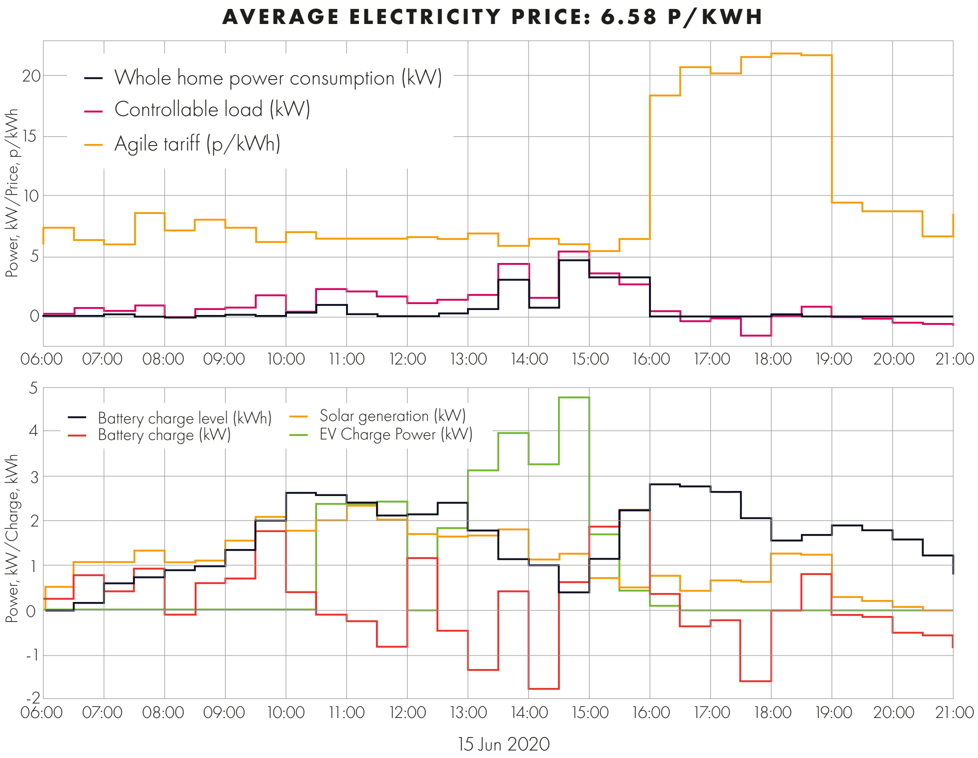

AVERAGE ELECTRICITY PRICE: 6.58 P/KWH

**Figure 19** – EV, Solar and Battery Coordination (Home 05, 15/06/2020).

# 7.5 PHASE 4: SUMMERTIME

**Phase 4 of the trial involved an investigation into how coordinated asset behaviour changed in summertime conditions, when solar PV generation was dominant over heating demand. During this phase, homes were optimised to the Octopus Agile and Octopus Go tariffs.**

This section of the report provides examples which illustrate typical summertime operation in the MADE homes under each of these the tariffs outlined above.

A key issue that arose during this phase was the overheating of homes when incentivised by high excess solar or negative electricity prices.

## 7.5.1 AGILE TARIFF

Figure 20 shows an example of typical summertime operation, with high external temperatures and high solar generation, under the Octopus Agile tariff. The combination of solar PV and battery keeps the home completely off-grid over almost all of this period, with significant net export of electricity as well.

The following can be observed from the figure:

- There is no heating demand. The home stays well above setpoint without the need for use of the heat pump or boiler
- High solar PV generation has moved the system back from two cycles a day to one cycle a day, as the system recognises that free solar is advantageous over cheap night-time electricity rates. The change is driven largely by two factors. The first is that the control algorithm can recognise the cost advantage of charging from free solar is more beneficial than charging from the grid, even with cheap overnight rates. It therefore decides to save battery capacity for the upcoming solar, demonstrating a cost benefit of coordination between the battery and solar. The second driver is the absence of morning heating demand. This coordination between the battery and heat pump allows for more efficient operation of the battery, which again results in cost savings for the householder
- The household imports only 4.76kWh of electricity over the three day period, but exports 34.8kWh of electricity in the same period. The percentage of household electricity consumption supplied by solar PV generation (and subsequent battery discharge) was as follows:

  ① Day one: 79%

  ② Day two: 90%

  ③ Day three: 95%

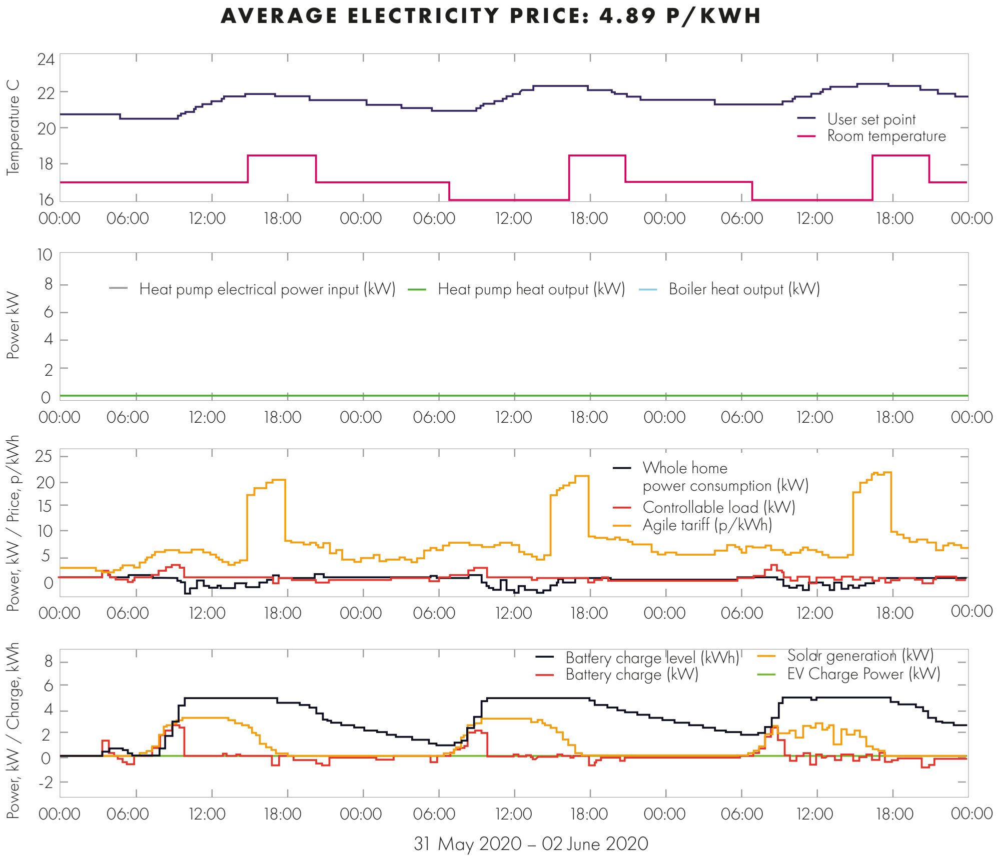


**Figure 20** – Summertime operation on Octopus Agile tariff (Home 1, 31/05/20 – 02/06/20).

Figure 21 below shows the average daily whole home power import profile over a one week period with high external temperatures and high solar generation on the Octopus Agile tariff for all five MADE homes. The average external temperature in this period was 16.5°C; an average of 20.4°C during the day (09:00 – 21:00 ) and 12.7°C overnight (21:00 – 09:00). Controllable load refers to heat pump plus domestic battery plus EV charging.

The following can be observed from the figure:

- There is a good amount of solar generation across the MADE portfolio in the week considered.
- There is no heating demand during this summer period (nor any negative Agile pricing to incentivise demand).
- There was some EV charging activity but only on a few occasions (so the average power values shown here are not very meaningful).

- Homes tend to draw from the grid overnight and export to the grid during the day. Most of the homes tend to charge the battery using excess solar from 06:00, and then start to export around 10:00 when the batteries become full.
  - One of the homes has a particularly low household consumption, therefore the battery typically accumulates charge from excess solar on previous days and the export transition happens earlier in this home at around 08:00.
- The battery discharges over the course of the evening to offset demand with 'free' stored solar power. As solar generation continues across the Agile peak tariff period, the battery discharge during this time is lower than the Phase 2 example (Section 7.2).
- Whole home power import remains low (or negative) throughout the day.

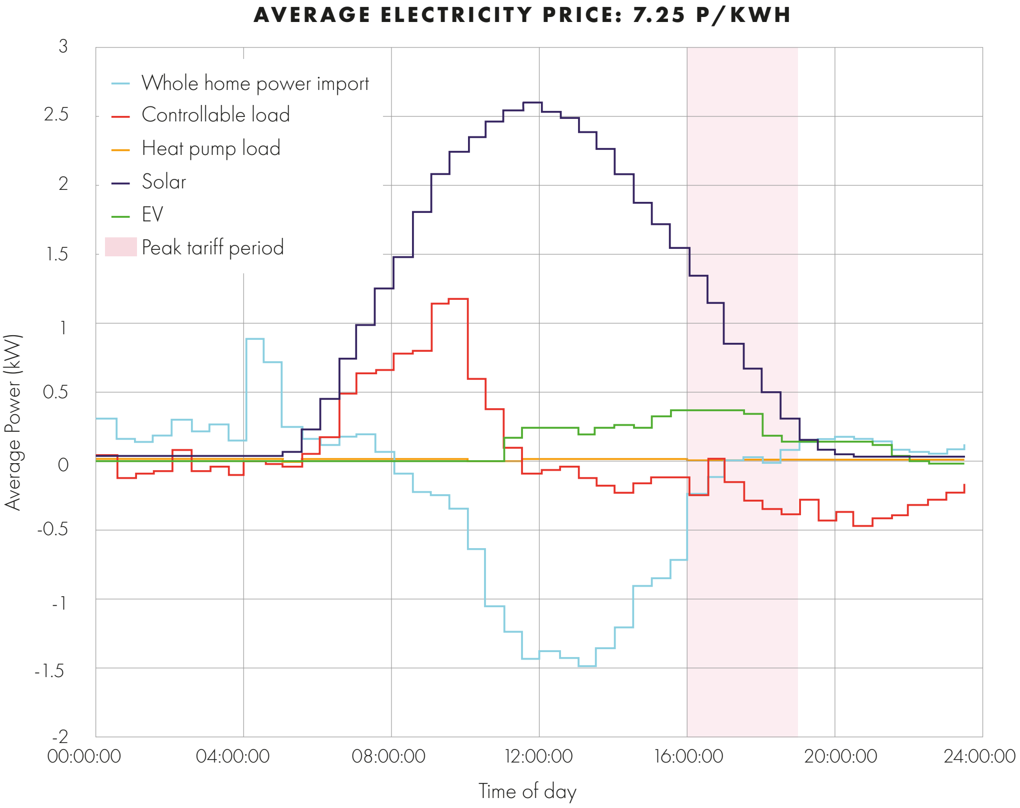


**Figure 21** – Average load profiles for summertime operation on Octopus Agile tariff (All homes, 25/05/2020 – 01/06/2020). Controllable load refers to heat pump plus domestic battery plus EV charge. Whole home power import = import from (/export to) the grid.

### 7.5.2 OCTOPUS GO TARIFF

Figure 22 shows an example of typical summertime operation, with high external temperatures and high solar generation, under the Octopus Go tariff. The combination of solar PV and the battery holding excess for the evening keeps the home completely off-grid over almost all of this period, with significant net export of electricity, and little need for the cheap overnight electricity.

The following can be observed from the figure:

- There is no heating demand. The home stays well above setpoint without the need for use of the heat pump or boiler.
- The battery does a small amount of charging during the cheap overnight tariff period to meet early morning demand before solar kicks in. However, the system recognises that that free solar is advantageous over cheap night-time electricity rates.
- The household imports only 4.3kWh of electricity over the three day period, but exports 22.6kWh of electricity in the same period.

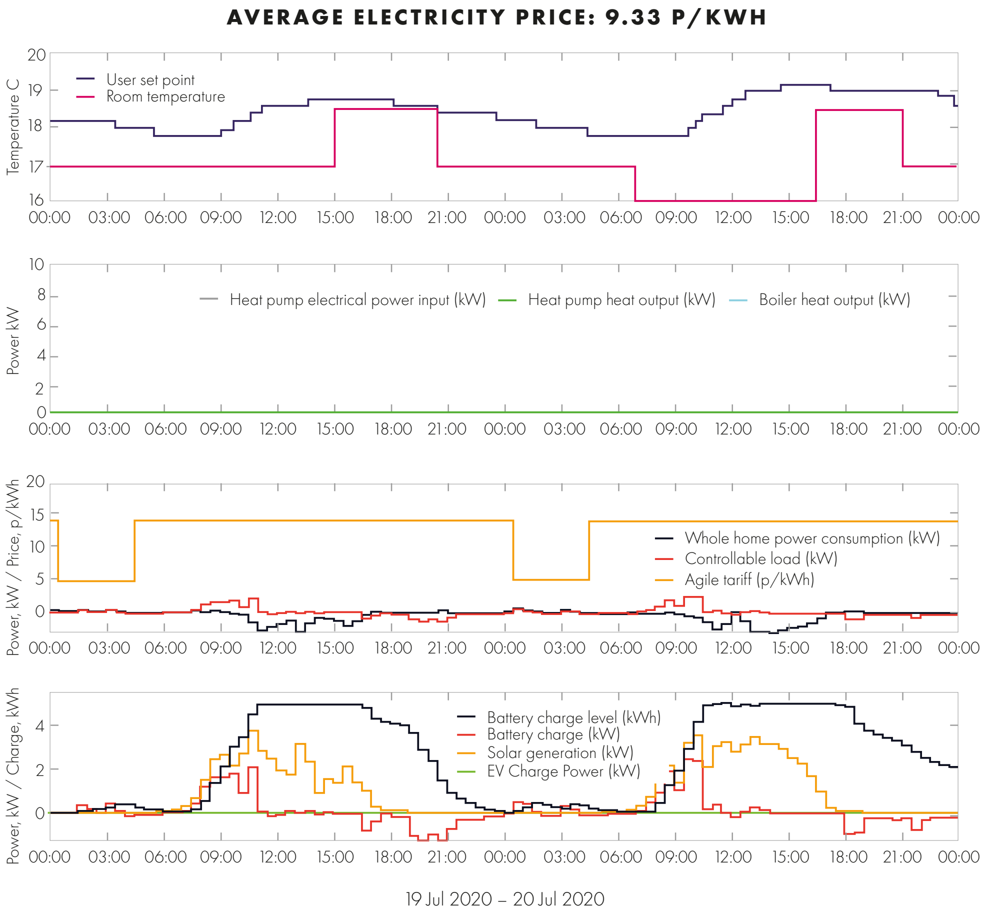


**Figure 22** – Summertime operation on Octopus Go tariff (home one, 19/07/20 – 20/07/20).

Figure 23 below shows the average daily whole home power import profile over a one week period with high external temperatures and high solar generation on the Octopus Go tariff for all five MADE homes. The average external temperature in this period was 15.3°C; an average of 17.4°C during the day (09:00 – 21:00 ) and 13.4°C overnight (21:00 – 09:00). Controllable load refers to heat pump plus domestic battery plus EV charging.

The following can be observed from the figure:

- There is a good amount of solar generation across the MADE portfolio in the week considered.
- There is no heating demand during summer, as expected.
- Homes tend to draw from the grid during the cheap overnight tariff period and export to the grid during the day. Homes tend to charge the battery using excess solar from 06:00, and then start to export around 10:00 when the batteries become full. Some additional battery charging takes place during the cheap overnight tariff period.
- The battery discharges over the course of the evening to offset demand with 'free' stored solar power.

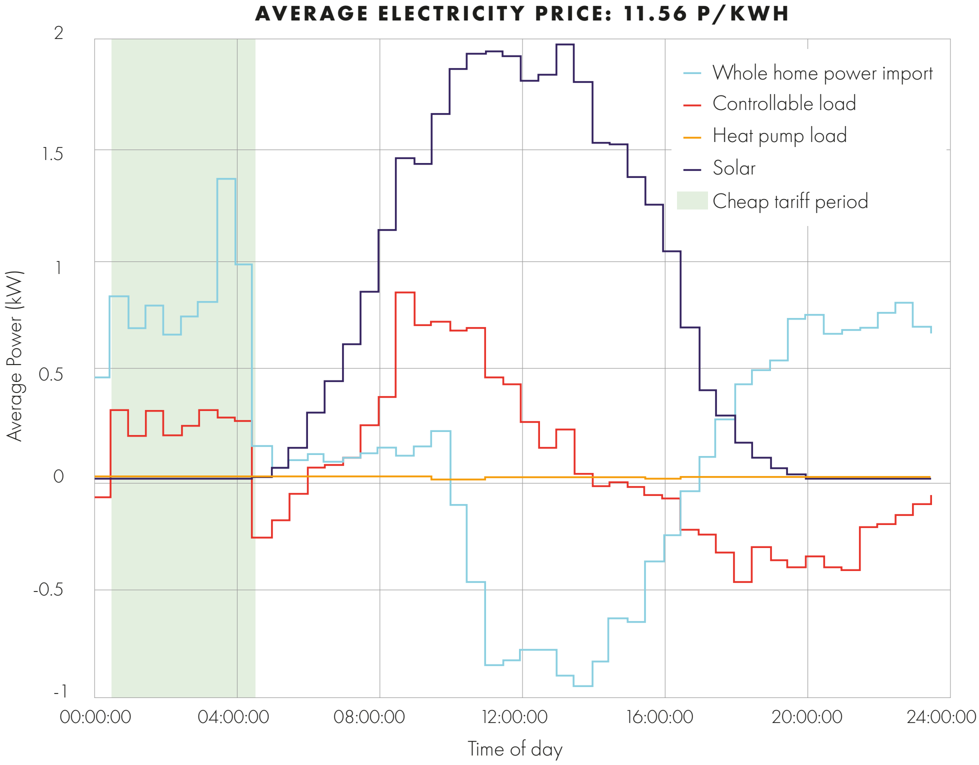


**Figure 23** – Average load profiles for summertime operation on Octopus Go tariff (All homes, 17/07/2020 – 23/07/2020). Controllable load refers to heat pump plus domestic battery plus EV charge. Whole home power import = import from (/export to) the grid.

# 7.6 DIGITAL TWIN: TRIAL DATA SIMULATED

**The focus of Section 7 was on presenting real world examples of key behaviour patterns from the MADE project, and through this the benefits of coordinated control were illustrated. However, it is hard to produce clear comparisons between different scenarios (such as the level of asset coordination) because the real world always introduces significant amounts of uncontrollable variability. Comparisons could be carried out simultaneously between different houses, but this is not possible with such a small portfolio because each house is different; and comparisons between different days are confounded by factors such as temperature, solar irradiation and user behaviour. As a consequence, simulation work has been carried out to allow illustration of a more direct comparison between different control strategies. The results of this simulation work are presented in this section.**

The approach was to execute multiple simulation runs with the same inputs, but to exercise different control strategies (such as the level of asset coordination). The simulation outputs were then analysed to provide insight into consumer cost savings, the impact of Flexible Power interventions, or the level of reduction of ToU tariff peaks.

Simulations have been carried out for four different scenarios:

**Day-ahead predictions with varying levels of asset control** – these focus on the predictive optimisation calculation within the PassivSystems controls system and contrast the different outputs that it produces for varying levels of asset coordination. The purpose of these simulation runs was to illustrate how asset demand shape changes with increasing levels of control.

**Two day simulations runs with varying levels of asset control** – these cover optimisation over a longer time period and are more closely aligned with likely real world performance. The purpose of these simulation runs was to provide examples of consumer cost savings associated with increasing levels of control.

**Simulations focused on Flexible Power scenarios** – these aim to provide understanding of the impact of participating in a service such as WPD's Flexible Power scheme. An approximate indication of the cost benefits to the householder for providing Flexible Power services are given in this section.

**Simulations focused on managing ToU tariff peaks** – these were performed to investigate demand peaks introduced by ToU tariffs and how they can be managed by a smart coordination system.

# 7.7 BENEFITS OF COORDINATION – OPTIMISATION OUTPUT

**This section of the report outlines how the optimisation output changes with increased layers of control. A digital twin of MADE Home 5 was used to perform these optimisation calculations, for the 23rd April as of 00:00. On this day the house requires some heat from the hybrid heat pump, and we assume that the EV is assumed to require 30kWh of charge by 07:00, the battery is assumed to have 1kWh of charge at the start of the optimisation window and optimisation is performed against the Octopus Agile tariff.**

**Figure 24 below shows the optimisation output under the Phase 1 (baseline) control strategy (where the heat pump is coordinated with PV but not the battery or EV).**

The following can be observed from the figure:

- The heat pump deliberately overheats the house during the middle of the day to make the most of free solar PV generation and to avoid having to run during the peak period, but is unaware that the battery would have been able to store this energy more efficiently for later consumption. The house is heated to a maximum of 22.6°C.

- The battery charges from excess solar and discharges to meet excess household load, but is not aware of the Agile pricing, so is not able to reduce the impact of the peak Agile period (it would have been more cost effective to fully charge the battery beforehand with grid import).

- No EV optimisation is performed, and thus the EV simply charges at full power at the start of the day. There is no coordination with the battery, therefore the only battery use during the EV charge session is when the battery discharges the 1kWh of charge it begins the day with as early as possible, despite the fact that this is actually the cheapest half hour period during the session.

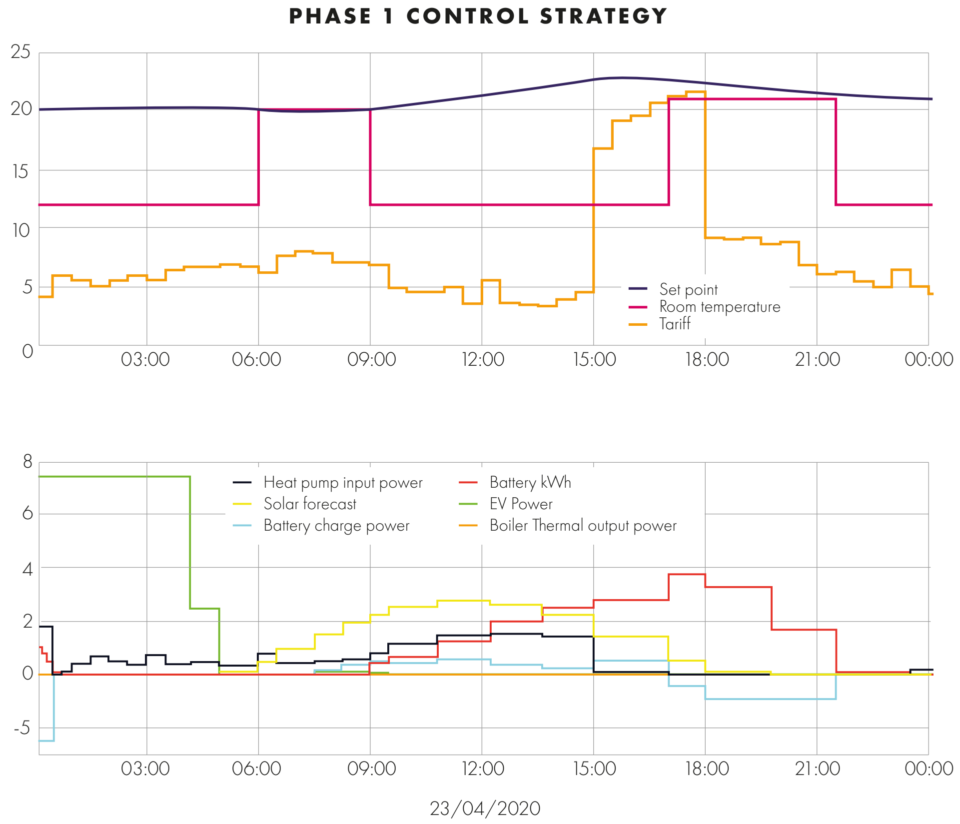


**Figure 24** – Phase 1 (baseline) control strategy (where the heat pump is coordinated with PV but not the battery or EV).

## Figure 25 shows the optimisation output under the Phase 2 control strategy where heat pump operation is coordinated with PV and battery but not yet the EV.

The following can be observed from the figure:

- Coordination between the heat pump and battery means that less heat needs to be stored in the fabric of the home (relatively inefficient) and the battery can be used instead to store PV for later use (and avoiding the peak period). The home is heated to a maximum temperature of 22.0°C vs 22.6°C in the previous example, and the heat pump is able to run in the peak period utilising stored battery power. Note that the coordination algorithm decides to use both storage mediums operating in tandem as the most efficient strategy.
- The battery now charges between midnight and 3am to arbitrage the more expensive electricity between 3am and 6am.
- The EV still charges at full power at the start of the day.

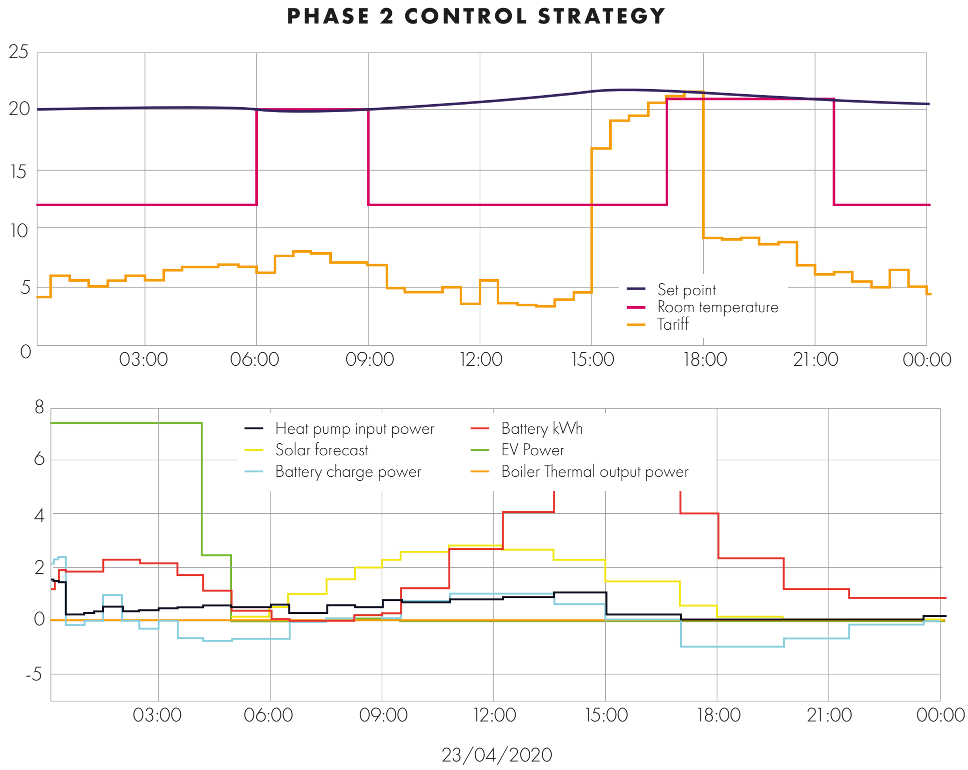


**Figure 25** – Phase 2 control strategy where heat pump operation is coordinated with PV and battery but not yet the EV.

## Figure 26 shows the optimisation output under the Phase 3 control strategy where all assets including the EV charger are coordinated.

The following can be observed from the figure:

- During the day, the heat pump and battery operate exactly the same as the previous example.
- The EV charge power is now optimised, with the EV charging during the cheapest overnight tariff periods.
- Under full coordination, the battery now charges more heavily in the first part of the night in order to be able to discharge 4am-7am to meet EV and heat pump load, avoiding the more expensive electricity at this time. During this more expensive period the EV charge rate (usual maximum 7.3kW) is reduced in line with the maximum battery discharge power (2.5kW) while being confident (through prediction) that the required EV charge level will be met in time.

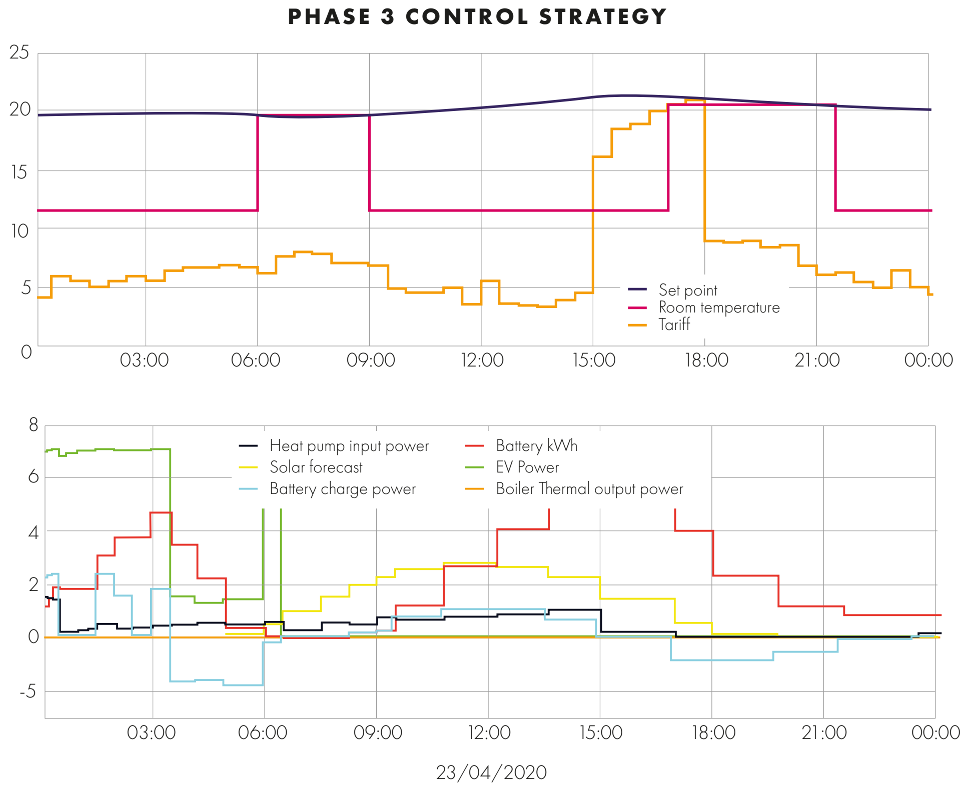


**Figure 26** – Phase 3 control strategy where all assets including the EV charger are coordinated.

## 7.8 SECTION SUMMARY

**The MADE field trial has shown that there is significant additional value extracted through the coordination of multiple LCTs within a single premise. Both at a system wide level and single property level, there are tangible benefits when assets are coordinated rather than operating individually.**

Predictive controls that can optimise and coordinate asset behaviour play a key role in delivering best value from the assets to the consumer, as well as negotiating patterns of behaviour desired by the local and national electricity grid. The greater the level of coordination between the low carbon assets, the greater the savings in consumer electricity costs.

Time-varying tariffs can offer significant running cost benefits to consumers with MADE assets, particularly where the battery and heat pump can be coordinated to store energy in the right balance between the battery and the thermal fabric of the building, and making the right decisions about waiting for available PV generation.

Even slight variations in tariff can introduce demand peaks, e.g. due to batteries delivering arbitrage. These peaks can easily be mitigated by a smart control system, at only a small incremental cost to the householder, as long as the provision of cheap electricity is not significantly reduced.

Electric vehicle charging, which naturally occurs at a bad time for the grid when the EV is plugged in early evening, can be reliably delayed and the required charge levels still delivered, as long as users specify their preferences properly (via an App). With a ToU tariff this delivers significant cost savings. Further savings are achieved by coordinating EV charging with domestic battery operation and any available PV generation, but only if the systems operate properly in tandem.

The availability of free or even negatively-priced electricity incentivises smart heating systems to overheat houses, which sometimes does not suit occupiers. This can be successfully mitigated by applying maximum temperature limits to set the balance between demand flexibility and consumer comfort.

Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

## 7.9 DETAILED FIELD ANALYSIS

**The full field trial analysis report is available on the MADE page of the WPD website.**

# 8 ENABLER FOR HOMEOWNERS TO PARTICIPATE IN FLEXIBILITY PLATFORMS: FLEXIBLE POWER

**Flexible Power is a proposition created by Western Power Distribution (WPD) in order to deliver the procurement of demand response services.**

Flexible Power offers two main services:

- **Secure:** Designed to manage peak demand on the network and pre-emptively reduce network loading. Firm commitments to reduce demand are agreed a week ahead for specific power reductions against an agreed baseline. Within MADE the system was instructed a day ahead to reduce power by as much as possible during a specified window the following day

- **Dynamic:** Developed to support the network in the event of specific fault conditions, usually during summer maintenance. An availability window is agreed a week ahead, and providers must then be ready to deliver services for at least two hours on 15 minutes notice during this window. Within MADE the system was instructed a day ahead to reduce power by as much as possible during a specified window the following day, as per Secure interventions. However, in the Dynamic intervention case, if no request was assumed to be issued upon reaching the availability window the window would be shortened every 15 minutes until the end of the window. Thus, the system was able to store sufficient energy to meet a request should it be issued but power was not actually discharged unless necessary

Domestic demand response could provide Flexible Power services via a portfolio of homes, most likely in aggregate via a service provider. Under the MADE field trial, the goal for Flexible Power interventions was to minimise power consumption (or maximise export) for one particular home as much as possible across the utilisation window. The aim was to understand the flexibility and responsivity of the multi-asset systems against these mechanisms, in order to gain insight into how much demand reduction is possible, reliability, and how future Flexible Power offerings might need to be adapted. It should be noted that WPD's need for demand response will vary across its Constraint Management Zones (CMZs) depending on local network needs.

In general, under both Phase 2 control (heat pump and battery) and Phase 3 control (heat pump, battery and EV), minimising power consumption involved targeting a controllable load of -2.5kW, since the heat pump and EV could be switched off and the battery could be discharged at a maximum rate of 2.5kW. As the batteries have a total capacity of 5kWh, this request could only actually be met for a maximum of two hours; however, with this limit in place the home would still try and limit controllable load to 0kW once the battery was fully discharged.

The increase in electricity costs associated with such interventions have been considered through analysis of supporting simulation work in Section 4.3 (where the issue of baselining is also discussed).

**Table 4 outlines the Flexible Power inventions that were tested over the course of the MADE field trial, in order to provide examples of how domestic flexibility could contribute to Flexible Power services with varying requirements.**

| Service | Agreed Availability Window | Utilisation Window | Day |
|---|---|---|---|
| **Secure** | N/A | 16:00 – 18:00 (2hrs) | Weekday |
| **Secure** | N/A | 16:00 – 19:00 (3hrs) | Weekday |
| **Secure** | N/A | 15:00 – 19:00 (4hrs) | Weekday |
| **Secure** | N/A | 14:00 – 20:00 (6hrs) | Weekday |
| **Dynamic** | 15:00 – 19:00 (Narrow) | 16:00 – 18:00 (2hrs) | Weekday |
| **Dynamic** | 07:00 – 20:00 (Wide) | 16:00 – 18:00 (2hrs) | Weekday |

**Table 4** – Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

## 8.1 SECURE

**Figure 27 below shows a Secure style Flexible Power intervention from Phase 2 of the project, prior to EV coordination being implemented. Thus, in this example controllable load refers to heat pump and battery power. For this intervention, the home was given advance notice to minimise import (or maximise export) between 16:00 – 19:00, using the heat pump and battery.**

The following can be observed from the figure:

- The home is overheated slightly in advance of the intervention period. This enables the set point to be met throughout the duration of the intervention period, without the need to run the heat pump during this time.
- The battery charges up in advance of the Flexible Power intervention period and then discharges over the intervention period, leading to negative overall controllable load.
- At this stage of the project, controllable load involved the heat pump and battery, but not the EV. On this day the EV was plugged in at 17:00 leading to a large increase of grid import, but the system could not yet shift the load away from the Secure intervention period. This demonstrates a clear use case where fully coordinated control across all assets in the home would be advantageous.

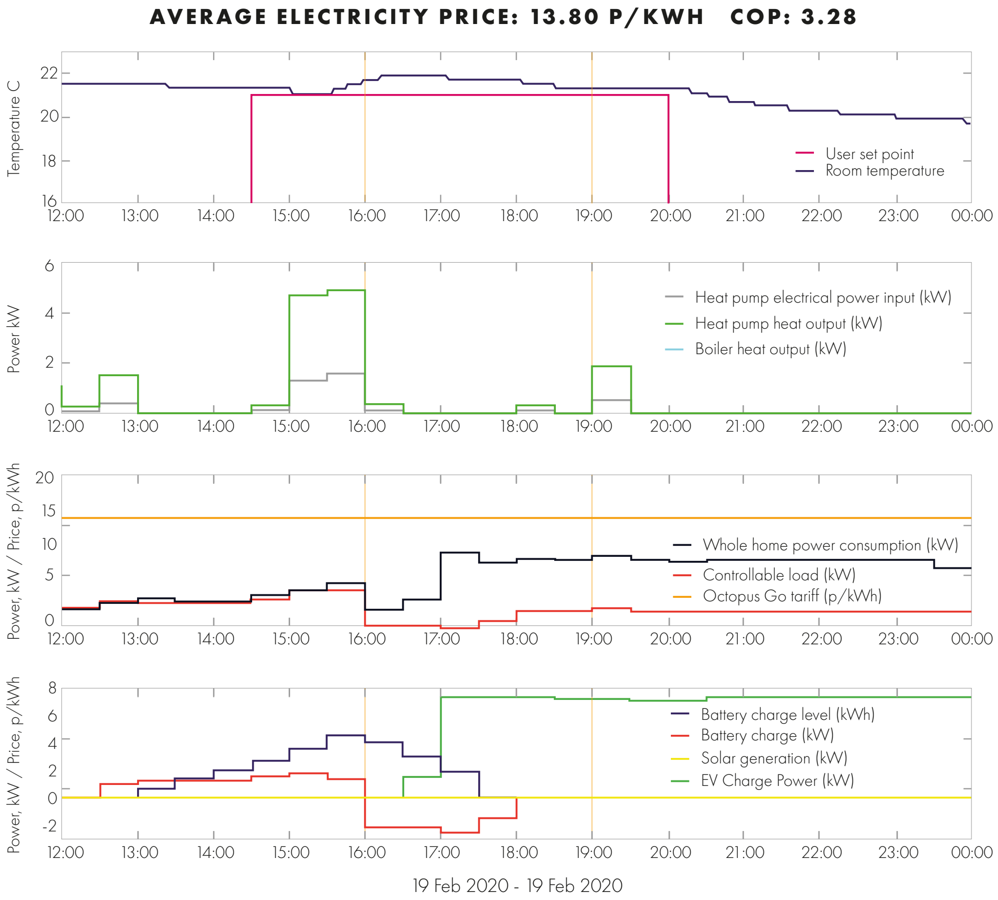


**Figure 27** – Secure style Flexible Power intervention from Phase 2 of the project, prior to EV coordination being implemented.

**Figure 28 shows the average daily whole home power import profile for all homes during a Secure style intervention. This intervention was carried out during Phase 3 of the field trial and thus controllable load refers to heat pump, battery and EV power here. In this intervention the homes were requested to reduce import (or maximise export) as much as possible between 16:00 – 18:00.**

The following can be observed from the figure:

- Controllable load is high during the day, largely due to the battery charging from excess solar generation.
- Controllable load is negative between 16:00 – 18:00 where the homes are honouring the negative maximum power limit and attempting to minimise import or maximise export.
  - Note the average controllable load is not at the minimum value of -2.5kW which would be expected during the intervention window. This is due to a Sonnen software bug relating to hybrid battery installations, where the manual discharge request is capped such that solar plus battery discharge (i.e. inverter power) is capped at 2.5kW. Thus, in the presence of solar generation, as is the case in this particular example, battery discharge is limited. However, in this case the system is still maximising export as much as possible with this limitation in place.
- Whole home power import is negative between 16:00 – 18:00, despite the fact that solar generation is positive. This is a nice example of where the hybrid nature of the battery has been utilised in order to control what happens to solar generation. Typically, in automatic mode, all excess solar would be stored in the battery when there is space, but in this case, it has been deliberately exported in order to serve the Flexible Power request.

AVERAGE ELECTRICITY PRICE: 7.09 P/KWH

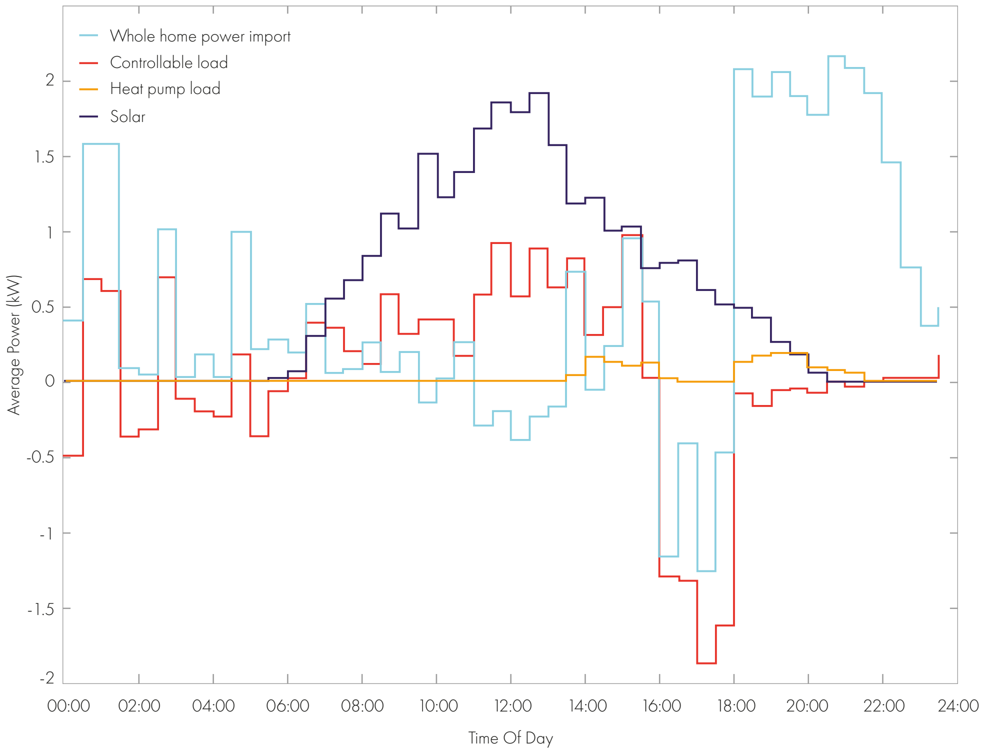


**Figure 28** – Average daily whole home power import profile for all homes during a Secure style intervention.

## 8.2 DYNAMIC

**Figure 29 shows a Dynamic style Flexible Power intervention. This intervention was carried out during Phase 2 of the field trial and thus controllable load refers to heat pump and battery load. For this intervention, the home was given advance notice of a Flexible Power availability window between 15:00 – 19:00 for both days shown on the figure.**

On day one, the home was operated as though no Flexible Power was actually issued. The following can be observed:

- The home is overheated slightly in advance of the availability window. This removed the need to run the heat pump for much of the availability window and meant that the home would stay sufficiently warm should a Flexible Power request come in and the heat pump be required not to operate.

- The battery charged up to full capacity in advance of the availability window. The battery then held this charge until 17:00 to ensure that the full capacity of the battery could be utilised should a request be issued at any point during the availability window. The battery was then able to start discharging at 17:00 to meet excess home demand, as the system could be confident that the battery would be able to discharge at full power for any remaining duration.

**On day two, the home was operated as though a Flexible Power request was issued between 16:00 – 18:00 (availability window 15:00 to 19:00 again). The following can be observed:**

- The home is overheated slightly in advance of the availability window. This removed the need to run the heat pump for much of the availability window and meant that the heat pump was not required to run at all over the request period between 16:00 – 18:00.
- The battery charged up to full capacity in advance of the availability window. The battery then held this charge until the Flexible Power request period. During the request period, the battery is then fully discharged.
- Controllable load was negative for the entire duration of the request period between 16:00 – 18:00.

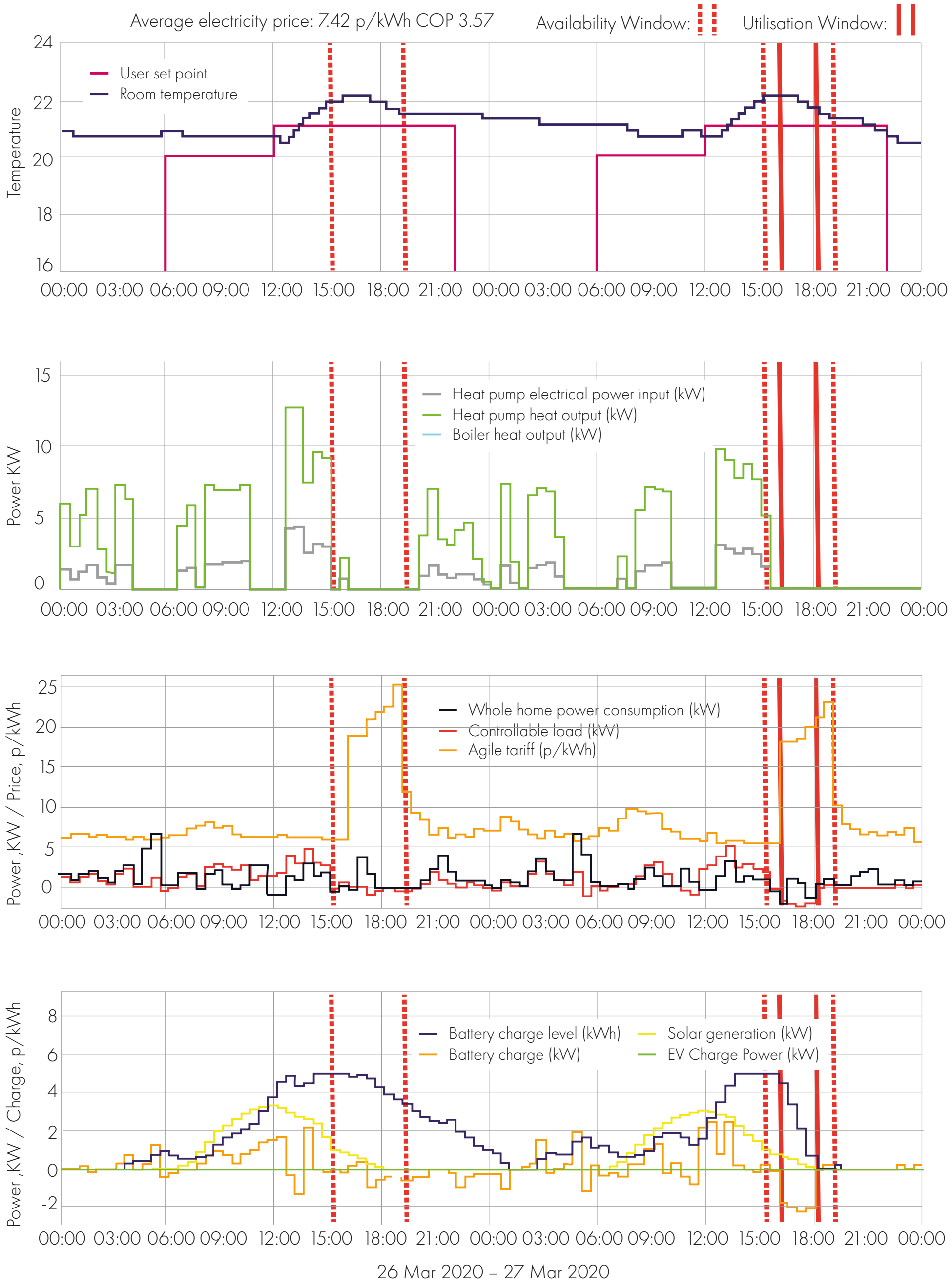


**Figure 29** – Dynamic style Flexible Power intervention. This intervention was carried out during Phase 2 of the field trial and thus controllable load refers to heat pump and battery load.

# 8.3 SUPPORTING SIMULATIONS

**In this section we demonstrate how digital twins can be used to understand the impact of participating in a service such as WPD's Flexible Power: the cost to the householder of both preparing for and executing a Flexible Power request can be evaluated by comparing the outcome of simulations in identical conditions.**

- A digital twin of MADE Home 2 was used;
- Both Octopus Agile and Octopus Go tariffs were investigated;
- Simulation runs were performed for three different Flexible Power windows, the primary focus was on a Flexible Power request window of 16:00 – 18:00 in line with when demand is typically expected to be highest. This section pulls out key observations from these simulation runs and supporting simulation analysis can be found in Annex B;
- Simulation runs have been completed for a winter scenario since this is likely to provide worst case householder costs due to low solar generation and high heating demands;
- The simulations in this section of the report focus on Dynamic Flexible Power scenarios, as the main focus of this section is to address the trade-off between preparing for a request which may or may not be utilised. However, the cost benefits for Secure scenarios are very similar to the case where a Dynamic Flexible Power request is utilised.

For each Flexible Power window, three simulation runs were performed:

**Baseline** – provides a baseline without any Flexible Power preparation.

**Available but no utilisation** – the home prepared to meet a Flexible Power request during the given window, but this request was not utilised.

**Request utilised** – the home prepared to meet a Flexible Power request during the given window, and this request was utilised.

An approximate indication of the cost benefits to the householder for providing Flexible Power services are given in this section. The Flexible Power payments were assumed to be as follows:

| | Secure | Dynamic |
|---|---|---|
| Arming fee | £125/MW/h | N/A |
| Availability fee | N/A | £5/MW/h |
| Utilisation fee | £175/MWh | £300/MWh |

**Table 5** – Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

In order to calculate potential payments from Flexible Power, it was necessary to make some assumptions about how **baselining** would work:

- In reality, the Flexible Power baseline is calculated as a rolling average of demand in the first three weeks of the previous month, with payments based on reductions of power beneath this level.
- Within these simulations, the reductions of power are calculated against the baseline simulation runs that have been conducted (with no Flexible Power intervention in place), assuming that the effect of any randomisation between simulation runs is negligible. (Note under Agile tariff, the baseline demand can be quite low to start with.)
- The cost benefits to the householder for providing Flexible Power services presented in this section are approximate values, designed to give an indication of the scale of such payments rather than exact values. These have been calculated by using the average power reduction across the Flexible Power window between the baseline and request cases, scaled by the corresponding Flexible Power payment amount.
- The assumption is also that Flexible Power payments are based on asset metering (of the combined controllable assets) rather than the whole home power level.

## 8.4 OCTOPUS AGILE TARIFF

**The following key observations were noted during the simulation runs on the Octopus Agile tariff with a Flexible Power window of 16:00 – 18:00.**

- When preparing for a Flexible Power request the home was heated to a maximum temperature of 19.8°C (compared to 19.2°C in the baseline case). This was to ensure that comfort levels could be maintained without the need to run the heat pump during the Flexible Power window should a request come in. Under normal operation on Agile, the system is able to run the heat pump using the battery during the peak tariff period whilst still keeping the home off grid, however, during the Flexible Power intervention the battery is fully discharged to ensure that demand is sufficiently lowered, with no further capacity to operate the heat pump.
- Due to the similarities of preparing for the peak Agile tariff period and preparing for a Flexible Power request between 16:00 – 18:00, battery behaviour was similar in all cases.
- Again, due to the similarities of preparing for the peak Agile tariff period and preparing for a Flexible Power request, in the example where the home was prepared but a Flexible Power request was not utilised the total electricity cost for the day did not change significantly, with a total increase of £0.08. Additionally, this was offset by a Flexible Power availability payment of £0.02 leading to a total net cost of £0.06 incurred by the householder.

- In the example where a Flexible Power request was utilised, the battery fully discharged between 16:00 – 18:00 in order to ensure that demand was sufficiently lowered during this interval. Thus, some import was required during the last hour of the peak Agile tariff period whilst the tariff was still very expensive. The total electricity cost for the day therefore increased by £0.49 compared to the baseline case. However, the Flexible Power cost benefit paid to the householder was estimated to be around £1.14 (in the Dynamic case) thus achieving a net benefit of £0.65 for the householder. The benefit for a Secure style intervention was very similar.

## 8.5 OCTOPUS GO TARIFF

**The following key observations were noted during the simulation runs on the Octopus Go tariff with a Flexible Power window of 16:00 – 18:00.**

- When preparing for a Flexible Power request the home was heated to a maximum temperature of 19.7°C (compared to 19.4°C in the baseline case). This was to ensure that comfort levels could be maintained without the need to run the heat pump during the Flexible Power window should a request come in.

- In all cases the battery completed a full charge during the cheap electricity period overnight. In the baseline case the battery then discharged over the course of the morning to meet household consumption including heating demand. However, when preparing for Flexible Power request the battery instead holds this charge until the Flexible Power window so that a request could be met using cheap electricity.

- In the example where the home prepared for a Flexible Power request, but this was not utilised, the total electricity cost increased by £0.13 which was offset by a Flexible Power availability payment of £0.03 leading to a total net cost of £0.10.

- In the example where a Flexible Power request was utilised, the cheap electricity stored in the battery was exported to the grid and thus more expensive electricity was required to meet demand over the rest of the day. Therefore, the total electricity cost for the day increased by £0.61, however, the Flexible Power cost benefit paid to the householder was estimated to be around £1.67 (in the Dynamic case) thus achieving a net benefit of £1.06 for the householder. The benefit for a Secure style intervention was very similar.

- The net benefit to the householder from meeting a Dynamic Flexible Power request whilst on the Octopus Go tariff was higher than on the Octopus Agile tariff (£1.06 vs £0.65). This is due to the fact that demand is likely to be low between 16:00 – 18:00 anyway on the Agile tariff, as this aligns with the expensive evening tariff period, and thus there is much less scope to reduce demand against the baseline case.

## 8.6 SIMULATION SUMMARY

**Table 6 summarises the total electricity costs and approximate net total householder cost for each simulation run performed, for both the Octopus Agile and Octopus Go tariffs. "Net cost figures" include both the payments for electricity to their supplier and the payments from WPD for providing the WPD Flexible Power service.**

| **Tariff** | **Flexible Power Window** MW/h | **Baseline profile** | | **Available but no utilisation** | | **Dynamic Flexible Power utilised** | |
|---|---|---|---|---|---|---|---|
| | | Electricity Cost (£) | Approx. Net Total Cost (£) | Electricity Cost (£) | Approx. Net Total Cost (£) | Electricity Cost (£) | Approx. Net Total Cost (£) |
| **Octopus Agile** | 14:00 – 16:00 | 2.37 | 2.37 | 2.44 | 2.39 | 3.22 | 0.39 |
| | 16:00 – 18:00 | 2.37 | 2.37 | 2.45 | 2.43 | 2.86 | 1.72 |
| | 19:00 – 21:00 | 2.37 | 2.37 | 2.54 | 2.53 | 2.72 | 1.81 |
| **Octopus Go** | 14:00 – 16:00 | 2.51 | 2.51 | 2.64 | 2.61 | 3.16 | 1.30 |
| | 16:00 – 18:00 | 2.51 | 2.51 | 2.64 | 2.61 | 3.12 | 1.45 |
| | 19:00 – 21:00 | 2.51 | 2.51 | 2.87 | 2.85 | 3.18 | 1.51 |

**Table 6** – Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

Table 7 summarises the results presented in Table 6 to give the net cost to the householder of preparing for a request which is not utilised compared to the approximate net benefit to the householder of a Dynamic Flexible Power request. It can be seen that the cost of preparing for a request was notably cheaper on the Octopus Agile tariff compared to the Octopus Go tariff, however, the Flexible Power payments are higher on the Octopus Go tariff. This is expected as, due to the fact that the Agile tariff is tied to wholesale prices, there is likely to be synchronisation between expensive Agile tariff periods and times where a Flexible Power request might be expected. On both tariffs the cost of preparing for a request was highest in the late evening scenario with the lowest net benefit to the householder also seen during this time period, thus requiring the highest utilisation percentage for the householder to break even.

Although these costs cannot be concretely relied upon due to randomisation between simulation runs and a dependence on the inputs assumed, in addition to daily tariff variations in the Octopus Agile case, the simulation runs performed suggest that there is good value to be obtained for the householder from participation in the Flexible Power scheme, provided that the utilisation percentage is sufficient, and that this percentage may need to be slightly higher if the householder is on a cheap overnight rate tariff.

## 8.7 SECTION SUMMARY

### Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets.

In advance of a scheduled Secure delivery period, energy was automatically stored in (a) the battery and (b) the fabric of the home via the heat pump. During the period the battery could discharge, the system could avoid needing to run the heat pump, and solar PV was deliberately exported (rather than charging the battery).

A Dynamic delivery period was prepared for similarly by keeping the battery fully charged (which has little disadvantage) and somewhat pre-heating the home (which needs a careful trade-off as it is lossy).

| Tariff | Flexible Power Window/h | Net cost to the householder of preparing for a request which is not utilised (£) | Approximate net benefit to the householder of a Dynamic Flexible Power request (£) | Approximate required utilisation percentage for house holder to break even (%) |
|---|---|---|---|---|
| **Octopus Agile** | 14:00 – 16:00 | 0.02 | 1.98 | 1.0 |
| | 16:00 – 18:00 | 0.06 | 0.73 | 8.5 |
| | 19:00 – 21:00 | 0.16 | 0.56 | 22.2 |
| **Octopus Go** | 14:00 – 16:00 | 0.10 | 1.21 | 7.6 |
| | 16:00 – 18:00 | 0.10 | 1.06 | 8.6 |
| | 19:00 – 21:00 | 0.34 | 1.00 | 25.3 |

**Table 7** – Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

# 9 TRIAL PARTICIPANT FEEDBACK

The MADE project included a workstream to collate and assess customer feedback of the technical field trial and coordinated control of Low Carbon Technologies (LCTs). The project consortium agreed on the following learning objectives at different times throughout the trial. A combination of in-depth interviews and surveys were utilised at various stages of the trial in order to assess customer experiences and perceptions of LCTs with integrated control throughout. This section provides a summary on the research undertaken at various stages of the trial.

## 9.1 CUSTOMER EXPECTATIONS

Customers taking part in the trial showed they were extremely satisfied with their existing system, and primarily joined the trial because the LCT equipment was free, and they believed they would save money on their energy bill. Despite the latter not being a key objective of the trial, respondents to the surveys claimed an excellent understanding of the goals and objectives and felt positive at the outset.

| Key focus | Key findings | Recommendations |
|---|---|---|
| **1. Attitudes towards their current fossil fuel system and controls** | **Shifting customers away from conventional fossil fuels system will be a challenge** – customers are overwhelmingly positive about their existing vehicle and heating system. | • **Awareness raising of LCTs is required:** both to installers who engage with customers and customers then to request or learn more about a technology that they are unaware of. Its high appeal shows it has potential.<br>• **LCTs for free business models should be explored:** free equipment was a critical driver for the trial, leasing, or LCT for free models should be explored to maximise future opportunities.<br>• **Running cost savings are also important to customers; exploring how best to deliver these is critical. Options include:**<br>  • **Focus on carbon conscious homeowners:** LCTs make most sense for carbon conscious customers who might be more open to a new technology / less satified with their current systems.<br>  • **Lobby / support / encourage development of different energy tariffs** – if energy prices were to change, or tariffs based on DSR become available LCTs would be more appealing. |
| **2. Reasons for joining the trial and expectations** | **Financial motivations were the main reason for joining the trial, customers liked having 'free' equipment, and expected to save money on their energy bill.** The expectations around this latter point need to be carefully managed given fossil fuel and electricity prices. | |
| **3. Awareness and appeal of LCTs** | **There is an awareness gap for LCTs** – LCTs have high appeal once explained, but, as expected awareness is low. | |
| **4. Understanding of the project goals and objectives** | **Respondents claimed to have a good understanding of both the project goal and the objectives** – this indicates the pre–trial information was high quality and well explained. | |

**Table 8** – Customer expectations summary.

## 9.2 CUSTOMER EXPERIENCES

Overall all respondents had a very positive customer experience throughout the pre-trial and Phase 1 of the trial. There are some simple steps that could be taken to ensure customer satisfaction remains high, for example, ensuring that everything is neat and tidy before the installer leaves the home, and providing a follow up visit as standard to check everything is ok with the homeowner and that they understand how to operate LCTs.

| Key focus | Key findings | Recommendations |
|---|---|---|
| **1. Pre-trial expectations of the LCTs and of the installation process** | The pre-trial phase can be considered a success, respondents had few concerns about whether the LCTs would work, and felt confident going into the installation process. | Installer training is critical: a competent and professional installer, that can 'hold the customers hand' could support increased uptake of LCTs by being able to reassure customers about both the reliability and maintenance requirements of LCTs, and the installation process (minimising the hassle, time and stress of the system install for the customer).<br>Providing a follow up visit a week after the install (as standard): this could be a way to iron out any of those customer 'niggles' early on before the escalate into major issues. You can check that customer still understand the smart controls too as they may have questions now the system is in use – additional 'user-education' may also help to minimise operational problems.<br>Provide the customer with advice on how to operate their system, and provide information on any tariffs, or incentives that they might be able to utilise. Most of all, be up-front and realistic about what they can expect. |
| **2. Feedback on the installation process** | On the whole the installation process went well. A majority were problem free and there was a high level of customer trust. Where there were issues, improvements could be made to how quickly these were followed up on to improve satisfaction. | |
| **3. Initial user experiences of the LCTs** | The initial customer experience of LCTs were very positive. Reassuringly systems performed well on requirements but customers were uncertain about potential running cost savings. | |
| **4. Operational 'problems' and running cost saving concerns** | There was a high number of 'operational problems' reported but a majority of these were easily dealt with to a high standard. Some of the faults were the result of customers not understanding how to use the system properly. | |

**Table 9** – Customer experiences summary.

## 9.3 ATTITUDES AND APPEALS TO LOW CARBON TECHNOLOGIES

Overall during the course of the trial, respondents were positive about the LCTs and their experiences with it. Unsurprisingly the up-front and running costs would likely be critical barriers to LCTs outside of the trial conditions, so industry needs to innovate. However, there are also simpler things, like bundling with smart controls that could improve customer appeal.

| Key focus | Key findings | Recommendations |
|---|---|---|
| **1. Participants' experience of the LCTs** | Overall participant satisfaction remained consistently high throughout the trial. A majority of respondents would be likely to recommend an LCT to a friend. | Economic factors are a key criteria for mass market success, business models will be needed in the near term to ensure that LCTs can offer cost-comparable solutions to existing fossil systems.<br>The reliability of the system is critically important, providing more data on how the system is working may ensure that confidence on this point is improved.<br>Including a smart controls/app in any bundle when LCTs are purchased would improve customer confidence, both in terms of convenience (and making it more exciting for them) and in reassurance (so they can see the systems is working as it should).<br>Involving customer in the siting of the LCTs is important for gaining acceptance of the outside unit and should be standard procedure at installation to improve satisfaction. |
| **2. If participant expectations met and would they recommend their LCTs to a friend** | Ease of use, requirement, comfort, reliability and up-front and running cost are the primary aspects of a vehicle and heating system which customers value. The LCTs with optimised controls perform well with respect to ease of use and comfort provided but the up-front costs and operating costs of LCTs today are likely too high for many customers. | |
| **3. Primary likes and dislikes of the LCTs** | The optimised smart controls/app was a top rated feature of the LCTs as customers really like the ability to remotely manage and monitor their LCTs. | |
| **4. Aesthetics of the LCTs** | The aesthetics of the LCTs should not act as a deterrent to uptake. Although there are minor improvements which could be made to external units, correct siting of the unit was more important. | |

**Table 10** – Customer attitudes towards LCTs and experiences summary.

# 9.4 CUSTOMER ATTITUDES TOWARDS THIRD PARTY COORDINATED LOW CARBON TECHNOLOGY CONTROL

Overall the controls and (in particular) the app were a key success of the trial. Customers engaged with them readily and easily and the remote control aspect had high appeal. In the future, the app could go further, and act as reassurance to the customer to help them understand when and how different parts of LCTs are working. This may minimise concern over future billing and maintenance call outs (e.g. by reassuring them over the responsiveness to temperature changes).

| Key focus | Key findings | Recommendations |
|---|---|---|
| **1. Participants, attitudes and experience of using the controls** | The in-home controls and app were consistently rated highly by customers – both were considered easy to use. | As previously mentioned – a 'smart' app should be included in any bundle sale for a LCT as it may support increased uptake.<br>The inclusion of the app can also reassure customers their system is working, especially if it includes information on the fuel being used or when the charge point or heat pump is operating.<br>Consider introducing different 'levels' of control. Some customers are really engaged and want a lot of information, it might be possible to have different 'levels' of control for different types of user. This could include a basic control where those less engaged are confident that they won't somehow 'break the system' (this might appeal to RSLs).<br>Sometimes simple is best – in particular for the in-home control, customers would like an instruction booklet. A single side, user-guide would be sufficient and could be attached to the control itself. |
| **2. Participants recommended improvements for the controls** | The in-home controls, were not used as frequently as the app. Their main purpose is a secondary control if the app was to fail to connect. However, due to their potential infrequent use, they need to be simple and easy to understand – customers forgot the instruction they received at install. | |
| **3. Participants attitudes and experience of using the app** | The app has been one of the customers favourite features of the whole LCTs. In particular remote control has high appeal. | |
| **4. Participants recommended improvements for the app** | Both the controls and the app can play a role in improving customer confidence. They need to provide enough data that reassures customers their system is working correctly without being overly complex. | |

**Table 11** – Customer attitudes towards third party summary.

### Customers' attitudes on domestic flexibility and supporting the local grid.

Domestic flexibility, including fuel-switching, was undertaken on the customer's behalf and for many this had high appeal. However, the indications are that DSR could go much further than this and that customers are open, with the right conditions, to other types of DSR which might benefit the networks, and customers. Today the biggest barrier is the 'trust' and 'risk' they associate with DSR, but the right business models, incentives and accountability can overcome this.

| Key focus | Key findings | Recommendations |
|---|---|---|
| **1. Awareness of and willingness to accept DSR** | Overall the respondents were more aware of DSR compared to the commissioned Delta-EE 750 survey, but there is room for improvement. It is likely raising awareness would result in improved acceptance. | Invest in increasing customers knowledge and awareness of the benefits of residential DSR. It is still a new concept and so customers associate a great deal of 'risk' to it.<br>Focus on building and improving customers' trust in DSR and DSR companies. This could be via "aligned incentives" (e.g. creating a business model where the customer receives a percentage of the DSR company's income providing DSR services) or by simply ensuring you provide transparency and accountability by notifying the customer on how, when, and why DSR is being performed.<br>Provide customers with the following critical DSR criteria:<br>Ultimate control of their LCTs<br>Tangible benefits/incentives for enabling DSR to be performed (e.g. savings on their energy bills or monthly payments) |
| **2. Who customers would trust to perform DSR and how it should be performed** | The biggest barrier to DSR is customers feeling confident to trust a third-party to perform DSR. At the moment this is reflected in their strong requirement to maintain ultimate control over the system, and the fact they would prefer a big brand name (like their energy company) to perform it. | |
| **3. What rewards and incentives (if any) might be required** | Energy bill savings was the most appealing incentive to allow DSR. Overall it is likely some sort of financial reward would be required for it to be accepted by customers. | |
| **4. Customers experiences of fuel switching during the trial compared to their perception of fuel switching as DSR** | There is a disconnect between customer experiences of fuel switching on the trial and what they say they would like – a majority of respondents liked the fuel switching feature of LCTs on the trial, but less than a quarter of participants found the fuel switching as a form of DSR appealing. | |

**Table 12** – Customer attitudes towards domestic flexibility participation.

## 9.5 SECTION SUMMARY

**Shifting customers away from conventional fossil fuels to LCTs will be a challenge – customers are overwhelmingly positive about their existing fossil fuel assets: In order for customers to engage with LCTs it must be able to compete on the priority areas of running costs, reliability and comfort. When combined with low LCT awareness the scale of the challenge is clear. There is a real need for education among customers, and installers (who largely hold the customer relationship). A near term option could be to target environmentally conscious homeowners, who are more likely to be motivated to reduce their carbon footprint as a basis for building expertise and customer momentum.**

The technology has been proven – customers were overwhelmingly positive about the LCTs: The trial has proven that both the installation of LCTs with third party controls, and the long-term use and operation of LCTs in a variety of house types and customer types is possible. The LCT with optimised controls largely met the comfort and reliability challenge, and all customers were satisfied. The most satisfied customers experienced a high quality customer journey throughout, from the information at pre-trial, to the installation and follow ups. This highlights how important it is to get the customer journey right. Bundling with smart controls also proved popular and can support increased customer engagement and confidence.

Financial criteria are a key priority for customers – innovative business models will be needed for market creation – participants were drawn to the trial because they would get free LCTs, but also because they believed they would save money on their energy bill (even though this was not a stated aim of the trial). Energy prices today make this difficult, and we know up-front costs are typically higher for LCTs than conventional fossil fuel equivalent replacements so the market will need to address these challenges to capture customer attention.

There is an opportunity around domestic flexibility which needs further exploration – The trial participants in this research demonstrated a high level of interest in future domestic flexibility propositions, although it is clear that many struggle to understand the concept, so there is an education piece here too. However, once explained, respondents were open to DSR. With the right incentives in place DSR could offer significant network benefits and support the creation of innovative energy tariffs – that in turn could support LCT uptake if it provides the running cost saving customers require in order to invest.

## 9.6 DETAILED CUSTOMER SURVEY AND INTERVIEWS

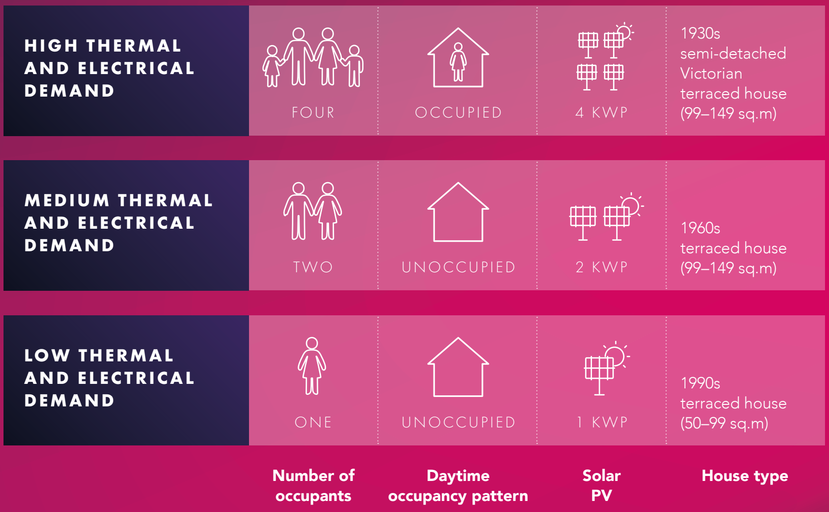
**The full customer engagement report is available on the MADE page of the WPD website.**

# 10 HOMEOWNER BENEFIT FROM MADE AND DOMESTIC FLEXIBILITY

**Everoze Consultants undertook techno-economic modelling to evaluate the feasibility and benefits of multi-asset coordinated delivery of flexibility at a domestic property level. This section provides a summary of this modelling work, extracted from Everoze's modelling work and results.**

## 10.1 APPROACH

Following discussions between project partners, Delta-EE outlined three base customer types, defined by the type of property and household make-up, to be considered in the modelling, as shown in Figure 30.



| | Number of occupants | Daytime occupancy pattern | Solar PV | House type |
|---|---|---|---|---|
| **HIGH THERMAL AND ELECTRICAL DEMAND** | FOUR | OCCUPIED | 4 KWP | 1930s semi-detached Victorian terraced house (99–149 sq.m) |
| **MEDIUM THERMAL AND ELECTRICAL DEMAND** | TWO | UNOCCUPIED | 2 KWP | 1960s terraced house (99–149 sq.m) |
| **LOW THERMAL AND ELECTRICAL DEMAND** | ONE | UNOCCUPIED | 1 KWP | 1990s terraced house (50–99 sq.m) |

**Figure 30** – Customer types used in the MADE modelling.

Three EV use cases and transport patterns with different intensity of EV use have been considered:

- **Commuter use case with heavy EV usage** – weekday commute to work, and weekend visits to friends and family.
- **Parent use case with moderate EV usage** – parent with school runs in the morning with high-intensity social use multiple times during the day.
- **Social use case with occasional low-intensity EV use** – three to four times a week (one to two evenings).

The base customer types and the EV transport patterns were used to inform the seven modelling cases considered by Everoze, which can be seen in Figure 31. These modelling cases provide a reasonable set of representative cases for Delta-EE to undertake its feeder-level modelling.

| | | Commuter | Parent | Social |
|---|---|---|---|---|
| **HIGH THERMAL AND ELECTRICAL DEMAND** | FOUR | ✓ | ✓ | ✓ |
| **MEDIUM THERMAL AND ELECTRICAL DEMAND** | TWO | ✓ | — | ✓ |
| **LOW THERMAL AND ELECTRICAL DEMAND** | ONE | ✓ | — | ✓ |

The Parent EV use case is only used for the high-demand customer type as that is the only customer type with children.

**Figure 31**

Two different modelling scenarios were considered for each customer type-EV use case combination:

1. **Baseline Case** which includes a selection of Low Carbon Technology assets with no coordinated flexibility provision;
2. **Optimised Case** with the Low Carbon Technology assets operating in a coordinated manner (at a residential level) for flexibility provision.

Figure 32 details the assumptions made for each of the modelled energy assets in both the baseline and optimised cases.

| | | | | |
|---|---|---|---|---|
| **BASELINE CASE** | Included, installed kWp based on customer type | Included, ASHP loads optimised against price signals | Included, load-shifting using surplus solar | Included, unidirectional charger with smart charging |
| **OPTIMISED CASE** | Included, installed kWp based on customer type | Included, ASHP loads optimised against price signals | Included, load-shifting surplus solar and pre-charging as well as ancillary service provision | Included, bidirectional charger with smart charging as well as V2H/V2G service provision |

**Figure 32** – Asset operation assumptions in the baseline and optimised cases.

The following revenue opportunities were utilised in the modelling:

- **Peak Shifting:** Surplus solar generation during the day is used to charge the domestic battery and EV (when available), which is then discharged during the evening peak demand period to reduce peak charges and reduce the impact of peak-time loads on the network. If surplus solar generation is not sufficient to meet the evening peak demand volume, the domestic battery and EV pre-charge when the energy price is low (e.g. night time) to top-up the balance volume for peak shifting.

  Value accrued from peak shifting is the spread between the peak-time charge (Sell action) and the cost of energy for charging the domestic battery/EV net of energy losses (Buy action). A target spread of 10p/kWh is assumed in the modelling – peak shifting is only performed for that day if the buy-sell spread is more than 10p/kWh.

- **Firm Frequency Response (FFR):** Night-time FFR for FFR availability windows 1 and 2 (11pm-7am) is assumed as part of the revenue stack. Weekly FFR auctions are considered in the modelling in line with the ongoing FFR auction trials; a success rate of 75% is assumed. An FFR tariff of £5/MW/hour is assumed – this is based on the clearing prices in the recent weekly FFR auctions. A 3kW service volume is assumed. As noted previously, route-to-market is expected to be through aggregation to meet the minimum volume requirements.

- **DSO Services:** DSO services are procured by WPD to manage constraints caused by a variety of reasons across its network (i.e. overloads under peak demand conditions, overloads during summer outage season). The seasonal, day-of-week and time-of-day need for demand response required by WPD varies across its Constraint Management Zones (CMZs) depending on the needs of the local network, which also informs the type of service procured by the DSO. WPD currently procures two products across its CMZs:

  1. SECURE – week-ahead notification of a scheduled demand turn-down or generation turn-up.

  2. DYNAMIC – week-ahead notification of availability to provide demand turn-down or generation turn-up, with a close to real-time notification to provide response.

Given the local nature of DSO service requirements, it is not possible to make a generalised assumption on the service profile for use in the revenue stack. To accommodate the variability in network constraint and service need across WPD's South Wales DSO region, a few scenarios with different DSO service stacks have been considered in the modelling.

One of these scenarios is considered for the base modelling for the seven modelling cases, with the assumption that the property is located in a part of the network where the system need is represented by this scenario. The remaining scenarios were considered as part of sensitivity analyses.

# 10.2 MODELLING VALIDATION

**PassivSystems collated the data from a number of homes participating in the MADE trial, and the data has been provided to Everoze.**

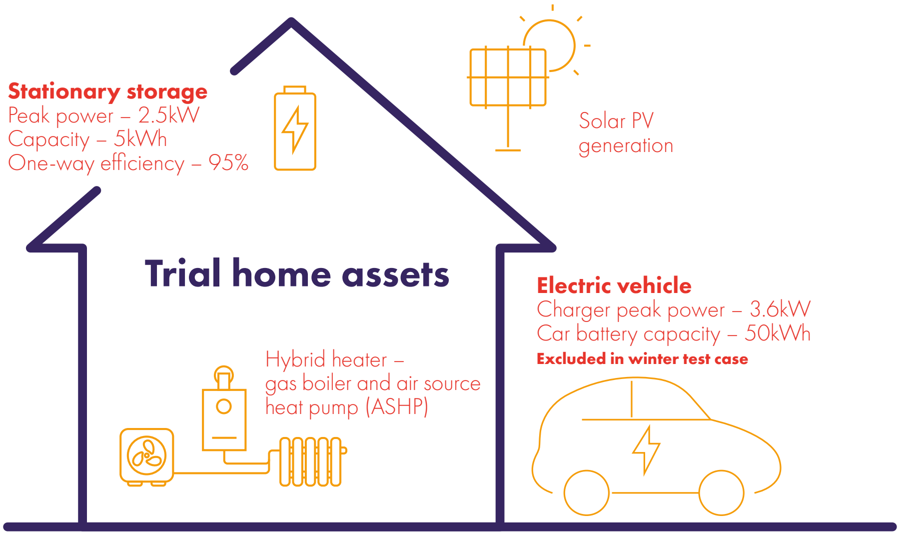


**Figure 33** – Home assets and capacity.

Everoze undertook a validation exercise comparing the Everoze modelling outputs for the trial home for the period considered with the real world trial data. The validation considers both winter and summer 2020.

| | Winter test case | Summer test case |
|---|---|---|
| **Heating** | Active with no use of the gas boiler | Inactive as no heating required for summer season |
| **Solar PV** | Low generation | High generation beyond baseload during the day (surplus solar) |
| **Stationary storage** | Fully active | Fully active |
| **Electric vehicle** | Not present | Plugged in at 8:30pm on Day 1 with c.10% of charge remaining |
| **General base consumption** | Averaging 0.5kWh per settlement period with a peak energy demand of 2.4kWh | Averaging 0.25kWh per settlement period with a peak energy demand of 1.4kWh |

**Table 13** – Winter and summer test cases.

The key capability of the Everoze modelling that was validated is the ability to simulate the coordinated control and optimisation of the home consumption using the suite of low carbon assets at the home. Therefore, the DSO and TSO services are excluded from the validation exercise as they are not relevant to the core capabilities being tested here.

The key input data supplied by PassivSystems are summarised in Figures 34 and 35 with the following characteristics as noted below. Similar to the original modelling, the optimised ASHP data used in the modelling was provided by PassivSystems.

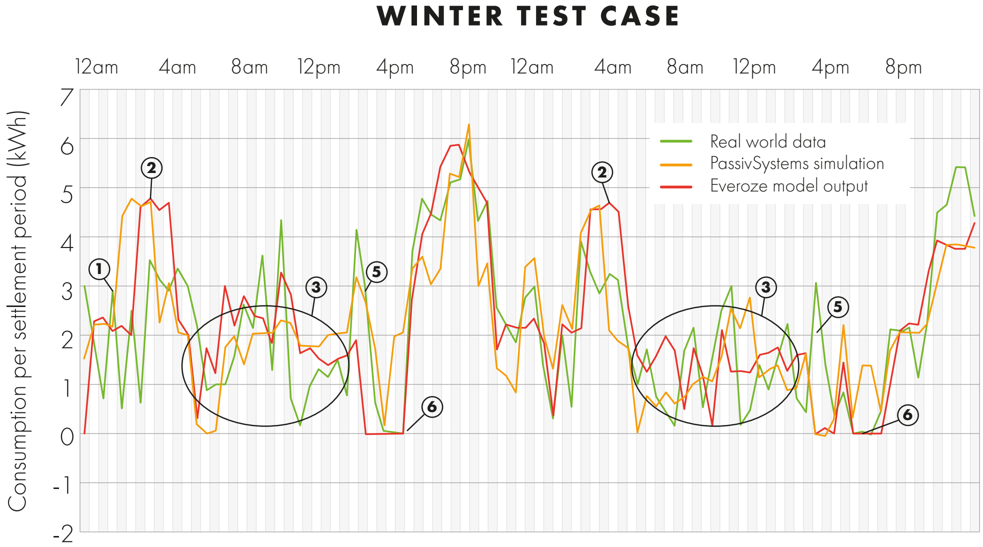


**Figure 34** – Validation of winter case.

1. PassivSystems advised there was a bug in the initial set up which caused the stationary storage to charge and discharge in alternating settlement periods.

2. The battery is pre-charged overnight when the energy price is low. There is some minor difference in timing of charging in day 1 but this difference is minor.

3. In the real world case, the battery is discharged during the day time when the energy price is marginally higher than the night time charging price. Everoze modelling does not perform this day time discharge for the battery. This is due to a minimum target price spread considered as an economic decision driver for the battery to perform load shifting. An assumed marginal cost of degradation for the battery is used as this minimum target price spread. This means load shifting in Everoze modelling is limited to peak periods only where the achieved price spread is greater than this minimum target value considered.

4. There are underlying differences between the modelling and real world data due to differing assumptions for the Air Source Heat Pump behaviour. The ASHP is optimised with all the assets in the real world case, but this was not possible for the modelling due to the approach adopted where Everoze modelling uses PassivSystems' ASHP optimisation as a modelling input. This difference leads to a different profile for ASHP usage and also some changes to the use of the stationary storage as it is generally more efficiently to store energy in the battery than in the thermal fabric of the home.

5. The PassivSystem simulation and real world data show an increase in consumption ahead of the peak period from discussion with PassivSystems, this is understood to be due to a forecasting error where solar generation during this period was over forecasted and the battery was instructed to capture this surplus solar generation. Everoze modelling considers the actual solar generation with 100% foresight, and so does not consider the impact of forecasting inaccuracies.

6. All profiles show a reduction in energy consumption during the evening peak. Everoze modelling has zeroed this from the start of the peak period by using pre-charged energy in the stationary storage with perfect foresight of peak shifting demand required. However, the battery runs out of charge and/or the inverter capacity is not big enough to fully offset the household demand during the entirety of the evening peak period.

**Conclusions:** The modelling, simulation and real world data largely follow similar trends with differences attributed to i) differences in modelled ASHP behaviour, ii) perfect foresight assumed in Everoze modelling for home consumption and solar PV generation, iii) minimum spread considered in the Everoze modelling, and iv) bug in the real world set up for battery charging/discharging. Points 1 and 2 identify areas of improvement for the modelling undertaken, and point 3 is a recommendation for PassivSystems to consider in its optimisation solutions. Overall, the real world outcomes for this test case show the Everoze modelling reasonably reflects the utilisation of the stationary storage asset.

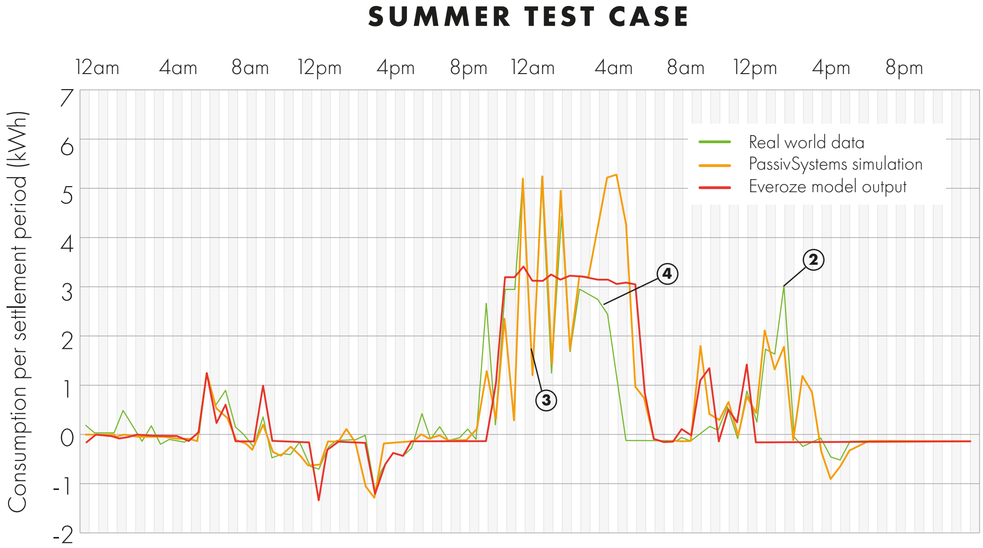


**Figure 35** – Validation of summer case.

1. Generally, the consumption from the grid for the home is very low during the day as there is a lot of solar generation during this period which offsets household demand and the surplus generation is used to pre-charge the stationary storage ready for when solar generation drops in the evening.

2. This peak in the real world data and PassivSystems simulation does not appear in the Everoze modelling outcomes as the modelling assumes perfect foresight of household demand and solar PV generation. So the model accurately estimates the amount of stationary storage charge needed to fully offset peak time loads, and this being met from capturing surplus solar PV generation only and not requiring any other pre-charging from the grid. Also, the model discharges the remaining surplus solar captured to reduce home consumption to zero for the rest of the day as much as is possible.

3. In the real world case the stationary storage exhibits behaviour of alternating charging and discharging during alternating 30 minute settlement periods during the night. PassivSystems has described that this is due to the battery charging during low electrical price settlement periods and then discharging during the next higher cost settlement periods to reduce import costs. The price differential captured in this night time arbitrage/load shifting is minimal. As described in the previous slide, Everoze modelling does not consider this night time arbitrage when the price spread is minimal. An assumed marginal cost of degradation is used as a minimum target threshold to reduce battery cycling for minimal gains. There is therefore a minor difference in approach which creates this difference in outcomes.

4. There is a significant period of prolonged high consumption due to the EV being charged during the night time. There is difference in the charge duration between the cases due to differences in the amount of charge required for the EV. Everoze modelling is done based on the manual user input which is observed to be incorrect in this instance, as the EV charging requirement in the real world data is notably less than that estimated in the modelling. Everoze modelling assumes perfect knowledge of the EV battery state of charge when plugged in whereas in reality this is a manual user import which is not always accurate.

**Conclusions:** The three data sets follow each other closer than the winter case, with the key differences attributed to i) battery cycling to capture small changes in the tariff during the night, and ii) uncertainty in the knowledge of actual EV state of charge prior to charging. The good conformance is likely to be due to a combination of no ASHP usage and generally good alignment of stationary storage utilisation between the data sets. Overall, the real world outcomes for this test case show the sophistication of the PassivSystems optimisation and coordinated control capability and that the Everoze modelling reasonably reflects the utilisation of the stationary storage asset and EV charging.

## 10.3 RESULTS AND CONCLUSIONS

**The estimated flexibility value (£/household/year) accrued is shown in Figure 36. Modelled benefits or 'value' from providing flexibility are calculated as the savings in electricity costs and revenues from ancillary services, less any cost of additional electricity imports. This does exclude asset capital or operating costs and so 'value' as used in this report does not imply life-cycle value. It should also be noted that DSO services are highly geographic and as such the revenues shown below will not be available in all areas. Additionally, price competition may reduce the value available from DSO services as widespread flexibility increases.**

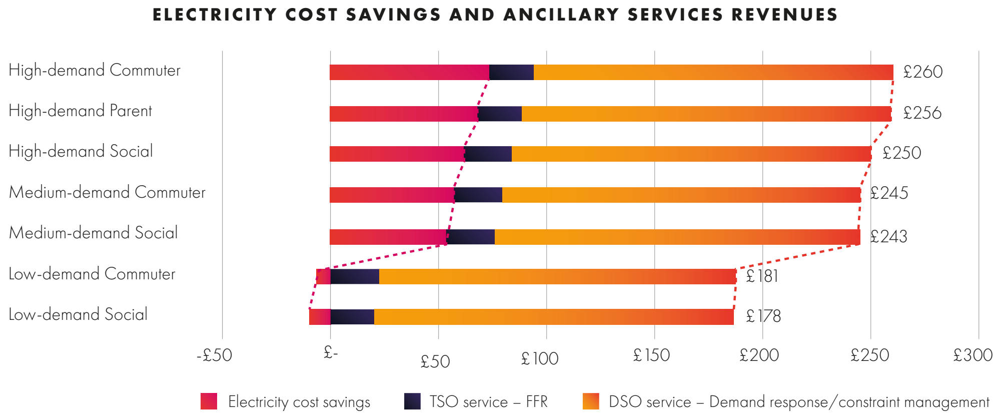


**Figure 36** – Estimated Flexibility Values for the considered property types/EV use cases.

The estimated flexibility value as a percentage of household bill is shown below in Table 14 for each customer type.

| Customer Type | Flexibility Value as a Percentage of Bill |
|---|---|
| High Demand, Commuter | 18.6% |
| High Demand, Parent | 21.1% |
| High Demand, Social | 21.5% |
| Medium Demand, Commuter | 21.0% |
| Medium Demand, Social | 26.2% |
| Low Demand, Commuter | 28.5% |
| Low Demand, Social | 44.9% |

**Table 14** – Estimated Flexibility Values as a percentage of household bill for the considered customer types.

It should be noted that there is a high degree of variability in the DSO service revenues depending on the type of service and the core delivery assumptions. Further sensitivity analysis around these numbers can be found in the full Everoze report.

### Key findings from the modelling regarding electricity cost savings are as follows:

- **Value from peak shifting is sensitive to consumer type:** Based on current wholesale cost profiles and network charges, savings from peak shifting is a smaller component of the overall value stack compared to ancillary services revenues. The property demand and consumption patterns, as well as surplus solar available at the property, have a high degree of sensitivity on cost savings that can be achieved.

- **Value from peak shifting tempered by additional energy imports for ancillary services:** The additional energy cost for providing ancillary services has a material effect of reducing the savings in energy costs from peak shifting. In some cases, this can be higher than the annual savings in energy costs

- **Low demand/EV utilisation customer types are only attractive for DSO services:** The value opportunity from peak shifting and smart charging is low for customer types with low demand and low EV utilisation levels, and the value stack is heavily reliant on DSO services. For such customer types, if DSO service opportunities are not available, then there is little benefit from coordinated flexibility at the household level. Moreover, if the EV is available for most of the time during the evening peak period, then with the EV by itself performing peak-shifting, a domestic battery would not be needed for such Low Demand consumer types (unless DSO services are available and pursued).

**Key findings from the modelling regarding ancillary services are as follows:**

- Value from DSO services can be lucrative but is extremely location sensitive: DSO services form a key part of the value stack but are subject to large variance in value depending the local network constraints and service need. WPD's Secure service offers better value over the year compared to the Dynamic service; although the latter has a higher utilisation tariff, the likelihood of utilisation is lower. The right kind of DSO service opportunities appropriate for the domestic portfolio would need to be pursued. If otherwise, revenues from DSO services are not attractive.

- Coordinated flexibility can help maximise value from DSO service opportunities: A household or a portfolio being able to offer a higher volume with coordinated and combined flexibility from the suite of a domestic battery and EV available would be able to maximise value.

- FFR is a less attractive value proposition: FFR is a small portion of the value stack, and so may not be worth pursuing given metering, testing and associated administration costs unless the entry requirements are streamlined.

## 10.4 SECTION SUMMARY

In summary, domestic flexibility is a notable value opportunity, with possible savings of up to £260 p.a. per household under best conditions. Additionally, domestic flexibility offers material peak load shifting potential for the DSO. Modelling based on half-hourly data indicates a reduction of between 35-40% in peak loads on the network compared to the Baseline Case.

## 10.5 DETAILED TECHNO-ECONOMIC MODELLING

**The full techno-economic modelling analysis report is available on the MADE page of the WPD website.**

# 11 WHOLE-ELECTRICITY SYSTEM INVESTMENT MODELLING (WESIM)

## 11.1 QUANTIFYING WHOLE-SYSTEM BENEFITS OF DISTRIBUTED FLEXIBLE TECHNOLOGIES

**Imperial College formed part of the project consortium to investigate the whole system impact of the MADE concept.**

Capturing the interactions across different time scales and across different asset types is essential for the analysis of future low-carbon electricity systems that include flexible technologies such as the MADE concept and domestic flexibility.

In order to capture trade-offs between different optimised flexible technologies, it is critical that they are all modelled in a single integrated modelling framework. To meet this requirement Imperial has developed the Whole-electricity System Investment Model (WeSIM), a comprehensive system analysis model that is able to simultaneously balance long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion.

WeSIM determines optimal decisions for investing into generation, network and/or storage capacity, in order to satisfy the real-time supply-demand balance in an economically optimal way, while at the same time ensuring efficient levels of security of supply. An advantage of WeSIM over most traditional models is that it is able to simultaneously consider system operation decisions and capacity additions to the system, with the ability to quantify trade-offs of using alternative mitigation measures, such as DSR and storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management.

A prominent feature of the model is the ability to capture and quantify the necessary investments in distribution networks in order to meet demand growth and/or distributed generation uptake, based on the concept of statistically representative distribution networks. These statistical archetypes used in the model have been calibrated to actual GB distribution networks to ensure a highly accurate representation of network length, number of transformers and network reinforcement cost.

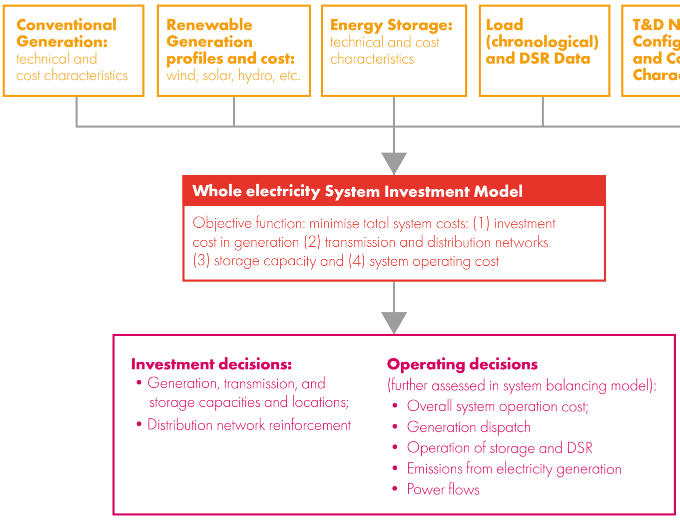


**Figure 37** – Whole electricity system Investment Model: Imperial College.

## 11.2 SCENARIOS AND KEY ASSUMPTIONS

### System benefit of MADE concept:

**Whole-system benefits of MADE concept are quantified for four different levels of uptake of MADE solution: 25%, 50%, 75% and 100% (relative to the number of eligible households). For each of the uptake levels the total system cost is compared to a counterfactual scenario that had a zero uptake of MADE concept but included some flexibility that would likely be provided even without a large-scale rollout of MADE or a similar solution for coordinated control of residential flexibility.**

Due to the whole-system nature of Imperial College's modelling approach, the resulting benefits are disaggregated into components of cost savings, distinguishing between generation investment cost (both low-carbon and conventional), operating cost and distribution investment cost. The cost of enabling MADE is also included in total system cost and net benefit figures. Table 15 defines the baseline scenario and MADE scenarios applied:

| Asset | Baseline scenario: Optimised assets in silo operation | MADE scenario: Optimised assets with coordinated control (MADE) |
|---|---|---|
| Hybrid heat pump: 8 kW | ✓ | ✓ |
| PV generation: 4 kWp | ✓ | ✓ |
| Electric vehicle: 40 kWh battery with charger | ✓ | ✓ |
| Domestic battery with 5 kWh and 2.5 kW diversified peak output | ✓ | ✓ |
| Optimised asset controls | ✓ | ✓ |
| MADE concept: Coordinated control |  | ✓ |

**Table 15**

**Imperial College has modelled the costs with and without the MADE concept at a 25%, 50%, 75% and 100% uptake. Any cost reduction achieved by deploying the MADE concept is interpreted as net system benefit of the MADE solution. This is expressed both as aggregate total benefits as well as benefit per participating MADE household, in both scenarios. The benefits are then combined with the estimated cost of enabling MADE to determine the net system benefits, both in aggregate terms and per participating household.**

It should also be noted that the analysis is focused on the benefit accrued to the system, rather than the value that can be achieved by participants. Routes to market for a number of the value streams are currently not mature enough.

**Assumptions on the number of households:**

According to the latest data from the Office for National Statistics, there are 28.535 million dwellings in Great Britain, of which 14.748 million are detached, semi-detached houses and bungalows, while the rest are terraced houses and flats. Given that a full deployment of the MADE concept will typically require a household with an opportunity to install an electric vehicle (EV) charger, rooftop PV, a hybrid heat pump system and a residential battery system, it was assumed that only detached houses, semi-detached houses and bungalows will have sufficient space to install a full range of LCTs that are included into the MADE concept. This is a simplifying assumption but is still useful to quantify the system-level benefit of MADE.

**Cost assumptions for residential flexibility:**

The cost of purchasing the domestic homes LCTs were not included in the cost estimate of the MADE concept, as it was assumed that these purchasing decisions would be made regardless of whether a household opts to participate in MADE-type control or not.

The cost of implementing the MADE concept was assumed based on information obtained from PassivSystems, also accounting for the likely cost reductions if this solution is rolled out at scale. The assumed cost of smart control was as follows:

- Upfront cost of hardware, PassivSystems' hub and connectivity: £80 per household
- Service cost: £60 per household per year
- Equipment lifetime: 10 years
- Cost of capital: 7%
- Total annual cost of MADE control: £70.10

Therefore, the total annual cost per MADE household, consisting of the cost of residential battery storage and the cost of implementing MADE control, is estimated at £163.30 per year.

**Electricity system scenario:**

The whole-system benefits of MADE concept in this report are assessed for a GB power system scenario that achieves a carbon intensity of 50g $CO_2$/kWh in the 2035 time horizon. This scenario assumed a high uptake of electric vehicles (EVs) and hybrid heat pumps in order to be able to assess a broad range of MADE uptake levels. A total of 37 million EVs was assumed on the system, of which 80% was assumed to be connected to MADE-eligible households. The number of hybrid heat pumps on the system were assumed to be one per MADE-eligible household, or 14.75 million in total.

**Initial features of the system were assumed as follows:**

- Variable renewables: onshore wind 29.5 GW, offshore wind 28.6 GW, solar PV 68.3 GW (of which 9.3 GW were large-scale PV and the remaining 59 GW were rooftop PV in MADE-eligible households)
- Nuclear: 7.9 GW
- CCS: 2 GW
- CCGT: 20 GW
- Other renewables: biomass 7.1 GW, hydro 1.7 GW, other 1.2 GW
- Interconnection: 20 GW
- Energy storage: pumped-hydro 2.7 GW, large-scale battery storage 5 GW (not including residential battery storage associated with MADE rollout)
- Domestic flexibility: 20% of DSR uptake was assumed in the baseline scenarios for the I&C sector, and for household appliances, while for the lower bound estimate the baseline scenario additionally included smart charging of the entire EV fleet (note that any MADE-enabled flexibility was additional to this)

In order to meet the 50g $CO_2$/kWh target, as well as system security, the model was allowed to add more CCS, onshore and offshore wind, CCGT and OCGT capacity, as well as to expand interconnection capacity if cost-efficient.

# 11.3 QUANTITATIVE RESULTS

**Due to the whole-system nature of our modelling approach, the resulting benefits will be disaggregated into components of cost savings, distinguishing between generation investment cost (both low-carbon and conventional), operating cost and distribution investment cost. The cost of enabling MADE i.e. the cost of residential battery storage and smart control is also included in total system cost and net benefit figures.**

Total system cost across the five scenarios (counterfactual plus four MADE uptake scenarios) is shown in Figure 38. Note that the figures for total system cost include the total cost of generation investment and operation cost, but only include the additional cost of reinforcement of distribution and transmission networks (i.e. do not include the cost of existing or fixed network assets). Additionally, the cost of enabling domestic flexibility outside MADE households is not included, although it would be the same across all scenarios and would therefore not affect the estimate of MADE system benefits. The cost of enabling MADE, i.e. the cost of smart control and residential battery storage is also included in the charts as a separate category. Total figures are reported using two sets of values, with and without including the cost of MADE.

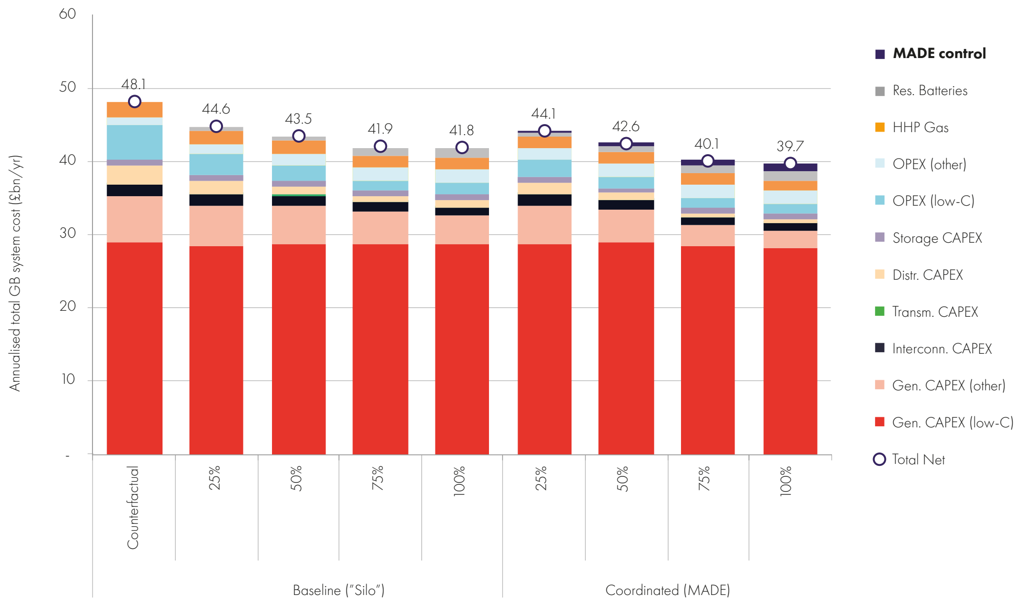


**Figure 38** – Total system cost across different MADE scenarios, silo operation Vs coordinated operation.

The majority of the system cost is associated with investment in low-carbon generation, with sizeable components associated with conventional generation CAPEX, generation OPEX, interconnection CAPEX and distribution network reinforcement cost. It can be observed that, if the cost of enabling MADE is ignored, the total system cost reduces as the uptake level of MADE concept increases. This cost reduction is the fastest at low MADE uptake levels, whereas at high MADE penetrations there is limited incremental benefit of increasing the number of MADE households. Once the cost of MADE is included in the total system cost, however, the total cost flattens at higher MADE penetrations between 75% and 100%. This suggests that at high levels of uptake the incremental system benefits approximately drop to the level of incremental cost of enabling MADE.

To put the above total cost estimates into context, Imperial College's recent estimate for the total system cost in 2020 was around £27bn/yr. CAPEX of the existing assets base for transmission and distribution, not included in the above figures, has been previously estimated at £2.2bn/yr. and £5.6bn/yr., respectively. Therefore, the system cost in our estimate here for 2035 would be about £9-18bn/yr. higher. Of that increase, about £2.5bn/yr. in the baseline case is the additional distribution CAPEX, dropping to £0.6bn/yr. in the scenario with 100% MADE uptake. However, note that the demand assumed for 2020 was significantly lower due to far lower electrification levels for heat and transport.

System benefits of a large uptake of the MADE concept across the four scenarios can be found as differences between a given MADE uptake scenario and the relevant counterfactual (or baseline) scenarios, as shown in Figure 39 savings are reported as annual values, consisting of annual operating costs and annualised investment costs for different asset types. As in Figure 38, total system cost savings are quantified both as gross benefits (without including the cost of MADE) and as net benefits (reflecting the cost of enabling MADE).

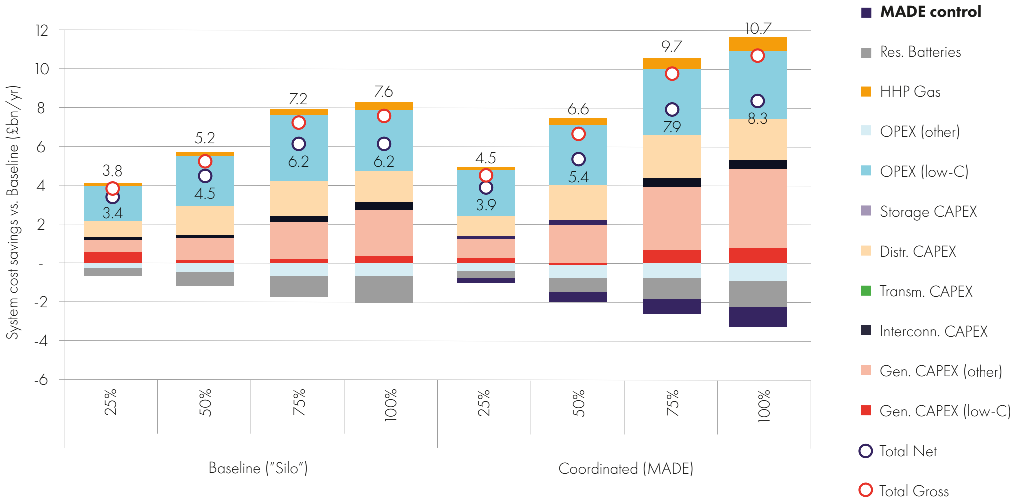


**Figure 39** – Gross and Net system savings, silo operation Vs coordinated operation.

The results in Figure 39 show that in addition to smart LCT controls, the flexibility delivered via MADE solutions can achieve substantial system benefits in the order of billions of pounds per year, reaching £3.1bn per year in gross, £2.1bn in net benefits for full MADE penetration. It is also evident that the increase in benefits slows down as the MADE uptake increases, suggesting diminishing benefits of adding new MADE households to an already significant number of MADE-enabled homes. Net benefits of MADE are lower and become saturated at high penetration levels.

Key components of MADE-enabled cost savings include:

- **Reduced investment cost of low-carbon generation:** distributed flexibility allows cheaper sources of low-carbon electricity (e.g. wind or solar PV) to be integrated more efficiently, and therefore to displace other low-carbon sources (e.g. CCS) while reaching the same carbon target;
- **Reduced investment cost of conventional generation:** flexible resources can be very effective at reducing peak demand and therefore greatly reduce the need to maintain a high volume of peaking generation capacity to secure a sufficient generation capacity margin and the resulting security of supply;
- **Reduced investment cost of distribution networks:** highly distributed flexible resources included in the MADE concept can help reduce the loading level of local distribution grids and therefore significantly decrease the requirements to reinforce distribution grids in order to cope with an increase in electricity demand;
- **Reduced operating cost of low-carbon generation:** as shown later, flexibility can also displace the output of low-carbon generation with relatively higher operating cost, such as CCS or biomass, which is then replaced by lower-cost generation such as wind generation.

## 11.4 SECTION SUMMARY

The analysis by Imperial College has shown that there is significant potential for distributed flexibility to deliver whole-system cost savings with over £8.3bn/yr net value provided in 2035. Unsurprisingly a large portion of this is attributed the deployment of Smart LCTs (£6.2bn/yr), however the benefits associated to coordinated control, the MADE concept, remain substantial at £2.1bn/yr. Even at lower penetration of the MADE concept, the value that can be unlocked is significant.

## 11.5 DETAILED GB WHOLE-SYSTEM NETWORK MODELLING

**The full whole-system network modelling analysis report is available on the MADE page of the WPD website.**

# 12 LOCAL DISTRIBUTION IMPACT OF MADE

## 12.1 MODELLING APPROACH

**As shown in Imperial College's earlier studies, significant distribution network reinforcements could be needed to accommodate rapid uptake of electric vehicles (EVs) and hybrid heat pumps if these assets are not managed in a network-friendly way. Heat and transport electrification could increase the total cumulative expenditure on distribution networks by up to £50bn by 2035 (or £1.8 billion per year in annualised terms). According to earlier analysis, the total replacement cost of the entire GB distribution network is estimated around £100bn, which makes the £50bn reinforcement cost quite material.**

Utilising distributed flexibility, in particular using smart resources such as residential battery storage, EVs and HHPs, could significantly mitigate the impact of electrification of heat and transport on distribution network reinforcement cost. As illustrated in Figure 43 the additional cost of reinforcing GB distribution grids in the baseline scenario (i.e. without any uptake of MADE concept or smart LCT control) is estimated at £2.7bn/yr. It is worth stressing again that these are reinforcement costs that are additional to the CAPEX of the already installed asset base, which in the previous assessments has been estimated at around £5.6bn/yr. (as mentioned earlier in Section 11). With smart LCTs deployed this drops to £1.1bn/yr, a saving of over £1.5bn/yr.

When the coordinated control of the MADE concept is rolled out at 100% uptake level, the distribution network reinforcement cost drops to £0.6bn/yr, resulting in a further distribution CAPEX savings of £0.5bn/yr.

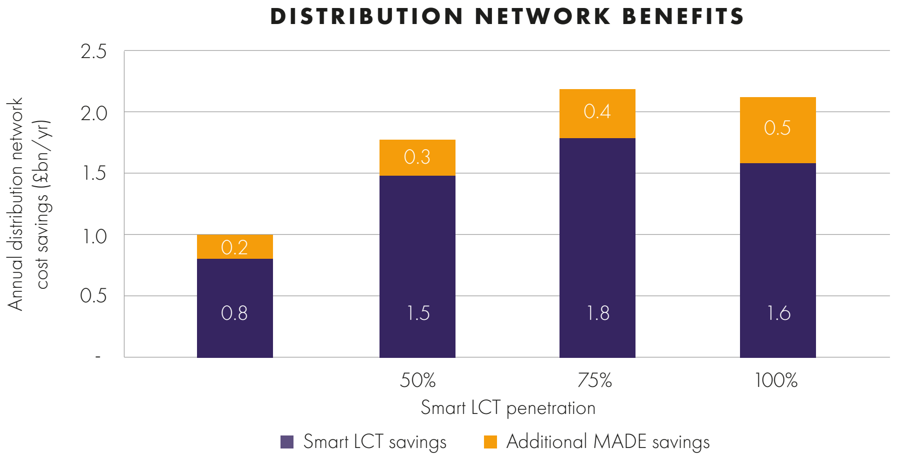


**Figure 40** – Distribution savings stack, domestic flex potential savings in silo operation, plus MADE benefit savings.

The results show that the total distribution network benefits of rolling out the MADE concept can reach up to £500m in terms of annualised reinforcement cost, with higher benefits achieved in LV than in HV networks. At higher MADE uptake levels the distribution network benefits tail off, with very limited additional benefits observed when moving from 75% to 100% penetration.

Within both LV and HV levels the predominant savings originate from avoided reinforcement of semiurban networks, which are characterised by a relatively high number of customers, longer network lengths per customer than urban networks, and higher proportion of cables as opposed to overhead lines compared to rural networks. Significant savings also materialise in urban networks, while savings in rural networks are quite low, both due to lower specific network cost and a lower overall demand.

## 12.2 SECTION SUMMARY

The analysis by Imperial College has shown that there is significant potential for additional distribution network benefits, beyond those achievable with individually smart assets, through multi-asset control of LCTs. This additional distributed flexibility could deliver network cost savings across different voltage levels and asset types, reaching £200m to £500m of avoided annualised reinforcement cost in the longer term.

## 12.3 DETAILED LOCAL DISTRIBUTION MODELLING

**The full local distribution modelling analysis report is available on the MADE page of the WPD website.**

# 13 MANAGING SYNERGIES AND CONFLICTS BETWEEN LOCAL AND NATIONAL SYSTEM OBJECTIVES

**As demonstrated in the previous section, the services delivered by flexible DER could bring very significant benefits to several sectors of the electricity industry, including distribution networks, transmission networks, and generation system operation and investment. However, energy supply, transmission, and distribution networks are operated by different entities with a level of coordination that is currently limited. Instead of using the DER-based services to maximise the whole-system benefits, individual entities tend to use these resources for maximising their own benefits, not considering the impact on other entities. Managing synergies and conflicts among the distribution network, transmission network, energy supply and EU-wide decarbonisation objectives when allocating DER flexibility will be critical for the optimal development of the system. As such, Imperial College investigated the potential options.**

Interaction between DSO and ESO services provided through flexible DER will have both short-term and long-term perspectives. Both of these are discussed in more detail in this section.

## 13.1 SHORT-TERM INTERACTION BETWEEN FLEXIBLE DSO AND ESO SERVICES

**Electricity price signals differentiated according to both location and time are generally seen as an efficient approach for coordinating a large volume of decentralised flexible resource.**

However, a naive application of dynamic pricing in combination with the envisaged automation in control of flexible loads may lead to a very significant loss of demand diversity and demand response concentration as shown in some of the MADE tests. At a high level, the demand shifting by flexible consumers can become highly concentrated during periods with lowest prices, potentially creating new demand peaks and thus causing inefficient system operation. Such demand response concentration effects are illustrated in Figure 41, considering two examples with a) smart-charging of EVs and b) wet appliances (WA) with delay functionality. In the first example, a 30% penetration of EVs in the UK system is assumed and their flexibility is enabled through smart charging. In the second example all WA in the UK system are considered, and their flexibility is reflected in the ability to delay their operating cycles by a maximum of 12 hours. The inflexible EV scenario assumes that EV start charging immediately after they are connected to the grid until they are fully charged, while the inflexible WA scenario assumes that their cycles cannot be delayed.

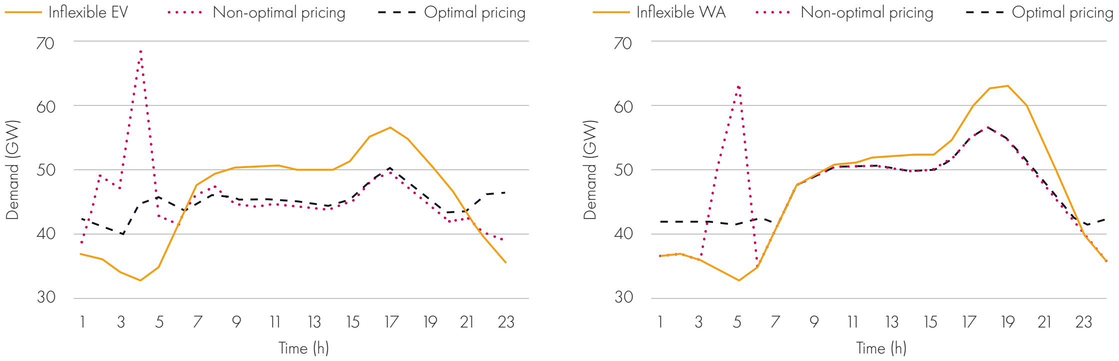


**Figure 41** – Performance of alternative strategies for the coordination of flexible EV (left) and WA (right).

Smart decentralised coordination strategies could therefore be used in order to address the challenge of demand response concentration and utilise the full potential of flexible loads. In this context, alternative smart strategies have been assessed using a combination of measures (relative flexibility restrictions, penalising the extent of flexibility or randomizing the prices transmitted to flexible loads) in order to diversify their responses and discourage concentration of demand in the lowest-priced periods. Figure 41 illustrates the performance of these strategies in mitigating demand response concentration and shows that these approaches can avoid the issue of demand concentration and generating new peaks.

# 13.2 LONG-TERM INTERACTION BETWEEN FLEXIBLE DSO AND ESO SERVICES

**It is evident that in order to achieve efficient outcomes from the whole-system perspective there will be a need for stronger coordination between system operators at both transmission and distribution levels. This coordination will enable the use of all available flexibility resources while managing synergies and conflicts across different networks. A whole-system approach will be required for both operation of the system and management of future networks at maximum efficiency. The modelling results from Imperial College in Figure 42 show that a whole-system-based network management approach may result in savings in system investment and operation cost that are approximately twice as high as the savings in the distribution-centric approach.**

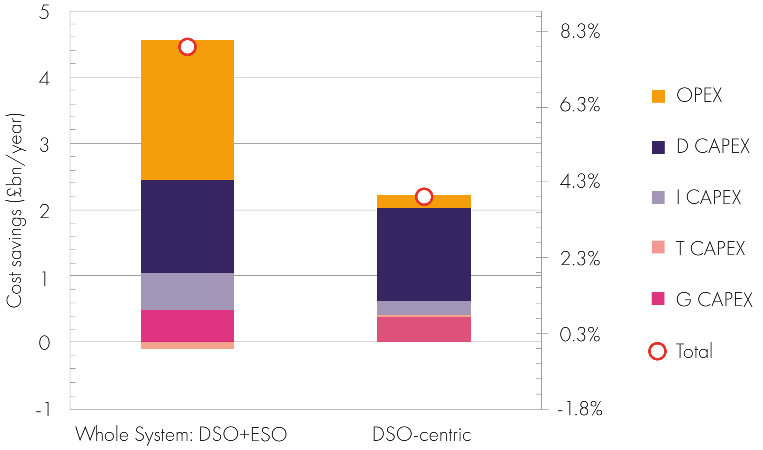


**Figure 42** – Potential benefits of improved transmission and distribution control interface. Right vertical axis shows cost savings relative to total system cost without added flexibility. DSO = Distribution System Operator, ESO = Electricity System Operator.

In this case, the DSO-centric approach focuses on the use of DER for deferring distribution network investment by reducing peak demand, although this may not be optimal for transmission system operation and investment. In contrast, the whole-system approach would allow the DER to be used towards meeting both local and national infrastructure objectives by managing the synergies and conflicts between various DER applications. The whole-system approach is still able to deliver almost the same level of cost savings in distribution network cost as in the DSO-centric case, suggesting that only a minor compromise on the distribution cost savings from using flexible DER can deliver significant additional savings in other segments of the power system. However, realising this additional potential requires close coordination between system operators, with clarity on their future roles and responsibilities.

Figure 43 shows the total system cost differences between the solutions that optimise the utilisation of domestic flexibility obtained by the whole-system and DSO-centric approaches assuming both inflexible and flexible generation systems (referring to the ramping, start-up and frequency regulation capabilities of conventional generators). In both cases, the whole- system solution is characterised by lower cost than the DSO-centric approach, which explains the net negative cost difference. The benefit of the whole-system solution is slightly larger in the inflexible system, highlighting the need to have a more intensive system coordination in the inflexible system.

In the case of the inflexible system, the modelling demonstrates that the whole system would benefit from investment in distribution network reinforcement. Such investment would enable end-use flexibility to reduce the system operating cost and also reduce the corresponding generation CAPEX needed to reach the $CO_2$ target cost effectively. In this case, flexible consumers would be willing to pay for distribution network reinforcement, as the revenues from providing balancing services at the national level would be greater than the cost of distribution network reinforcement, which would reduce their energy bills.

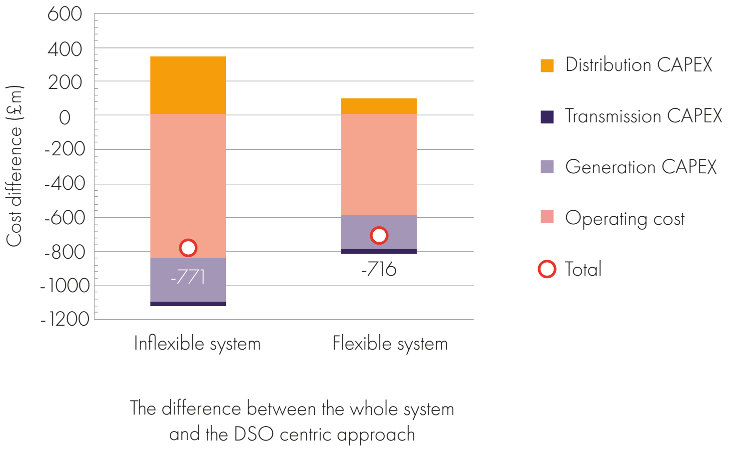


**Figure 43** – Impact of generation flexibility on the role and value of domestic flexibility. Cost differences shown are between whole-system and DSO-centric approaches, for two flexibility levels of conventional generation fleet.

On the other hand, in the presence of flexible generation and high level of interconnection with the EU that would provide national level balancing services, end-use flexibility resources should be primarily used to manage peaks and minimise reinforcement in distribution networks, while supporting balancing of demand and supply at the national level only when this activity would not conflict with local distribution network constraint management objectives.

## 13.3 SECTION SUMMARY

**At present, the actions of flexible DER tend to focus more on local district or national level markets, while not directly facilitating cost-effective decarbonisation of the entire energy system. Appropriate policies and commercial frameworks should be developed in the future to reflect the impact of their decisions on wider-system costs, which will require integration of wholesale and retail markets, with location-specific and time-varying energy prices. A full coordination between local, regional, national and international level objectives will be necessary to maximise whole-system benefits of flexible resources, which is a major challenge for future market design.**

The role and responsibility of DSO will need to evolve to efficiently ensure access for DER to provide transmission-level services, which will require the development of a commercial framework that adequately remunerates these services. The capability of DER to provide services to the ESO will vary dynamically according to the conditions in the local distribution network, and therefore real-time monitoring and active management of the network will be required.

## 13.4 DETAILED ASSESSMENT OF THE SYNERGIES AND CONFLICTS BETWEEN LOCAL AND NATIONAL SYSTEM OBJECTIVES

**The full local and national system synergies and conflicts report is available on the MADE page of the WPD website.**

# 14 MADE CONSUMER PROPOSITIONS

**In this section we present three conceptual customer propositions which consider the significant value to be unlocked through the MADE concept post-technical trial. They focus on using combined operation and optimised control of electric heating (hybrids/heat pumps), electric vehicles, storage and solar PV output, in combination with residential flexibility value streams or variable tariffs.**

## 14.1 THE £260 PER ANNUM OPPORTUNITY

Through a third party control aggregating multiple low carbon technologies, the MADE project has identified and validated a £260 per annum, per home benefit or 'value opportunity' from providing domestic flexibility services. This opportunity is derived from calculating the savings in electricity costs and revenues from ancillary services, less any cost of additional electricity imports. In this section we investigate which parties could be involved in unlocking this benefit and how they fit into the value case.

| Beneficiary | Customer Proposition |
|---|---|
| **Homeowner** | • Annual savings unlocked through coordinated control. This may need to be shared with other facilitating organisations. |
| **Energy supplier** | • Customer savings used as a driver to recruit new customers or retain existing customers. This could sit alongside LCT propositions.<br>• Potential to revenue share with the customer. |
| **Financiers** | • Marginal additional investment when financing LCTs could improve rate of return. |
| **Aggregators** | • Provision of control could bring in new assets to derive revenue from. |
| **Local authorities & Registered social landlords** | • Control could be used to ensure tenant comfort whilst minimising energy costs |
| **UK Government** | • Financial incentives to promote the use of LCTs, building out the core assets required to provide the benefits seen. |
| **DSO** | • Ensure services are as accessible as possible to ensure that network value can be achieved |
| **ESO** | • Ensure services are as accessible as possible to ensure that system value can be achieved |

**Table 16** – MADE opportunities summary.

How each of these parties unlocks the value will depend on the specific business models used to deploy the control. These business models are detailed in the sections below.

## 14.2 IMMEDIATE TO SHORT-TERM OPPORTUNITIES

**The propositions are constructed using the framework outlined below, energy supplier workshops and from studying similar business models. The value streams on which these propositions rely on are not all mature in the UK at present.**

**The propositions are:**

- All energy services (heating, personal transport and other energy needs) provided through a single monthly fee.
- Company optimises energy demand across technologies and pays income to customer.
- Balancing electricity demand over the home to reduce peak demand, in return for a cheaper tariff.

They also rely on a greater awareness and appeal of low carbon heating systems, particularly in options where the customer is expected to buy the technologies upfront or already own them. This means that they are expected to be suitable in the future but not ready for market currently.

**Key components of MADE-enabled cost savings include:**

- **MADE concept:** The flexibility available through coordinated control as demonstrated in technical trial;
- **Technologies:** The purchase arrangement of the technology and whether the customer owns or leases these technologies;
- **Energy supply:** Whether energy supply is included in the proposition orif it is bought separately;
- **Contract:** Details of what is included in the contract and whether the proposition has a fixed contract length;
- **Customer value streams:** How the customer gets value out of the relationship;
- **Company value streams:** where value can come from to both reduce costs and access new revenue;
- **Risks:** level of risk to customer and company and how these risks are managed;
- **Target customer:** who the specific customer proposition might appeal to, to judge the size of this target market;
- **Most suitable provider:** whether the business model is best delivered by an energy supplier, manufacturer or third party energy service provider.

**Table 17** – Business model framework.

## 14.3 CUSTOMER PROPOSITION 1: ALL INCLUSIVE

### All energy services (heating, personal transport and other energy needs) provided for single monthly fee.

This option focuses on minimising the cost of buying electricity from the grid by maximising self-consumption.

The main aim of this business model is to deliver heating to the home using electricity generated by the solar panels. Control strategy of the heat pump would predict when heating is needed and pre-heat the home using available electricity if appropriate. If insufficient electricity is generated, then cheap electricity could be bought from the grid or heating could be delivered via the boiler.

Any excess electricity could be used to charge the EV, supplemented by grid electricity which is expected to be sufficiently cheap overnight. Excess stored electricity could also be sold back to the grid at times of high demand.

| Business Model | Customer Proposition |
|---|---|
| **Technologies included:**<br>Heat pump, Gas boiler, EV, Solar PV, Battery storage, Smart controller hub.<br>**Company value streams**<br>• Minimising electricity demand on the electricity grid, and only buying at low cost times by optimising self consumption and storing cheap electricity.<br>• Selling electricity back to grid at times of high demand.<br>**Target customer**<br>Customers who seek low carbon heating and personal transport. House may need a minimum level of thermal efficiency to be viable. | **Technologies** provided at no upfront cost.<br>**Monthly fee** to include:<br>• Cost of technologies<br>• Energy supply (monthly cost based on some description of service demand, and potential to change if energy demands change significantly)<br>• Maintenance, servicing and insurance.<br>**Contract** could be either:<br>**1.** Fixed contract period (i.e. 5 years) – monthly fee higher for a shorter contract length.<br>**2.** Rolling contract (with no minimum length) with get-out fee for removal of technologies if before e.g. 10 years.<br>Risks are low for the customer as main risks are taken on by company. Perceived risks of entering an extended contract. |

**Table 18** – Customer proposition 1, all inclusive.

## 14.4 CUSTOMER PROPOSITION 2: PURCHASING AN ENHANCED CONTROL

### Flexible package where company optimises energy demand across whichever assets the customer has. Customer buys technologies and energy separately.

This option provides flexibility to the customer who can include whichever technologies they have or want to buy and has no tie-in to a contract.

The main feature of this business model is the smart controller hub which optimises energy demand for heating across heat pump and boiler and optimises EV charging based on pricing signals or other choices given by the household (i.e. it could be to minimise cost or $CO_2$ emissions).

The customer is responsible for buying the technologies and energy separately, and the company delivers energy savings compared to each technology being controlled separately. If the package includes battery storage, additional revenue can be gained from selling electricity back to grid at times of high demand and the customer is paid credit for each of these DR events.

| Business Model | Customer Proposition |
|---|---|
| **Technologies can include:**<br>Heat pump, Gas boiler, EV, Solar PV, Battery storage, Smart controller hub.<br>**Company value streams**<br>• Sale of smart controller hub<br>• DR revenue from selling electricity back to grid at times of high demand.<br>**Target customer**<br>Customers who seek low carbon heating and personal transport. House may need a minimum level of thermal efficiency to be viable. | **Technologies** bought upfront or through finance arranged by the customer<br>**Energy supply** bought separately by customer.<br>**No monthly fee, no minimum contract**<br>• Cost of technologies<br>• Greater savings can be made if customer is on a ToU tariff<br>• Credit paid back to customer as share of revenue for selling electricity back to grid at times of high demand.<br>**Risks** are low if the customer was seeking to buy these technologies already. It would take some years to pay back capital cost so not suitable if cost is main motivation. |

**Table 19** – Customer proposition 2, enhanced control.

## 14.5 CUSTOMER PROPOSITION 3: MINIMISING PEAK DEMANDS

**Minimal benefits to customer, and minimal risks. Main benefits are in balancing electricity demand over the home to reduce peak demand, in return for a cheaper tariff.**

This option is the closest extension to the Freedom project, testing the ability of control across the house to minimise costs and reduce peak demand.

The main aim of this business model is to minimise overall power draw of the house by controlling the heating and EV charging assets without the a requirement for storage and PV*.

Hybrid heating system operation is controlled to optimise efficiency of the heat pump, overall cost on a dynamic ToU tariff, and ideally also minimising gas usage. EV charging is optimised for times of low electricity demand in the home and cheap grid electricity.

Where chargers are compatible, some stored electricity in the EV could also power the heat pump operation.

| Business Model | Customer Proposition |
|---|---|
| **Technologies can include:**<br>Heat pump, Gas boiler, EV, Solar PV, Battery storage, Smart controller hub.<br>**Company value streams**<br>• Sale of smart controller hub<br>• DR revenue from selling electricity back to grid at times of high demand.<br>**Target customer**<br>Customers who seek low carbon heating and personal transport. House may need a minimum level of thermal efficiency to be viable. | **Technologies** bought upfront or through finance arranged by the customer<br>**Energy supply** bought separately by customer.<br>**No monthly fee, no minimum contract**<br>• Cost of technologies.<br>• Greater savings can be made if customer is on a ToU tariff.<br>• Credit paid back to customer as share of revenue for selling electricity back to grid at times of high demand.<br>**Risks** are low if the customer was seeking to buy these technologies already. It would take some years to pay back capital cost so not suitable if cost is main motivation. |

**Table 20** – Customer proposition 3: Minimise peaks.

*Solar PV and storage are not included in this proposition. This tests the performance of the hybrid heating system and EV combination in homes where PV and storage are not possible. Different combinations of technologies may be suitable for different households.

# 14.6 SECTION SUMMARY

## Summary table of customer proposition options

| | **Option 1:**<br>**All inclusive** | **Option 2:**<br>**Buying enhanced control** | **Option 3:**<br>**Minimising peak demand** |
|---|---|---|---|
| **Technologies can include:** | Heat pump, gas boiler, EV, Solar PV, Battery Storage, Smart controller hub. | Smart controller hub plus any combination of heat pump, Gas boiler, EV, Solar PV, Battery storage. | Heat pump, gas boiler, EV, Smart controller hub. |
| **Purchase / ownership of tech** | Leased at no upfront cost to customer. | Bought upfront by customer (or through finance arranged by customer). | Bought upfront by customer (or through finance arranged by customer). |
| **Energy supply** | Included within monthly fee. | Bought separately by customer. | Included but paid per unit energy used. |
| **Contract** | Monthly fee covers lease of technology, energy supply, MS&I. Approx. 5 years (could offer choice). | No monthly fee, no minimum contract length. | No monthly fee, no minimum contract length. |
| **Customer value streams** | Monthly fee which is an acceptable price to customer, easier budgeting, peace of mind. | Energy bills are reduced by smart control hub. Credit paid back from any DR revenue. | Cheap flat rate energy price (not being exposed to ToU variation). |
| **Company value streams** | Minimising cost of electricity through self consumption and buying at cheap times (company keeps costs savings), selling electricity to grid at peak times. | Sale of smart controller hub DR revenue from selling electricity back to gird at times of high demand. | Minimising peak power draw over home (no current value in this in the UK), Minimising cost of heating and charging EV via Dynamic ToU signals, DR Revenue – turning down demand. |
| **Risks** | Low for the customer, except for perception of entering a contract. Main risks taken on by company. | Low if the customer was seeking to buy these technologies already (but long payback period if all tech bought). | Low if the customer was seeking to buy these technologies already. |
| **Target customer** | Customers who seek low carbon heating and personal transport. | Customers who own or would like low carbon heating and personal transport. | Customers who are looking to buy low carbon heating and personal transport. |
| **Most suitable provider** | Energy Service Provider (could be energy supplier, manufacturer or other. | Controls company. | Energy supplier, DNO. |

**Table 21** – Summary table of customer proposition options.

# 14.7 DETAILED BUSINESS MODELS AND CONSUMER PROPOSITIONS

## The full business models and consumer propositions report is available on the MADE page of the WPD website.

# 15

# MARKET, REGULATORY AND POLICY RECOMMENDATIONS

**The MADE concept offers an optimal domestic flexibility solution, improving operating efficiency through smart control schemes, as trialled by PassivSystems in the MADE project. However, limitations in the current market and regulatory framework have been identified, with suitable recommendations provided to realise the multiple system benefits of smart, coordinated LCTs in energy, balancing and capacity market segments.**

As identified in the Government's Clean Growth Strategy, transitioning to this smart, flexible energy system of the future could unlock savings of up to £40 billion to 2050. As it stands today, domestic flexibility faces several policy challenges. High participation in residential flexibility will require market reform across four key areas:

## Further access to ToU tariffs:

The project has shown a clear ability for assets to optimise against ToU tariffs, and the benefits that can be achieved through this. However, the penetration of current ToU tariffs remains low.

Domestic level banded tariffs have been available from DNOs for a number of years now. In addition, following the acceptance of DCP 268, from 2021, all DUoS tariffs will include time bands.

However, to date, very few supplier tariffs make the most of this. The roll out of smart metering and half-hourly settlement are crucial to making this more widespread, exposing suppliers, and then their customers to more cost reflective price signals. These processes are both underway, this project highlights some of the benefits they would unlock and the need for them to progress swiftly.

The output of the Ofgem's Significant Code Review into access and forward looking charges could have a large impact on the shaping of DUoS signals into the wider market.

## LCT interoperability standards:

There is clear evidence that coordinated control of assets can provide significant value. However, the process of providing this control is not straightforward. Significant time and effort was needed within the project to integrate with proprietary control systems. Clear standards would ease the control across and between assets. Work is already underway within the BSI. As part of PAS 1878, the findings of the project are being fed into this work to highlight the value, as well as the practical challenges.

## Clear incentives for the adoption of LCTs

There already exists a wide range of flexible technologies that could deliver customer cost and carbon savings whist also helping manage the wider system. These include electric vehicles, smart hybrid heat pumps, heat pumps, solar PV, batteries and smart EV/V2G chargers that could all be providing services at this time if the right signals and instructions were being administered. Harnessing the potential of these technologies is critical to ensuring green energy supply isn't unnecessarily wasted.

Clear incentives are needed to ensure sufficient volume of LCTs are deployed to help hit Net Zero. These could be under many forms but need to be clear and investible. Ensuring that assets are installed with the option to be flexible is essential to make sure that consumers can easily access the value that can be generated.

## Clear economic and investable business models

As highlighted in Section 14, it is essential that any business models developed go beyond asset installation (as highlighted above) and include the potential for coordinated control. It is expected that these will need to be quite diverse to help target various segments of the market based on key factors such as access to capital as well as appetite for control.

# 16 CONCLUSION

**The MADE project has shown that there is significant additional value extracted through the coordination of multiple LCTs within a single premise. Both at a system wide level, and at a single property level there are tangible benefits, including de-risking the distribution network from unpredictable demand when assets are coordinated rather than operating individually.**

Following a market assessment by Delta-EE and supplemented by National Grid ESO's Future Energy Scenarios (FES) it is evident that the deployment of low carbon technologies will grow rapidly out to 2050. Strong growth in the sales of all low carbon technologies is expected in the medium to long-term. Under almost any scenario the number of air source heat pumps and hybrid heating systems installed in UK homes will be well into the millions by 2030. The uptake of EVs will also be rapid from the late 2020s in to the early 2030s with over 10 million on the roads by the mid 2030s in all scenarios. Domestic solar PV installations will also see a significant increase with anywhere from 2 to 5 times more installations than today by 2050. The MADE project has demonstrated that by optimising these technologies in mature market conditions it will support to maximise value and limit network and system impacts.

Predictive controls are a key enabling technology for all of the above benefits of tariff optimisation and asset coordination. Under the MADE project PassivSystems has trialled a sophisticated control system uniquely able to make the right quantitative trade-offs to underpin the complex decisions in controlling multiple low carbon assets simultaneously.

Through complex techno-economic modelling, Everoze Consultants has identified a notable £260 value opportunity for homeowners, suppliers and aggregators by implementing a multiple low carbon asset control.

The modelling has demonstrated that with current wholesale cost profiles and network charges, savings from peak shifting is a smaller component of the overall value stack compared to ancillary services revenues. The property demand and consumption patterns, as well as surplus solar available at the property, have a high degree of sensitivity on cost savings that can be achieved.

The additional energy cost for providing ancillary services has a material effect of reducing the savings in energy costs from peak shifting. In some cases, this can be higher than the annual savings in energy costs, however, this is more than offset by the additional revenue generated.

The value opportunity from peak shifting and smart charging is low for customer types with low demand and low EV utilisation levels, and the value stack is heavily reliant on DSO services. For such customer types, if DSO service opportunities are not available, then there is little benefit from coordinated domestic flexibility at the household level. Moreover, if the EV is available for most of the time during the evening peak period, then with the EV by itself performing peak shifting, a domestic battery would not be needed for such low demand consumer types (unless DSO services are available and pursued).

In collaboration with PassivSystems, Everoze has identified that distribution networks can utilise the MADE concept by limiting loads to 33% of the 14kW fuse limit at a property level without compromising household consumption behaviour and savings that can be achieved (based on half-hourly average loads). There is a notable potential for using residential consumers to manage peak loads on the network.

The MADE concept offers material peak load shifting potential for the distribution network of between 35 and 40% reduction in peak loads on the network compared to optimised low carbon technologies optimised but in silo operation.

Imperial College has assessed the opportunities to deliver whole-system cost savings by utilising distributed flexibility based on the MADE concept are significant and increase with the level of uptake of the MADE flexible solution. In the 2035 horizon with an ambitious carbon target and high uptake of EVs and HHPs the gross benefits could reach £3.1bn per year, through allowing the electricity system to achieve the carbon target more cost-effectively, while at the same time reducing the need for high volumes of peaking generation capacity and distribution network reinforcements. Highest achievable net benefits, after deducting the cost of enabling residential flexibility through MADE, are lower (£2.1bn per year).

The net benefit is still considerable despite moderate levels of flexibility already being present in the system in the form of DSR, large-scale battery storage and interconnectors, as well as smart EVs in the lower bound estimates. There is also a significant potential for distributed flexibility to deliver distribution network cost savings across different voltage levels and asset types, which can reach £200m to £500m of avoided annualised reinforcement cost.

With clear value available, Delta-EE has identified business models and customer propositions which could be deployed in the short to medium term and long term. These propositions are built upon a well-used framework for developing business models and customer propositions and build on insight taken from studying similar business models. The propositions identified by Delta-ee are as follows:

1. **All Inclusive:** All energy services (heating, personal transport and other energy needs) provided for a single monthly fee.

2. **Buying Enhanced Control:** Company optimises energy demand across technologies and pays income to customer.

3. **Minimising Peak Demands:** Balancing electricity demand over the home to reduce peak demand, in return for a cheaper tariff.

To validate the modelling activities of the MADE concept, PassivSystems successfully completed a 12-month technical field trial, with five homes having multiple LCTs operating through one consumer interface.

It has been demonstrated that it is possible for third party controls to integrate with and optimise a range of different LCT assets from a number of different manufacturers. Predictive controls that can optimise and coordinate asset behaviour have been shown to play a key role in delivering best value from the assets to the consumer as well as negotiating patterns of behaviour desired by the local and national electricity grid. The greater the level of coordination between the low carbon assets, the greater the savings in consumer electricity costs.

Time-varying tariffs can offer significant running cost benefits to consumers with MADE assets, particularly where the battery and heat pump can be coordinated to store energy in the right balance between the battery and the thermal fabric of the building and making the right decisions about waiting for available PV generation. Such benefits can be unlocked without requiring behavioural change from consumers when smart controls are applied.

Even slight variations in tariff can introduce demand peaks, e.g. due to batteries delivering arbitrage. These peaks can easily be mitigated by a smart control system, at only a small incremental cost to the householder, as long as the provision of cheap electricity is not significantly reduced.

Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets, by pre-charging both the battery and the home in advance of the availability window.

With advanced controls it is expected that this flexibility and the associated benefits can be obtained without affecting customer comfort. This is essential if wide scale acceptance of advanced control of LCTs is to be achieved.

# 17 NEXT STEPS AND OPPORTUNITIES

**The MADE project has successfully achieved its core objectives. As we have gathered more learning about the feasibility of such controls a number of potential follow up opportunities have been identified.**

## Large scale trial of optimised LCTs and coordinated control

To date the MADE trial has focused on the small-scale demonstration of the concept. This provides an interesting insight but would be enhanced by a larger scale field trial and/or more extensive simulation work to understand the quantitative impact of MADE assets on household demand shape and running costs, and their statistical variability. With such variation in UK housing stock, customer requirements, and even weather patterns, a larger, longer trial would help understand the potential variability.

The MADE project focused on hybrid heat pumps and no other heating appliance. Exploring the potential of the next generation of heat pumps and storage heaters may deliver further value from the MADE low-carbon assets. The MADE project was also limited by the relative immaturity of EV and charge point connectivity. Exploring the potential of the next generation of V2G charge points could deliver further value from the MADE low-carbon assets.

## Leaving no customers behind

Further work is needed to understand how accessible the MADE concept is to customers in vulnerable situations, or who suffer from fuel poverty. Considering the potential benefits to such customers, collaboration with local authorities, registered social landlords, distribution networks and Ofgem may be needed to ensure everyone can benefit. Elements such as business models need to be further developed as well as education and support to understand how to maximise the benefits. Utilising frameworks such as CSE’s Smart and Fair framework could help us understand the accessibility of the proposition as well as any potential mitigations that could widen access.

## LCT forecast tool

There is a need amongst the local and national networks to ensure optimal network planning, asset dispatch and manage uncertainties. Current models do not adequately consider LCT optimisation, homes having multiple LCTs, coordinated LCTs and limited heat appliance profiles. The next step is to calibrate existing models or develop a new model to consider more granular home electricity profiles, adopt a stochastic portfolio view, probe energy service and mobility requirements in greater detail, consider market trends (e.g. LCT sale forecasting and ToU adoption) and better assess predictability of consumer behaviour. As control systems develop and market signals become more developed our understanding of how LCTs will operate and the potential impacts on the network will need to evolve. Static profiles are unlikely to provide realistic and actionable forecasts.

## Improved understanding of connected LCTs

DNO and industry knowledge of assets connected to the distribution network is improving with new developments such as the embedded capacity register and innovation projects such as LCT detection.

It is important that DNOs better understand what is connected to the network, but also to understand how they might operate. Understanding the technical capability as well as likelihood to flex is important. As shown in MADE, control systems and tariffs have a very large impact on asset operation and developing a better understanding of these dynamics could provide significant future value.

## Review the connection process for domestic LCTs

The network connection process for multiple LCTs is far from straightforward and often uses unlikely assumptions on asset operation. Where systems can be shown to reliably limit import or export capabilities these should be considered in the assessment of maximum demands both from the installer and the DNO. A review of control systems like the one tested, with standards such as G100 could allow for this.

## Support Ofgem and BEIS market, regulatory and policy recommendations

The project partners will continue to share the latest project/technology news and resources with the industry. This includes key departments of Ofgem, BEIS and various industry trade bodies. Feeding the learning and the key findings with policy and decision makers is important to ensure that value is maximised.

# 18 MADE PROJECT ENQUIRIES

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