MADE: Multi Asset Demand Execution

Field Trial Results

Revision history

Version	Change Description	Initials	Release Date
v0.1	Initial draft, presenting early findings and report structure.	BS	26/03/20
V1.0	Finalised for release	BS, EC	5/8/2020

1 EXECUTIVE SUMMARY

The Multi Asset Demand Execution (MADE) project set out to make an exploration of the impact of multiple low carbon assets in the home on the electricity distribution network, and the initial potential for reducing this impact by coordinating the assets.

One scenario for the transition to 2050 decarbonisation goals is that a large proportion of UK homes will be heated by hybrid heat pumps, have solar PV panels generating electricity to use at home and export to the grid, have a battery installed to store the solar generation and also take advantage of cheap renewably-generated electricity from the grid, and the occupants will drive 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.

The project consists of carrying out a small field trial of the technologies, and a parallel stream of modelling work that aims to extrapolate to the wider population of homes and assess the value of flexibility, together with a stream of customer engagement work. This report is focused on the MADE field trial and the insights discovered about coordinating low-carbon assets within the home.

Field trial outline

The MADE project installed the following combination of assets within five trial homes :

- A **hybrid heat pump** (HHP) to providing heating and hot water for the home, consisting of an (electric) heat pump supplementing a previously existing fossil-fuel boiler,
- **Solar photovoltaic (PV) panels** to generate electricity,
- A **domestic battery** (electric) installed to store and shift electrical load,
- An **electric vehicle charge point** to charge an electric vehicle (EV) at home,

together with **smart predictive controls** that enabled the operation of the four technologies to be coordinated with each other at the same time as meeting the needs of the householders. The householders were issued with a smartphone App to control their heating and also specify EV usage requirements.

A field trial was carried out from autumn 2019 until summer 2020 (together with supplementary simulation work) to explore a number of scenarios:

- **Time of use tariffs,** which provide the primary driver for demand shaping through a straightforward mechanism which exists in today's market and rewards the consumer directly. MADE focused mainly on (a) a cheap overnight tariff (often targeted at EV drivers, e.g. Octopus Go) and (b) a dynamic tariff which captures the major national-scale and distribution-scale drivers (Octopus Agile).
- **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 the opposite is true in summer.
- **Interventions:** to explore the flexibility of the system to respond to local network needs and mitigate peaks introduced by time of use tariffs.

Field trial results

The key findings from the field trial were:

- **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.
- **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 time-of-use 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.

Recommendations and next steps

We recommend that the MADE research is continued by using 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. Combining this with transformer/substation-specific monitoring would give insight into how robustly smart systems can help avoid unnecessary grid reinforcement for low carbon technologies.

Technologically, the MADE project was limited most by the relative immaturity of EV and charge point connectivity. We recommend exploring the potential of the next generation of V2G charge points to deliver further value from the MADE low-carbon assets.

2 INTRODUCTION

The Multi Asset Demand Execution (MADE) project set out to explore the implications for the electricity distribution network of homes having multiple low carbon assets, and the potential for reducing this impact through active control and coordination of these assets.

The decarbonisation of heat and transport is now a priority for the UK government, following their commitment to bring all greenhouse gas emissions to net zero by 2050. It is likely that as we transition to reach this goal, a large proportion of UK homes will:

- Be heated by a **hybrid heat pump** (HHP), consisting of an electrically powered heat pump together with a fossil-fuel boiler;
- Have **solar photovoltaic (PV) panels** generating electricity to use at home and export to the grid;
- Have a (electric) **battery** installed to store excess solar generation and to take advantage of cheap renewably-generated electricity from the grid;
- Have occupants who drive an **electric vehicle** (EV) which can be charged via an EV charge point at home.

The project aimed to replicate this combination of assets within the home for the first time, crucially together with **smart controls** which enabled the operation of the four technologies to be coordinated with each other. This meant the project could explore how to make the most of the combined flexibility from the assets, and how they could potentially be orchestrated between homes to offer grid services and stay within any local grid constraints.

The 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. This document is focused on the results of the MADE field trial (winter 2019 - summer 2020). The scope of this document is to present key results from the field trial together with simulation work that was performed to capture additional scenarios, and to discuss the conclusions that can be drawn from these results.

2.1 Aims

In particular, the field trial aimed to:

- Improve understanding of the real world complexities of installing hybrid heat pumps, solar PV panels, batteries and 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;
- Answer the following research questions:
  - How does real-world overall household demand shape (and balance between the assets) change depending on time-of-use 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?

For context, wider activities from the MADE project included:

- Building a microeconomic model for domestic multi-asset, multi-vector flexibility for GB today;
- Assessing the whole-energy system benefits (including network infrastructure) and carbon benefits of large-scale deployment of the MADE concept;
- Consideration of conflicts and synergies between local community and national level objectives in the context of the flexibility enabled by the MADE concept;
- Estimating consumer benefits of the MADE concept and informing the design of the market framework that would enable consumers to access the revenues that reflect the benefits delivered.

The outputs of these activities will be described in separate reports from project partners.

2.2 Deployment summary

The MADE field trial involved five homes, each of which had all four low-carbon assets. Table 2.1 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 Motion 32A	Nissan Leaf 40kWh
4	9 kW Samsung ASHP	LPG system boiler	3.78kWp	Sonnen hybrid 5kWh	New Motion 32A	Tesla Model 3 75kWh
5	9 kW Samsung ASHP	Oil system boiler	4.41kWp	Sonnen hybrid 5kWh	Alfen 32A	Nissan Leaf 40kWh

Table 2.1 - 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, so domestic hot water production does not enter this report.

- **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 simulations, as shown in Table 2.2. This will aid validation of Everoze's modelling work performed under MADE using the field trial results.

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

Table 2.2 - Mapping field trial homes to customer types using in MADE modelling

2.3 Field trial design

The field trial was divided up into four phases, as outlined in Figure 2.1 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 synchronizing 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.

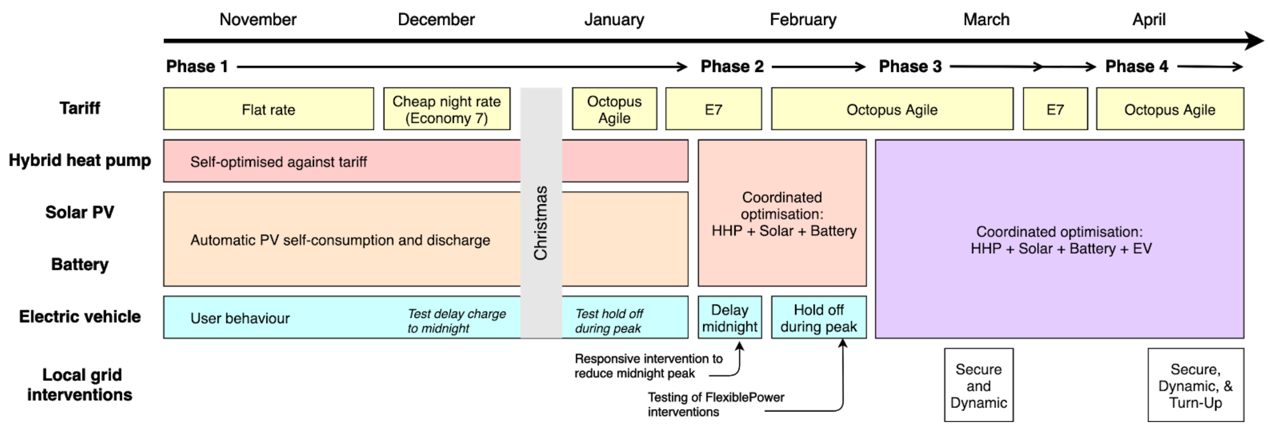

Figure 2.1 - Field trial plan overview

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 thus some of the key examples of fully coordination control were conducted slightly later in the year resulting in lower heating demand than originally anticipated.

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

- **Time of use 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 as a baseline, (b) cheap night-time tariffs like Economy 7 and (c) the Octopus Agile, 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.

2.4 Control overview

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

- Householders have 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. This takes into account many factors, including:

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

- 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

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 later in the report).

2.5 Report overview

This report is structured as follows:

- **Section 3 (Field Trial Results)** presents detailed results from the field trial, focusing on specific real world examples of asset behaviour. Typically we present one to two-day samples from individual homes, and also where possible an aggregated view of the combined behaviour of all five homes. These examples cover all four phases of the project, as the amount of asset coordination increases, and the season changes from winter to summer. In each of these phases we contrast the effect of different tariff patterns, focusing mainly on a market-based tariff (Octopus Agile) and a cheap overnight tariff (Octopus Go). In addition we cover the consequences of applying interventions on top of these scenarios, (a) demonstrating how the demand peaks introduced by the tariff patterns can be reduced, and (b) demonstrating the effect of the current WPD Flexible Power service.

- **Section 4 (Simulation results)** presents results from supplementary simulation work which was carried out to allow illustration of a more direct comparison between different control strategies, without the effects of uncontrollable variability which the real world introduces. These simulations provide quantitative (if still anecdotal) examples of the cost benefits of asset coordination and the impact of interventions.

- **Section 5 (How coordination affects the demand profile)** addresses the key research questions which the MADE project originally set out to answer, drawing out and pulling together the themes from the previous sections.

- **Section 6 (Field trial findings)** describes a wide range of findings that we discovered during the MADE field trial.

- **Section 7 (Summary)** summarises the conclusions of the field trial and provides some recommendations following the trial.

2.6 Glossary of terms

This section defines key terms used during this report:

Term:	Definition:
(Low carbon) Asset	In this project refers to: (hybrid) heat pump, solar PV panels, battery or EV.
Baseload	During this report, baseload refers to electrical demand within a home which cannot be controlled (i.e. electrical appliances such as kettles, electronics, fridges), as opposed to the MADE assets which are controllable.
Battery	Domestic battery used to store electrical energy within the home and discharge later. ● Sonnen batteries were used during the MADE field trial.
● *Automatic* (Sonnen control mode)	Default mode of operation of a Sonnen battery where the battery charges when there is excess solar and discharges when there is net demand from the home.
● *Manual* (Sonnen control mode)	The Sonnen battery can be overridden to "manual mode" by a third party control system (in this case Passiv) where it is instructed to charge or discharge at a specified rate (power). During MADE a hybrid battery/solar system was used and the manual charge and discharge rates corresponded to requested power at the inverter.
Controllable load	Combination of low carbon assets whose net demand is controlled by the smart control system. This changed through the project as more assets were coordinated: (1) heat pump + solar (2) + battery (3) +EV
EV	Electric vehicle. Within MADE there is no direct communication link with the EV, and charging is controlled via the EV charge point.
EV charge point	Physical power supply for charging an electric vehicle installed at a domestic property, typically a wall box with a connection for a charging cable. Within MADE these are internet connected and can be influenced remotely to reduce charging rate.

	• NewMotion and Alfen EV charge points were used during the MADE field trial.
Flexible Power	Flexible Power is a proposition created by Western Power Distribution (WPD) in order to deliver the procurement of demand response services.
• *Dynamic*	Flexible Power service 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.
• *Secure*	Flexible Power service designed to manage peak demand on the network and preemptively reduce network loading. Firm commitments to reduce demand are agreed a week ahead.
Hybrid Heat Pump (HHP)	An electrically powered heat pump which together with a fossil-fuel boiler provides all of the house's heating and hot water needs.
Octopus Agile Tariff	An electricity tariff with half-hourly varying energy prices, calculated from wholesale prices and the peak early-evening DUoS charges[1], and updated daily (day-ahead prices published the evening before). The project has no particular connection with Octopus but this tariff captures the major national-scale and distribution-scale drivers.
Octopus Go Tariff	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. The project has no particular connection with Octopus but this tariff provides a good real example of overnight cheap rates and is highly relevant for EV owners.
Solar PV	Solar photovoltaic panels
Whole home power import	Net grid position of the home (positive = import, negative = export)

Table 2.3- Glossary of terms used in this report

[1] https://octopus.energy/blog/agile-pricing-explained/

3 FIELD TRIAL RESULTS

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.

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.

The results presented in this section are structured as follows:

- Phase 1: Baseline operation (see Section 3.1);
- Phase 2: Asset coordination - Hybrid heat pump, battery and solar (see Section 3.2);
- Phase 3: Full coordination including EV (see Section 3.3);
- Phase 4: Summertime (see Section 3.4);
- Interventions (see Section 3.5);
- Trial participant feedback (see Section 3.6);

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 time-of-use 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).

3.1 Phase 1: Baseline operation

Phase 1 of the trial focussed 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. 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, with as much as possible of the heat demand provided by the heat pump. This is in line with the baseline case considered in the Domestic Level Techno-economic Modelling performed by Everoze under MADE[2].

- **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 other household demand, and operation is purely instantaneous (based on the grid import vs export position) without any foresight or planning (which is a fairly optimal operation mode in the absence of time-varying tariffs or grid constraints). This battery behaviour mode is in line with the baseline case considered in the Domestic Level Techno-economic Modelling performed by Everoze under MADE.

- **EV:** During this phase, no EV optimisation was performed. The charge point was used as and when the householder decided to charge. This allowed insight to be gained into typical plug in times. (Note that EV charge points do not generally offer tariff optimisation off-the-shelf.)

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

- **Flat Tariff:** Flat rate of 14p/kWh.

- **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.

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.

[2] MADE: Modelling Results, Everoze, October 2019, Doc No: PASSIV001-S-02

3.1.1 Flat tariff

Phase 1 commenced with homes on a flat tariff, with an electricity price of 14p/kWh. Figure 3.1 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, which as outlined above is being controlled by Sonnen's "automatic" control algorithm, 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.

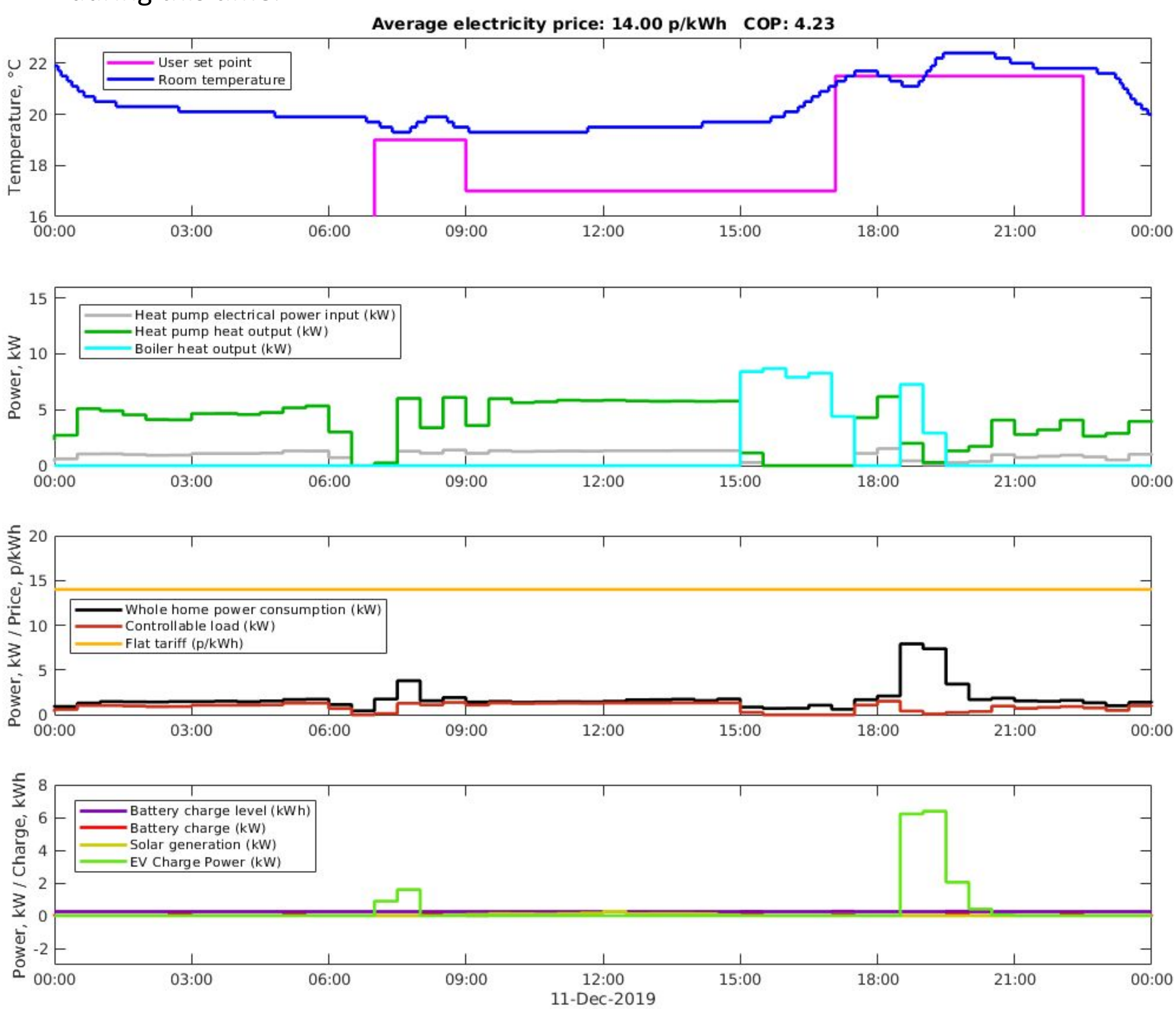

Figure 3.1 - Baseline operation on flat tariff *(Home 5, 11/12/2019).*

Figure 3.2 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.

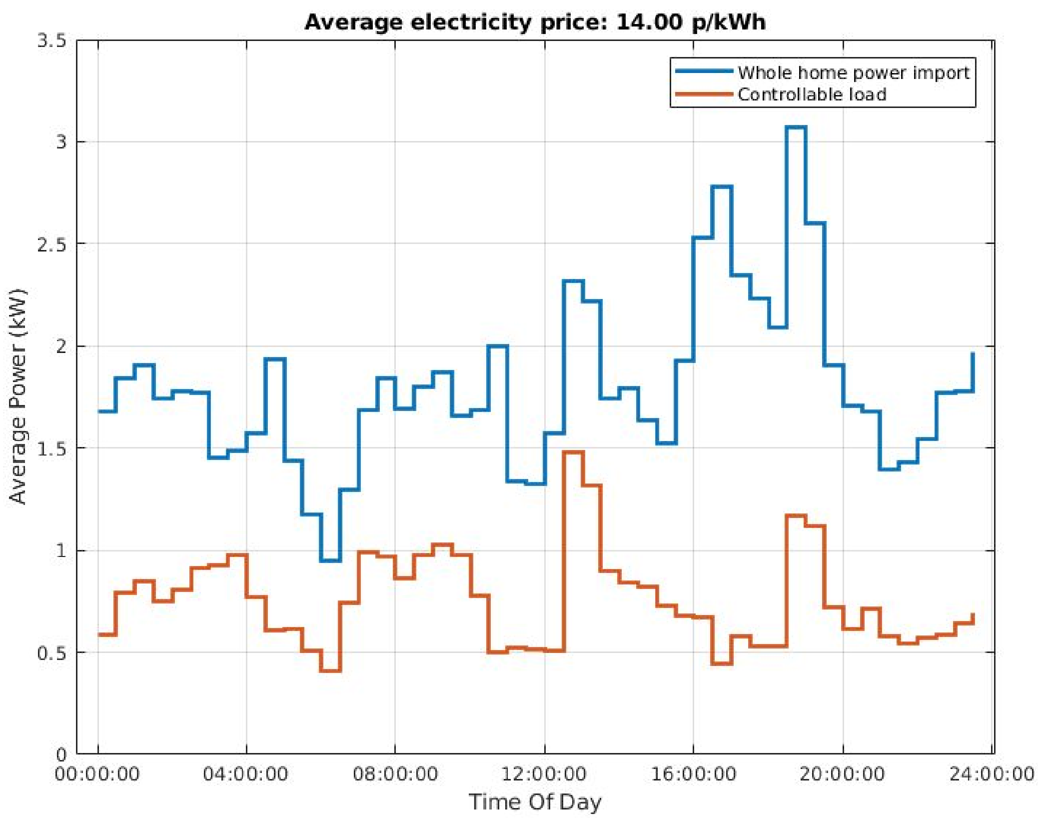

Figure 3.2 - Average load profiles for baseline operation on flat tariff *(All homes, 09/12/2019 - 15/12/2019)*. Controllable load is just the heat pump in this case. Whole home power import = import from (/export to) the grid.

3.1.2 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 3.3 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 with the PV generation being less than the household consumption, 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, where baseload is considered to be load which is not from any of the MADE energy assets. 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

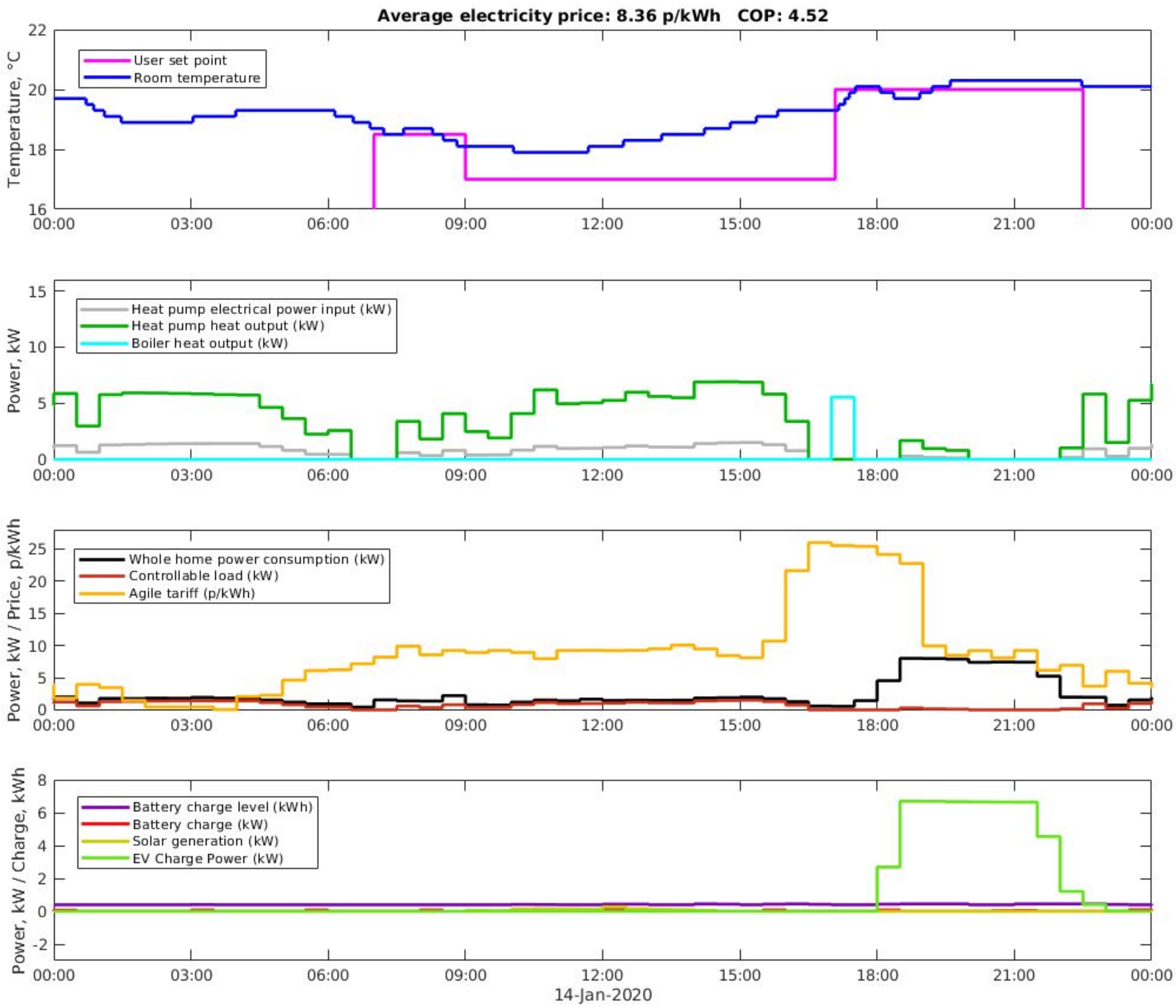

Figure 3.3 - Baseline operation on Octopus Agile tariff ***(Home 5, 14/01/2020)***

Figure 3.4 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, which during this phase of the project consisted of heat pump load only, has been reduced during the evening peak peak period (c.f. Figure 3.2 for behaviour on a flat tariff), in line with the particular example shown in Figure 3.3. 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 3.2 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%.

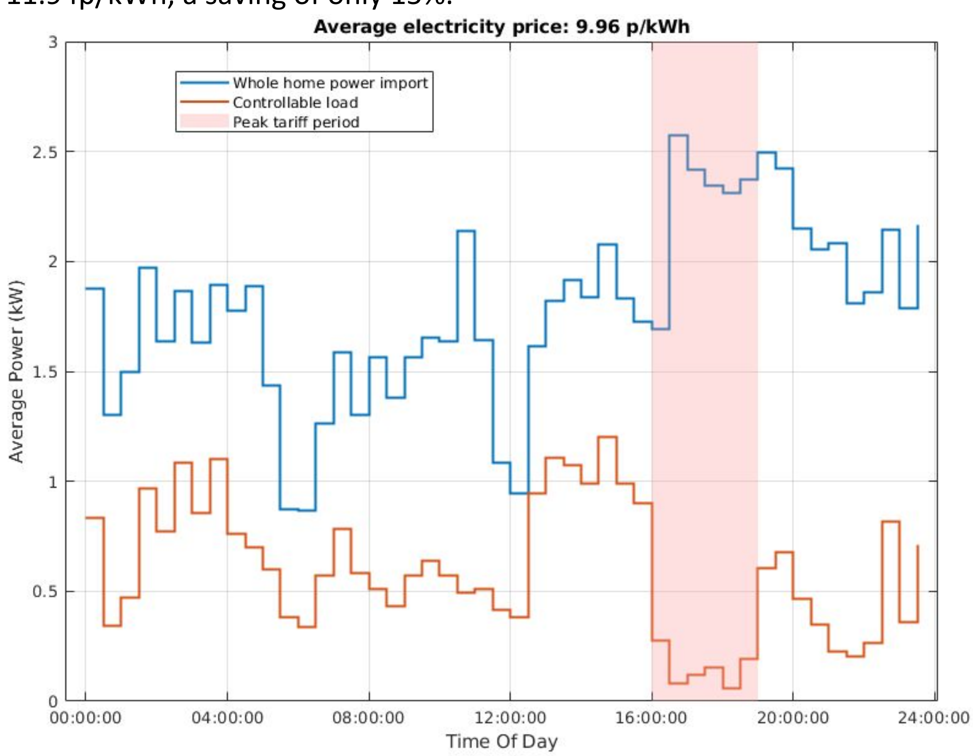

Figure 3.4 - Average load profiles for baseline operation on Octopus Agile tariff *(All homes, 10/01/2020 - 16/01/2020)*. Controllable load is just the heat pump in this phase. Whole home power import = import from (/export to) the grid.

3.1.3 Electric vehicle control

During the baseline phase of the MADE field trial, there was no control strategy implemented on the EV charging: the vehicles simply charged as soon as the user plugged them in. Figure 3.5 shows the average EV charge power across the day for the MADE homes. It can be observed from this figure that the EV's in this field trial were most commonly charging over the early evening peak. This is in line with findings from previous projects such as Electric Nation, and illustrates a significant opportunity for householder cost-savings and network peak-reduction by automatically delaying these charges.

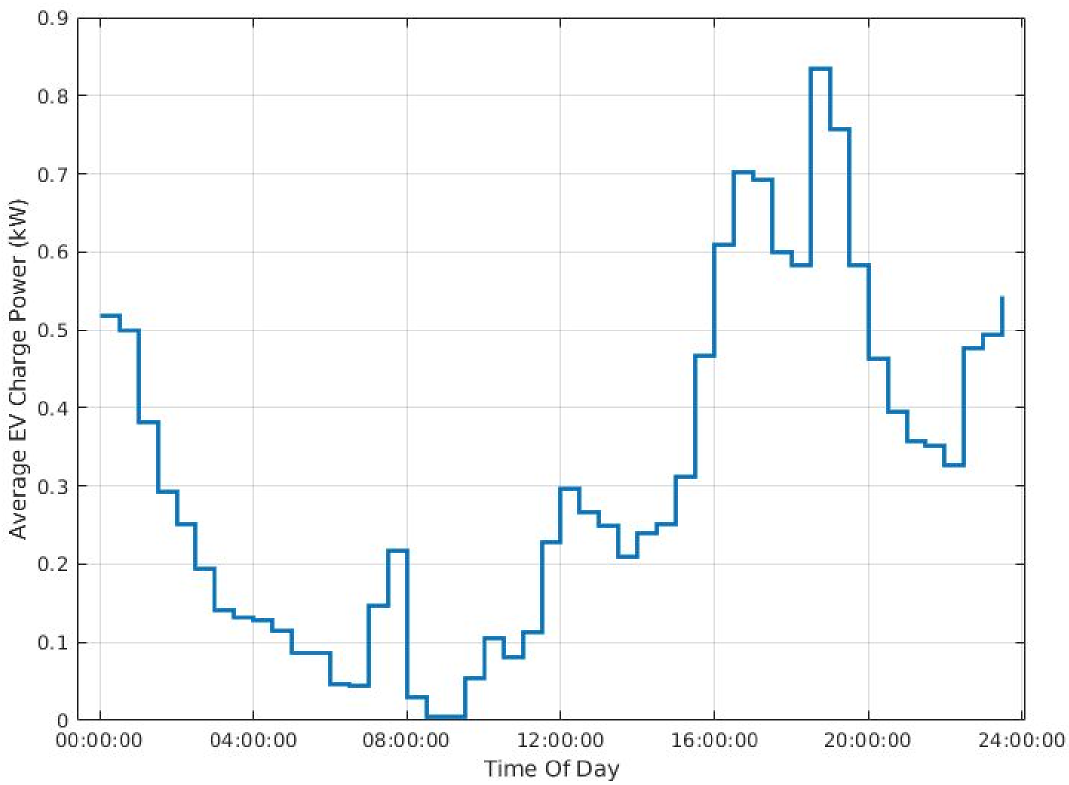

Figure 3.5 - Average EV charge power across the day for the MADE homes *(Homes 2,3,4 & 5, 01/12/2019 - 15/01/2020. Note that Home 1 was not included in this analysis since the charge point was installed at a later date.)*

3.2 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. 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:** controlled via a combination of Passiv's battery control algorithm and Sonnen's internal "automatic" control algorithm, with Passiv's 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. (Note that EV charge points do not generally offer tariff optimisation off-the-shelf.)

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

- **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.
- **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.

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)**.

3.2.1 Octopus Go tariff

Figure 3.6 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, and 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).

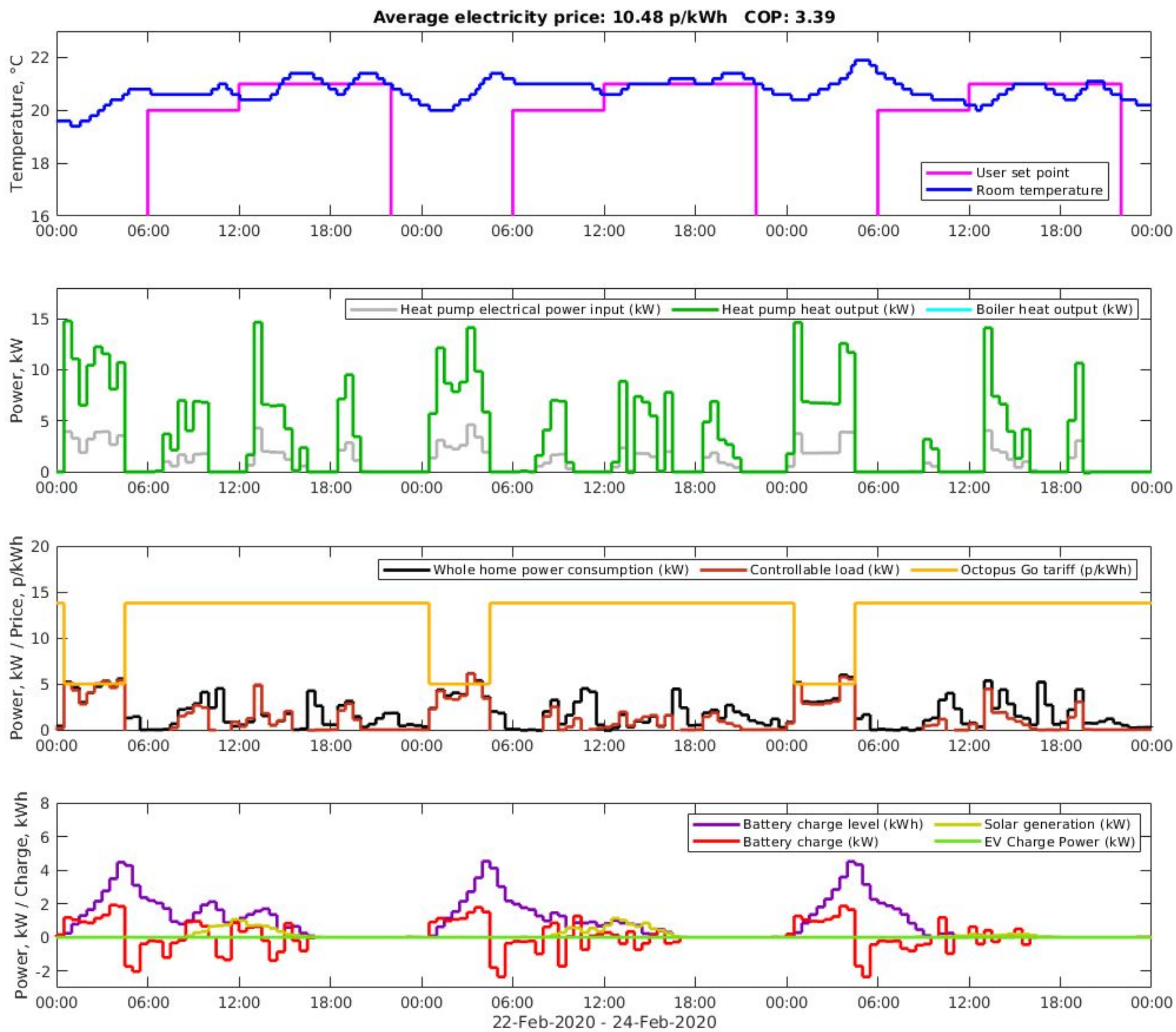

Figure 3.6 - Coordinated control on the Octopus Go tariff *(Home 03, 22/02/2020 - 24/02/2020)*

Figure 3.7 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 3.6, electricity demand is notably highest during the cheap period between 00:30 and 04:30 on the Octopus Go tariff. This is driven by a high controllable load during this period, with both the heat pump and battery taking advantage of the cheap electricity price.
- The average controllable load, which during this phase of the project consists of heat pump and battery 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).

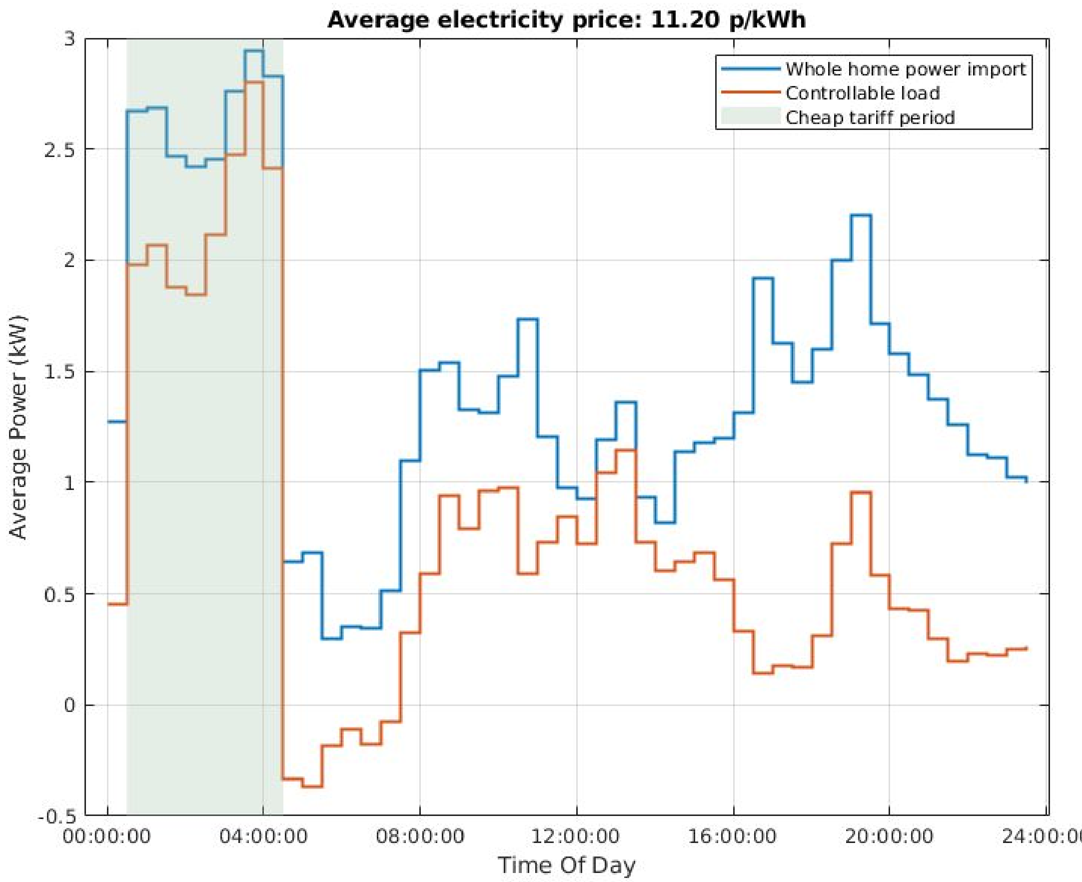

Figure 3.7 - Average load profiles for phase 2 operation on Octopus Go tariff *(All homes, 18/02/2020 - 27/02/2020, note that three days worth of data were excluded from this range due to interventions which significantly affected the demand profile).* Controllable load is the combination of heat pump and battery in this case. Whole home power import = import from (/export to) the grid.

3.2.2 Agile tariff

Figure 3.8 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 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.

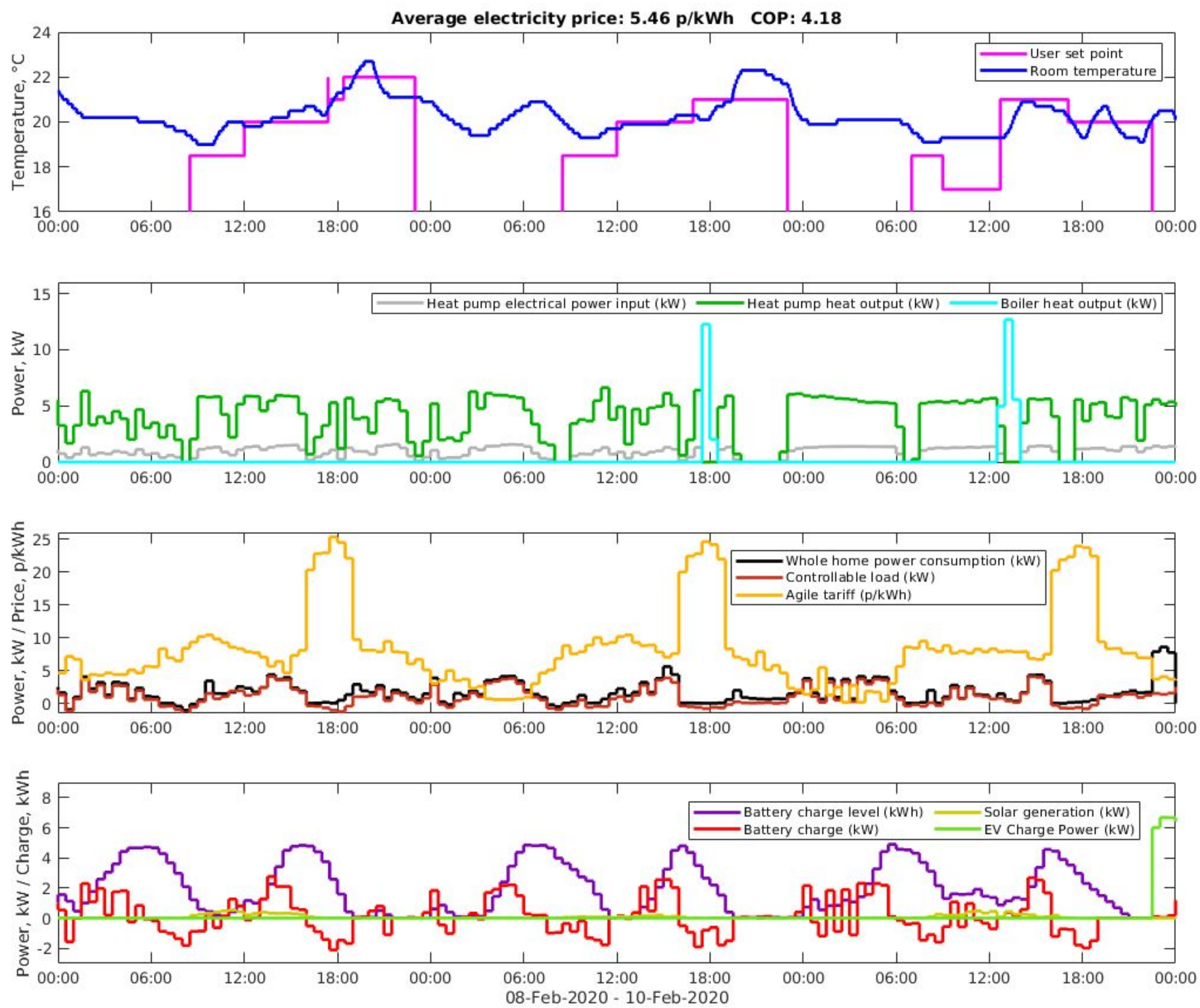

Figure 3.8 - Coordinated control on the Octopus Agile tariff *(Home 05, 08/02/2020 - 10/02/2020)*

Figure 3.9 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 (heat pump plus battery) 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 9 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 tarif period. Again, this is in line with the example shown in Figure 3.8.
- 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.

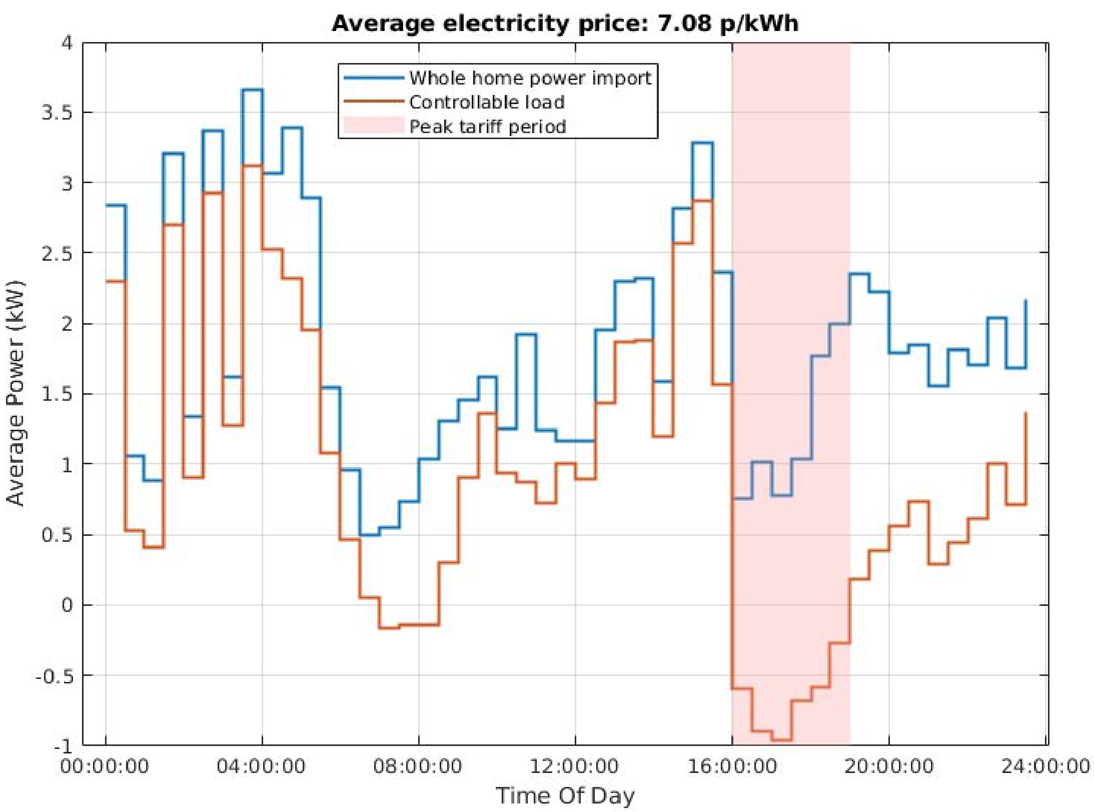

Figure 3.9 - Average load profiles for phase 2 operation on Octopus Agile tariff *(All homes, 07/02/2020 - 13/02/2020).* Controllable load is the combination of heat pump and battery in this case. Whole home power import = import from (/export to) the grid.

3.2.3 Electric vehicle control

Before fully integrating the EV in the coordinated control strategy (Phase 3), individual experiments were carried out to test EV charger control and demonstrate the impact of delayed charges during Phase 2 of the trial. Here EV charging was delayed in order to align charging with cheap tariff periods.

Figure 3.10 demonstrates EV charging being controlled against the Octopus Go tariff. The householder plugged in their EV at 21:00, and at 21:30 a request was sent to the EV chargepoint to delay charging until the Octopus Go tariff became cheap at 00:30. The bulk of the charging thus took place during this cheap period, with a saving of £1.29 achieved compared to if no intervention had been applied. The length of time between plug in and the command to restrict charging would in practice tend to be much shorter than the half an hour demonstrated here, however this scenario allows for clear indication of plug in time and the period over which EV charge is being constrained to be displayed on the graph .

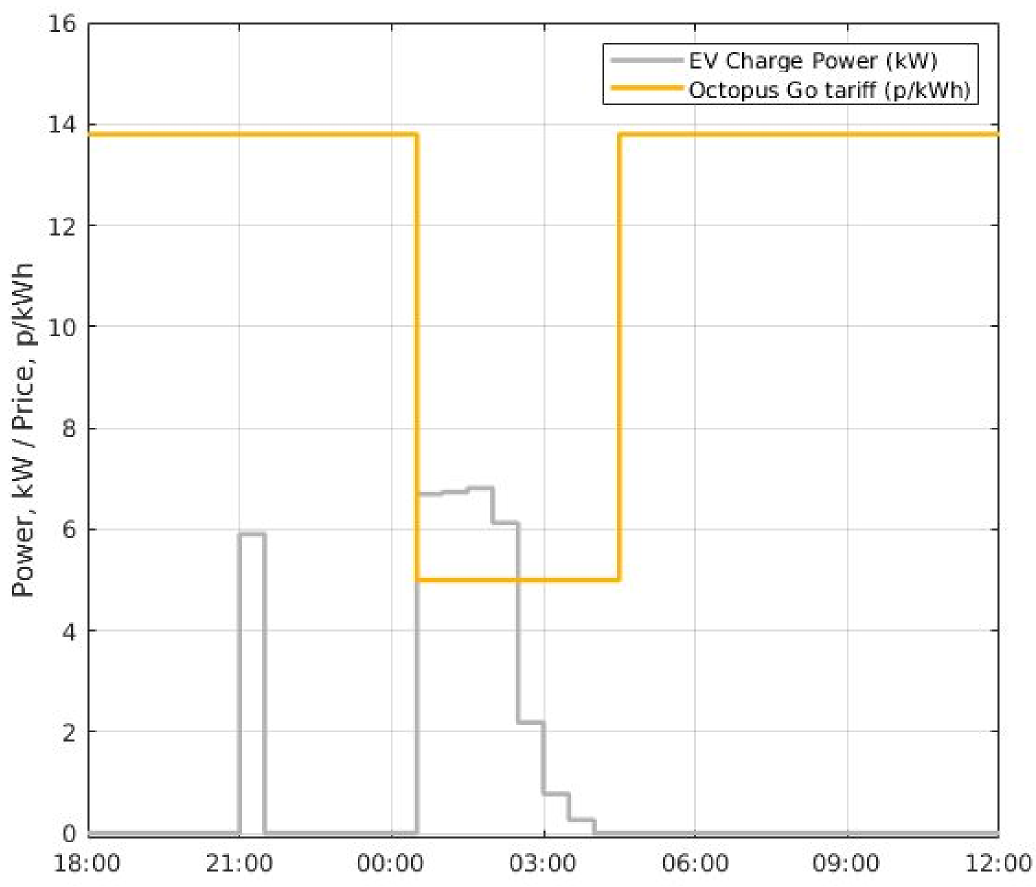

Figure 3.10 - Delayed EV charging on Octopus Go tariff *(Home 3)*

Figure 3.11 demonstrates EV charging being controlled against the Octopus Agile tariff. Charging is constrained over the peak agile tariff period, and the electric vehicle resumes charging at full power at 19:00, once the peak tariff period has passed. This results in a total saving of £2.79 compared to if no intervention had been applied.

- It is apparent that the EV charge power has not been restricted to zero during the peak period. One key project finding from MADE has been the discovery that Tesla EVs enter a "sleep mode" if charging is entirely restricted and subsequently stop responding to any further chargepoint power increases, thus charging can never be resumed. We discovered that the minimum value to which Tesla charging can be reliably restricted was 6A (~1.4kW), which is the charge rate maintained in Figure 3.11.

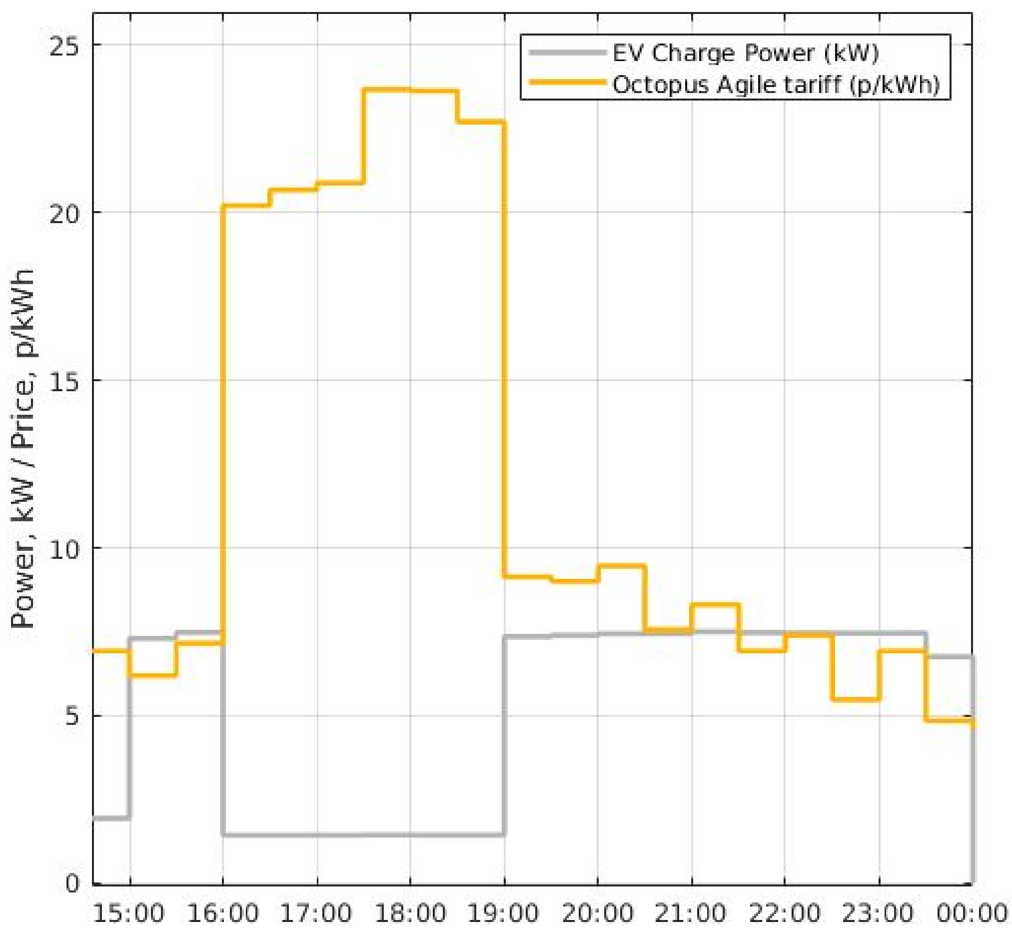

Figure 3.11 - Constraining EV charging on Octopus Agile tariff *(Home 4)*

3.3 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 3 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 Passiv's EV control algorithm, based on user information inputted via the Passiv 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:** 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.

- **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.

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**.

3.3.1 Octopus Go tariff

Figure 3.12 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 battery where available.
- Room temperature is well maintained, with a minimum of 17.7° and a maximum of 18.6° 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.

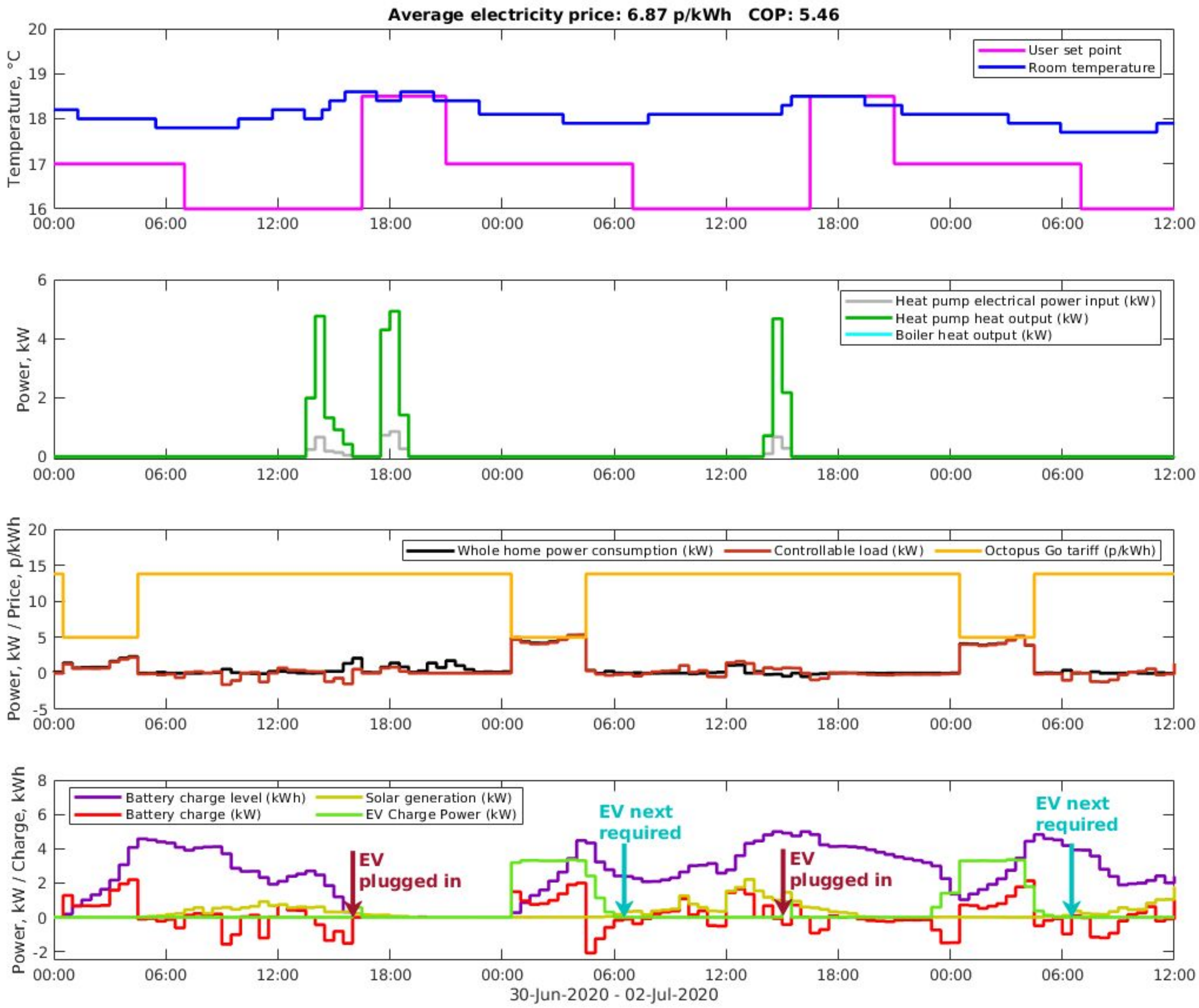

Figure 3.12 - Fully coordinated control on the Octopus Go tariff *(Home 1, 30/06/2020 - 01/07/2020)*

3.3.2 Agile tariff

Figure 3.13 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° and a maximum of 18.9° across the two day period. For reference, the average external temperature was 15.3° over this same period, with a high of 19.0° and a low of 13.3°.
    - 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. This demonstrates an advantage of coordination between the EV and the battery.
    - 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.

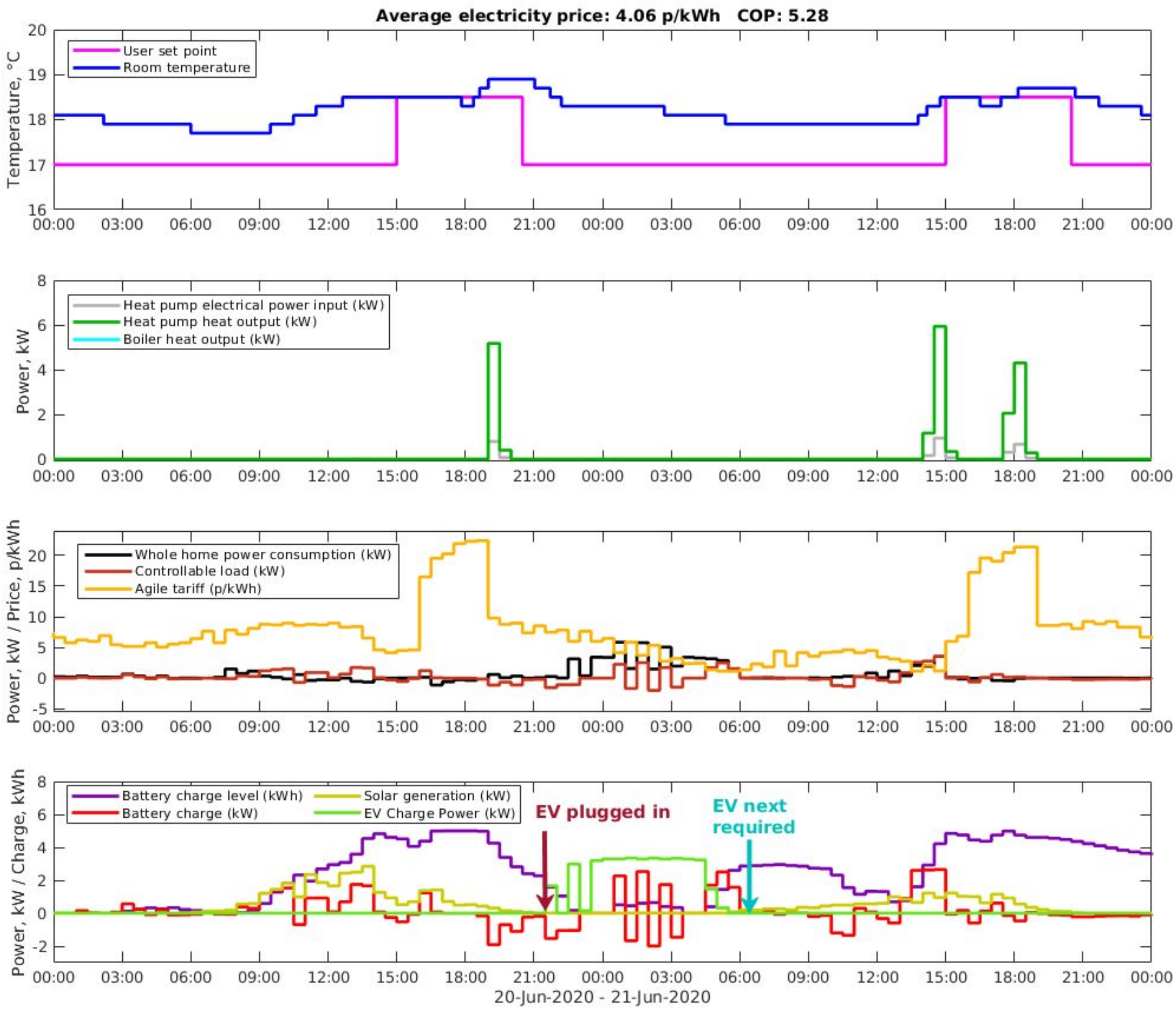

Figure 3.13 - Fully coordinated control on the Octopus Agile tariff *(Home 01, 20/06/2020 - 21/06/2020)*

Figure 3.14 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.

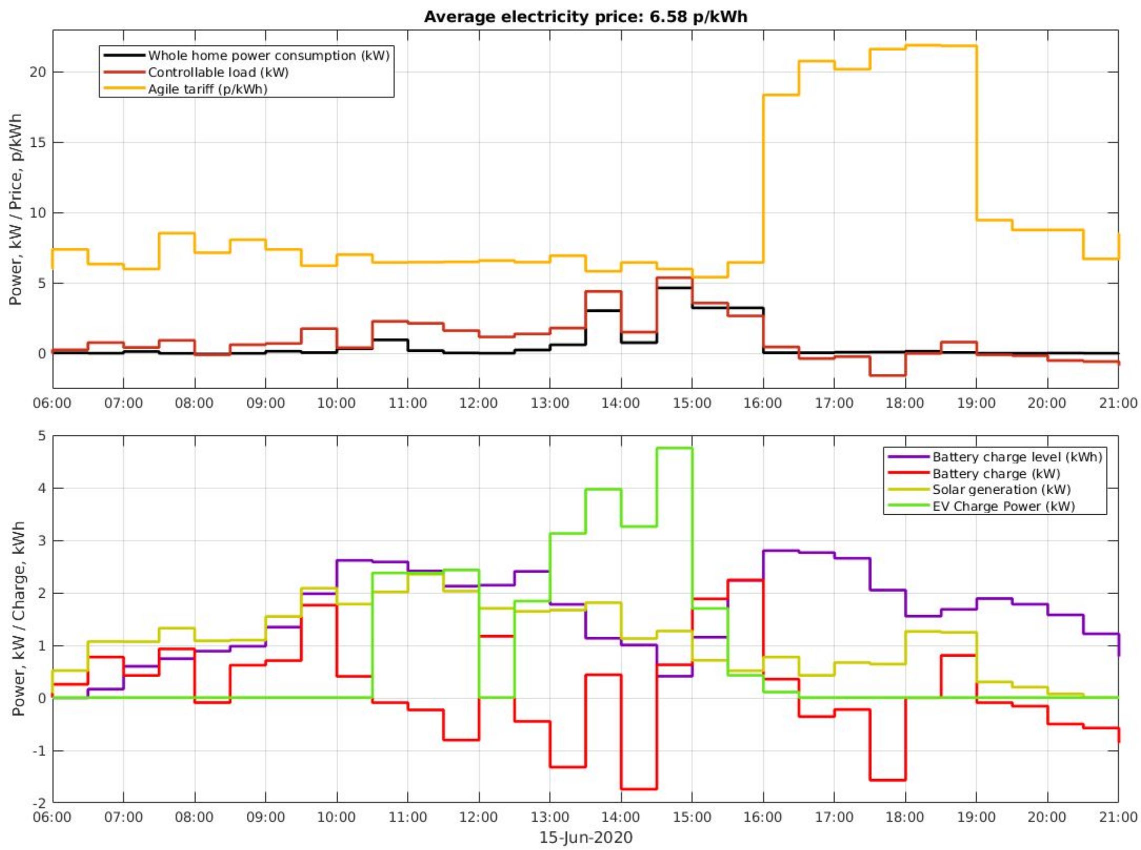

Figure 3.14 - EV, Solar and Battery Coordination *(Home 05, 15/06/2020)*

3.4 Phase 4: Summertime

Phase 4 of the trial involved 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 Octopus Agile (dynamic wholesale plus peak) tariff and the Octopus Go (cheap overnight) tariffs (c.f. Glossary in Section 2.5).

This section of the report provides examples which illustrate typical summer time 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. Section 3.4.3 discusses this issue further and describes the measures that were put in place to successfully mitigate the overheating issue.

- Note this issue did also occur in winter and spring, in previous phases of the field trial, but we discuss it in detail in this section as the effects are more pronounced and noticeable by trialists in summer time.
- Note we use the term "overheating" to specifically mean that caused by deliberate running of the heat pump for financial gain etc., rather than its more common meaning of homes being warmer than desired due to summertime solar gains without heating running (although of course there is an overlap as solar gains give less room for heat pump running).

3.4.1 Agile tariff

Figure 3.15 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 (observed previously) to one cycle a day, as the system recognises that free solar is advantageous over cheap night time electricity rates.
    - As discussed in Section 3.2.2, during Phase 2 of the project under the Octopus Agile tariff the battery typically exhibited two cycles per day; charging overnight when electricity was typically very cheap in order to meet morning demand, and charging in advance of the peak Agile tariff period in order to minimise import over this period. Under summertime conditions, it can be seen from Figure 3.15 that the battery has moved to one cycle per day. This cycle involves charging

during the day from excess solar and then discharging over the course of the evening, keeping the home virtually off grid during this time.

- ○ The change in cycle pattern is driven largely by two factors. The first is that the control algorithm can recognize 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 (or indeed other electrical demand to discharge the battery), thus the battery is not required to harness cheap overnight electricity in order to prevent import required for heating once the tariff becomes more expensive. 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:
  - Day 1: 79%
  - Day 2: 90%
  - Day 3: 95%

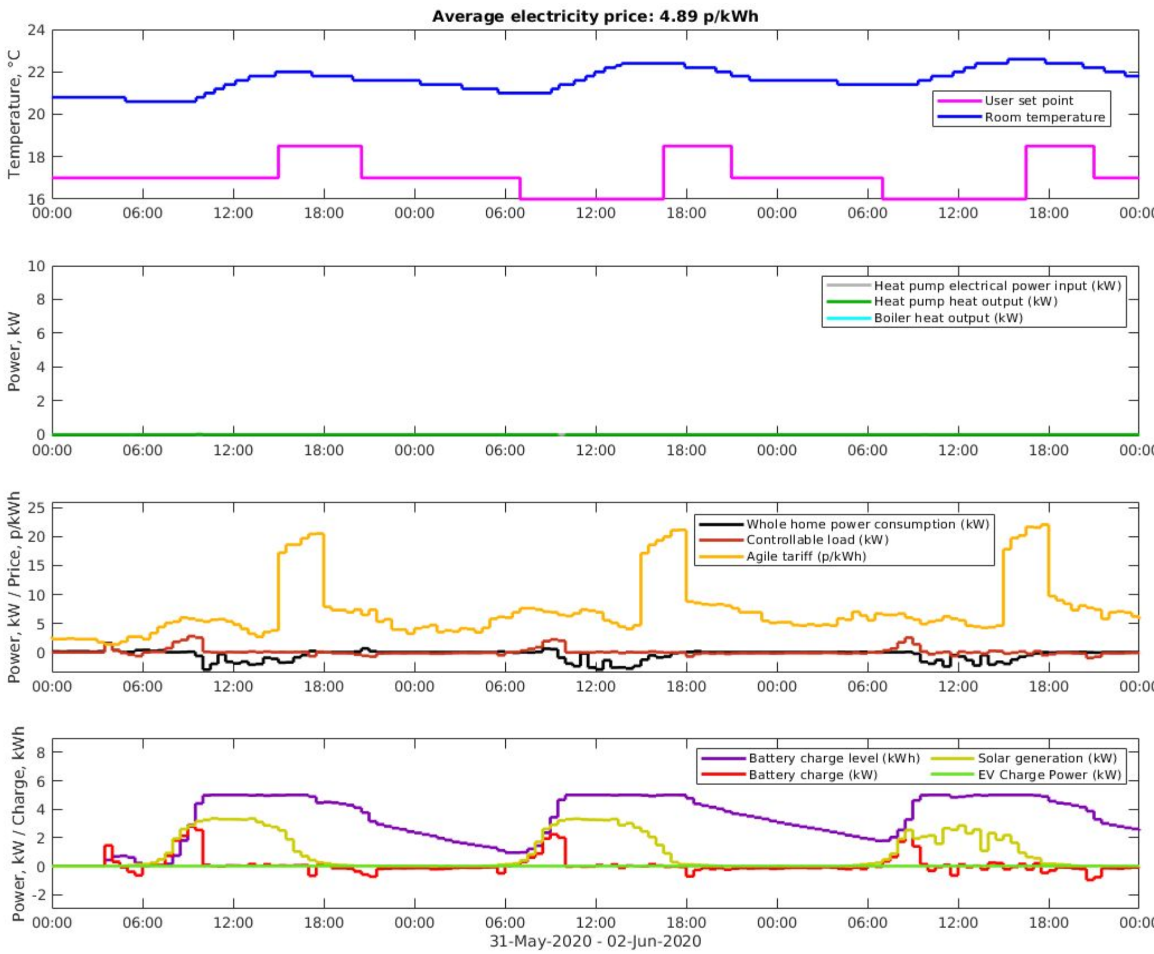

Figure 3.15 - Summertime operation on Octopus Agile tariff *(Home 1, 31/05/20 - 02/06/20)*

Figure 3.16 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 (Home 2) 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 (See Section 3.2.2).
- Whole home power import remains low (or negative) throughout the day.

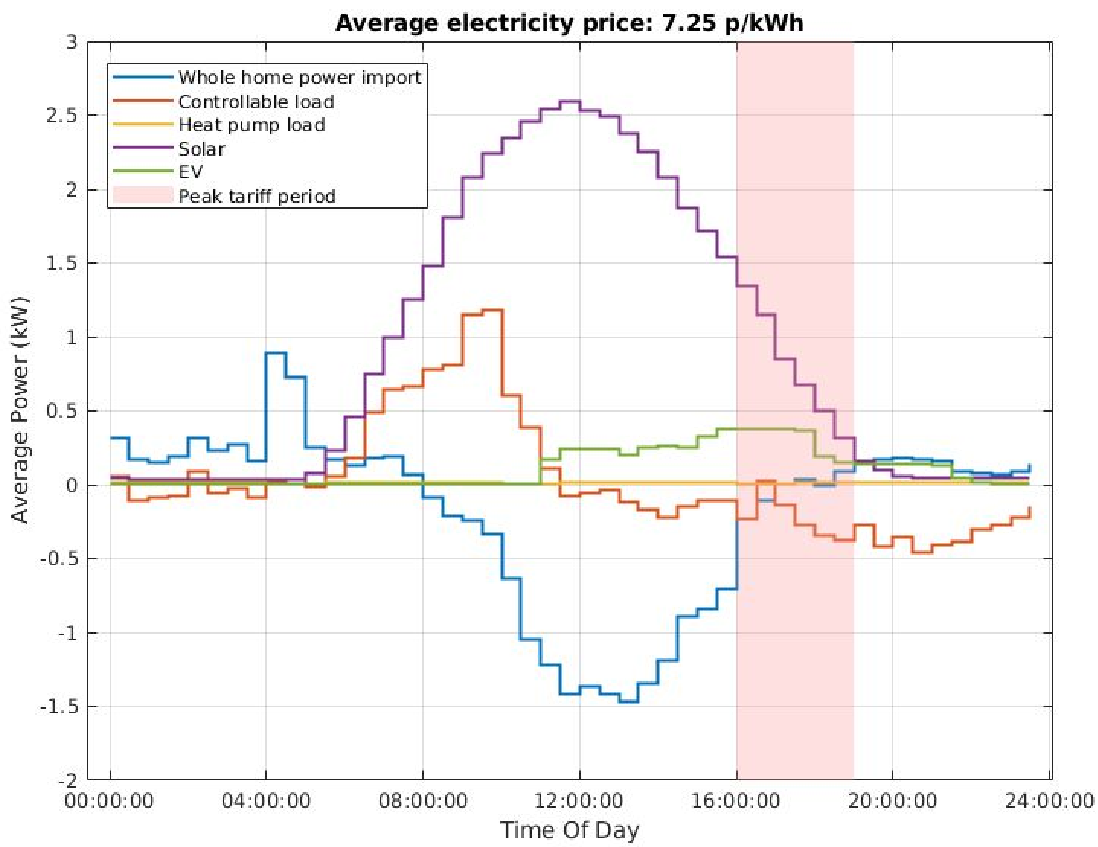

Figure 3.16 - Average load profiles for summertime operation on Octopus Agile tariff *(All homes, 25/05/2020 - 01/06/2020).* Controllable load refers to heat pump plus domestic battery plus EV charge. Whole home power import = import from (/export to) the grid.

3.4.2 Octopus Go tariff

Figure 3.17 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.

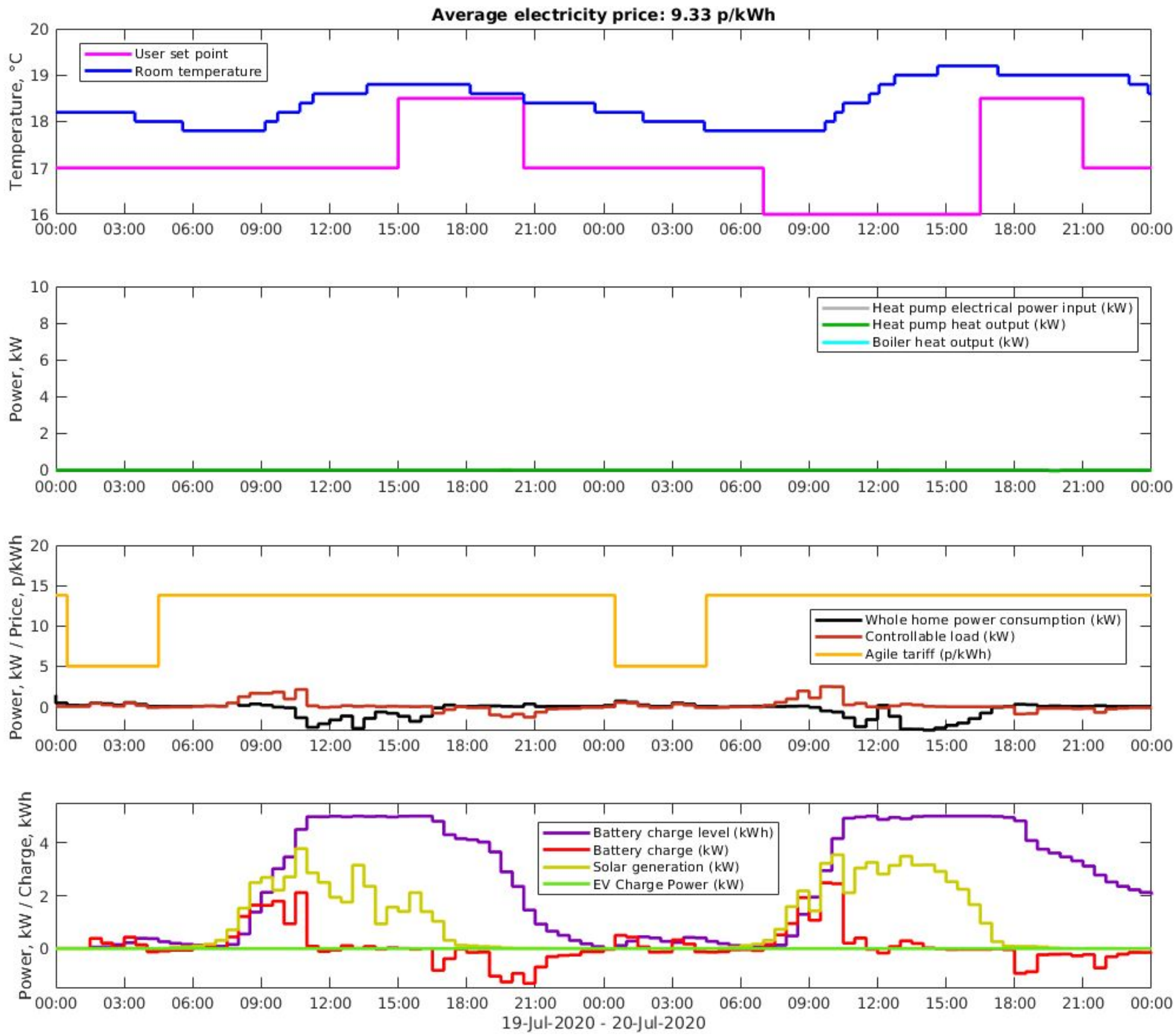

Figure 3.17 - Summertime operation on Octopus Go tariff *(Home 1, 19/07/20 - 20/07/20)*

Figure 3.18 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.

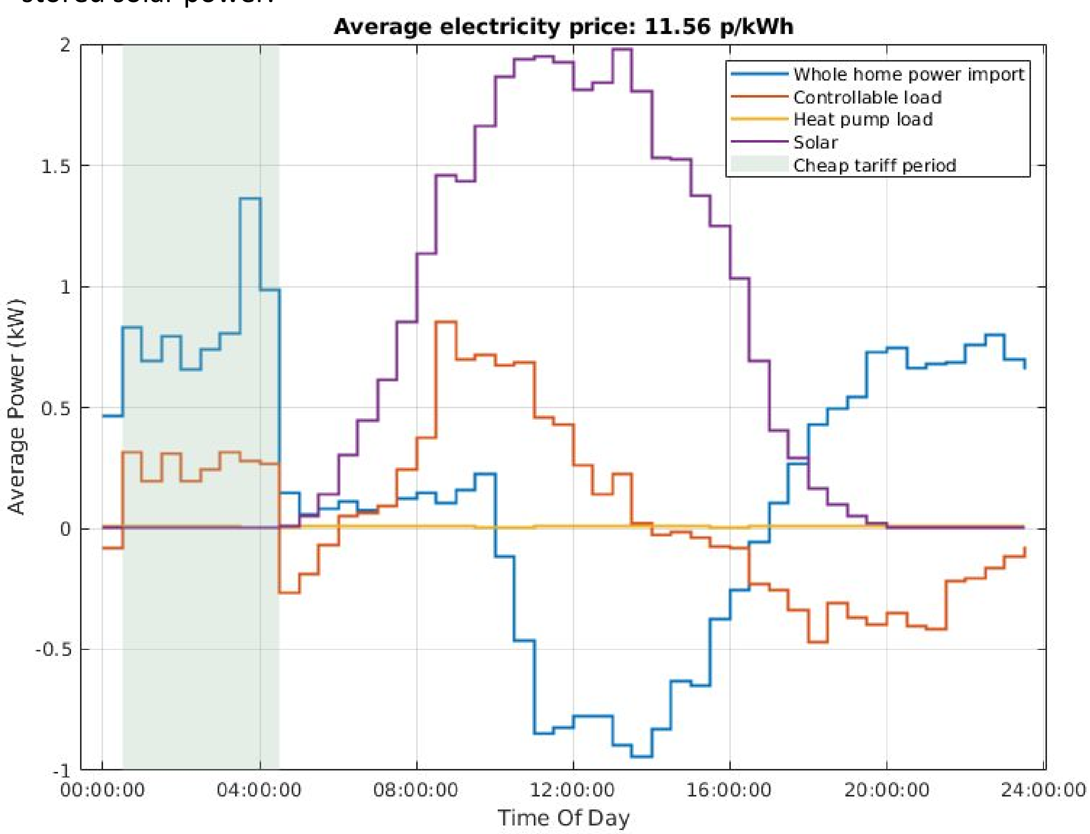

Figure 3.18 - Average load profiles for summertime operation on Octopus Go tariff *(All homes, 17/07/2020 - 23/07/2020).* Controllable load refers to heat pump plus domestic battery plus EV charge. Whole home power import = import from (/export to) the grid.

3.4.3 Managing overheating

During periods of high excess solar or negative Agile tariff periods, the control system would at times deliberately heat the home more than required. This overheating made sense from a cost perspective because:

- Overheating using excess solar, which is effectively free electricity for the householder, can avoid the need to heat the home later on via electricity imported from the grid which would incur a cost.
- Running the heat pump during a negative Agile tariff price period results in the householder being paid to consume electricity.

Initial feedback from MADE trialists indicated that they would not want this unlimited overheating to occur, even if it was to their financial advantage, because of their homes being uncomfortably warm. Nevertheless, there was some flexibility in their thermal comfort so that some amount of overheating was acceptable.

As a consequence “comfort limits” were applied within the heating control system which typically imposed an overheating limit of 2°C above their usual heating setpoint. This was found to be sufficient to keep the occupants comfortable and also afforded a good buffer for demand flexibility.

Figure 3.19 below demonstrates how overheating can be controlled using an upper comfort limit.

- On day one on the figure there was no temperature limit in place. It can be seen that on this day the heat pump runs hard during a period with high solar generation, and as a consequence the home reaches 23.3°C. Whilst this occurs during a period when the occupant’s schedule indicated they were out of the house, they were actually at home due to the Covid-19 lockdown, and feedback was that the house was uncomfortable warm. Apart from this, it was the “right” decision by the control algorithms (free solar was utilised to hit the set point the following morning very accurately).

- On day two, a maximum temperature limit setting of 21.5°C was configured in the control system. As a result, the heat pump was not utilised, as the system predicted this limit would be reached due to solar gains alone, and later on the room temperature hit a maximum value of 21.9°C.

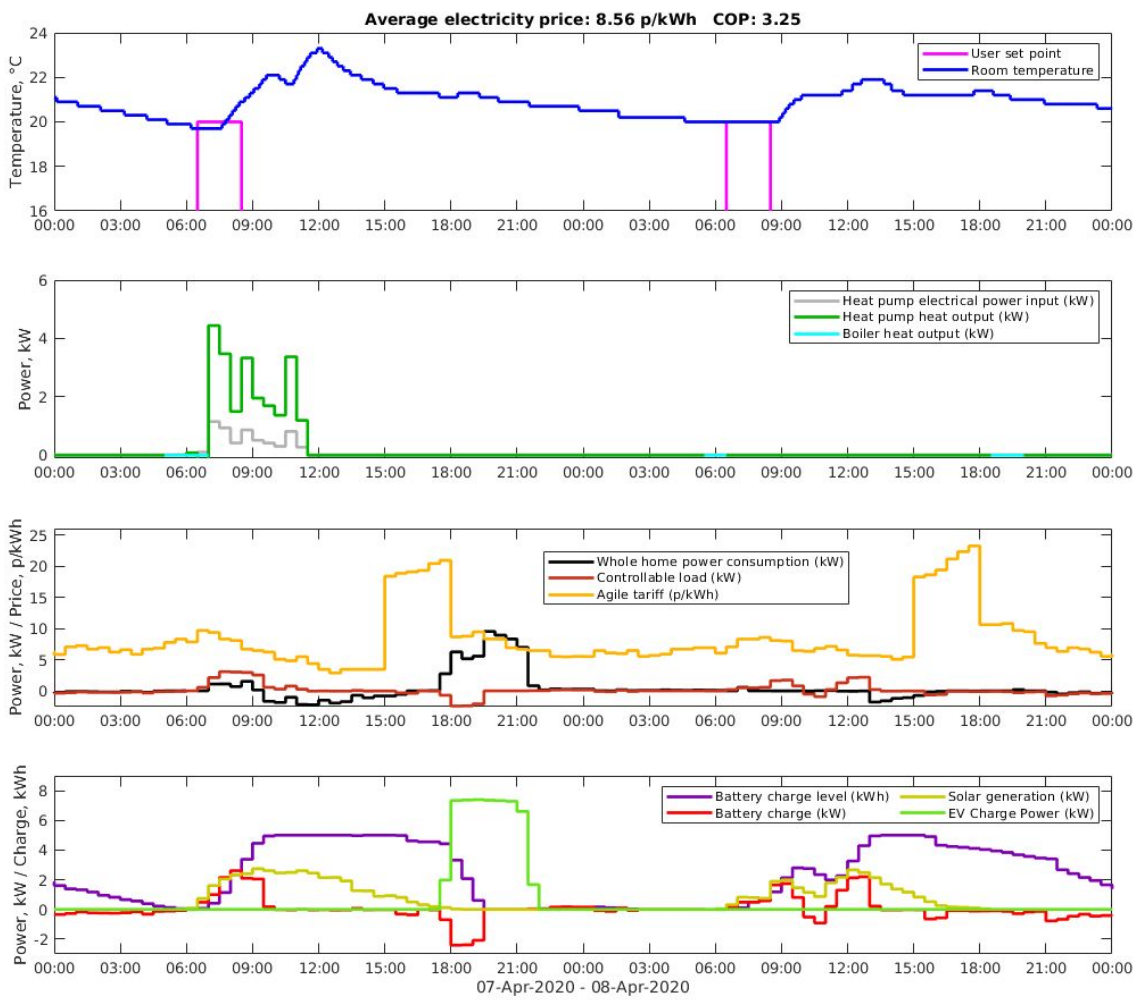

Figure 3.19 - Managing overheating via upper comfort limit *(Home 2, 07/04/2020 - 08/04/2020)*

Figure 3.20 also demonstrates how overheating can be controlled using a maximum room temperature limit.

- On day one there was no maximum room temperature limit in place, and the home is heated as high as 24.9°C driven by negative Agile pricing as well as solar gains.
- On day two, a maximum room temperature limit of 23°C is applied to the home. There is some heat pump operation as the Agile tariff becomes very slightly negative (-0.021p/kWh), however this stops once the home reaches 22.9°C.

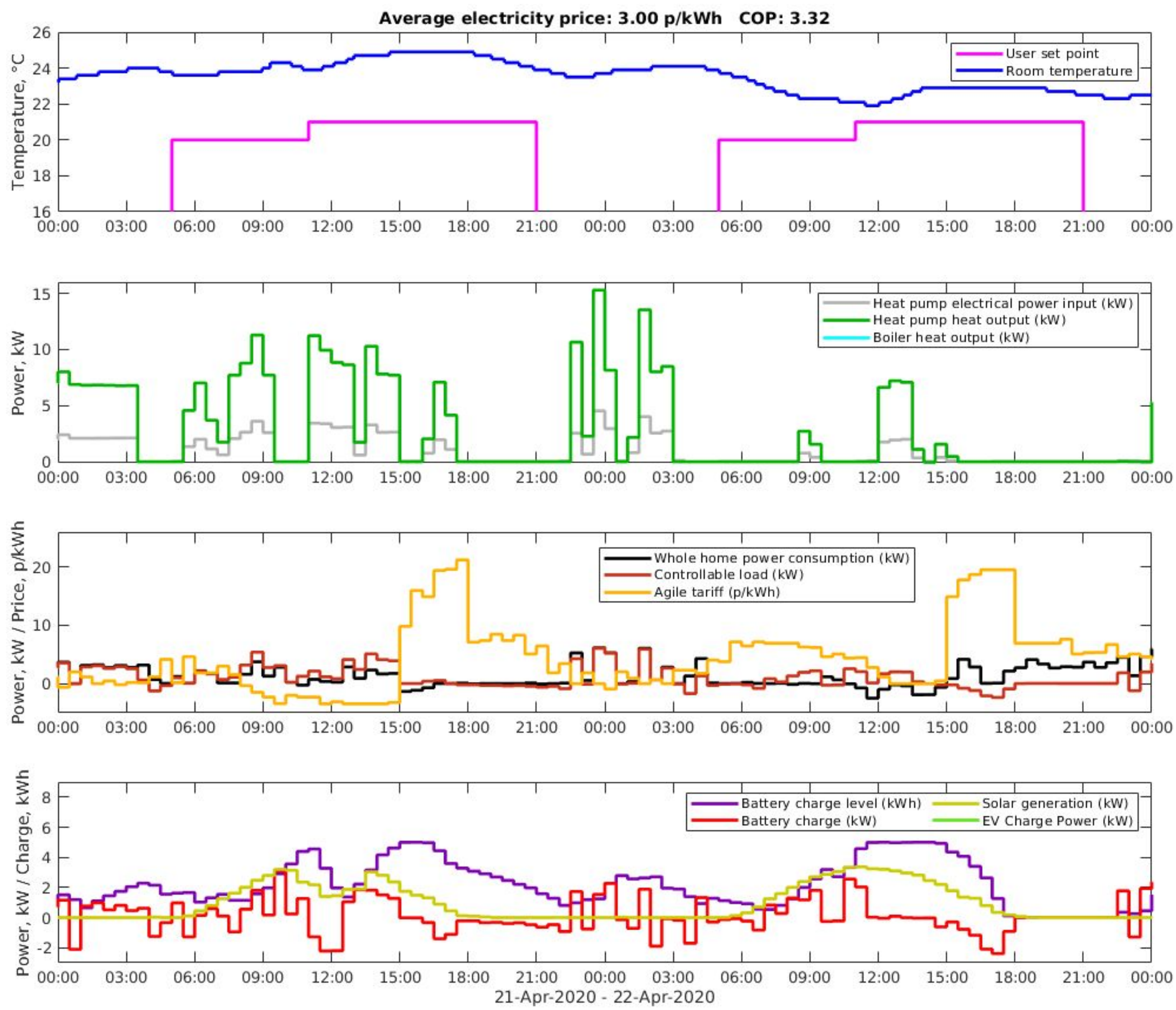

Figure 3.20 - Managing overheating via max room temperature increase limit *(Home 3, 21/04/2020 - 22/04/2020)*

3.5 Interventions

The top-level focus of the MADE project was to investigate the impact on the electricity distribution grid of multiple low-carbon assets that are coordinated within the home. However a coordination system such as that offered by PassivSystems is also able to intervene and make adjustments to the demand shape according to the needs of the network. Such interventions change the pattern of operation of assets so that it is no longer optimal for the householder, but better suited to the grid, so in practice some financial incentivisation would be needed for these interventions in future, perhaps via an aggregator.

Within the MADE project a range of interventions have been demonstrated to explore the flexibility of the system to respond to the needs of the network (beyond the baseline response represented by the ToU tariff) and illustrate how the impact of low-carbon assets on the grid can be mitigated. A typical example of these is the suppression of a demand peak: multiple assets consuming demand at the same time makes no difference to the householder, and is indeed beneficial in many cases, but is to the detriment of the grid. The aim of these interventions was to illustrate that a multi-asset system need not introduce problems to the network as long as it is controlled by a sufficiently smart system.

It should be noted that in future deployments with a larger number of homes, these interventions would be automated in aggregate as demonstrated in the FREEDOM project, but for a small number of homes as in the MADE trial it was more effective to demonstrate manual interventions on an individual home basis.

3.5.1 Reduction of ToU tariff peaks

Optimisation against time of use tariffs has the potential to introduce new peaks in demand, with multiple householders trying to take advantage of cheap electricity at the same time. This is likely to be particularly problematic when numerous energy assets are involved. This section of the report highlights some examples where additional demand peaks may be seen under different tariffs, and demonstrates how these peaks can be successfully mitigated through smart control and coordination between energy assets.

The mitigation that PassivSystems have applied to limit these demand peaks is a “maximum power limit” which is applied to the sum of the controllable loads. Fully coordinated control is particularly useful in this scenario to ensure that this maximum power limit is honoured in the most efficient way possible, prioritising which energy assets operate, and enabling the battery to offset necessary heat pump or EV load whilst still honoring the maximum power constraint.

The increase in electricity costs associated with such interventions have been considered through analysis of supporting simulation work in Section 4.4.

3.5.1.1 Octopus Agile tariff

The Octopus Agile Tariff generally has a very high electricity price during the evening peak period between 16:00 and 19:00. This has the potential to introduce a new demand peak prior to 16:00 as assets charge up in preparation for the peak price period. In detail:

- **Heat pump:** In winter the heat pump will generally heat the home in advance of the peak Agile tariff period, to ensure that comfort levels specified by the user can be met in the cheapest way possible. This will often involve heating above the set point specified by the user, storing heat energy in the fabric of the building, in order to remove any further need to heat the home during the peak tariff period as the home cools back down to setpoint.

- **Battery**: Throughout the year the battery will charge up in advance of the peak tariff period based on predicted demand over peak period. During summer, the battery is likely to charge throughout the day from excess solar and thus is not likely to contribute to a demand peak in advance of 16:00, but during winter the battery is likely to charge from the grid in the run up to 16:00. This cycle is likely to contribute to a demand peak during the Winter, particularly when combined with heat pump demand as outlined above.

- **Electric Vehicle:** If the EV is plugged in prior to the peak Agile tariff period, depending on the charging parameters specified by the user and upcoming tariff it may commence charging in advance of the peak tariff period, worsening the demand peak. It is then likely to suspend charging during the peak tariff period.

Figure 3.21 demonstrates the maximum power limit in action, during Phase 2 of the field trial with homes on the Octopus Agile tariff. On the 14th February, all five MADE homes had a maximum power limit applied between 13:30 and 16:00. Each home had a different maximum power limit applied (selected to ensure that typical use within the home was restricted but not beyond a reasonable level) and combined this gave a maximum average controllable load limit of 1.7kW between 13:30 - 16:00 on the 14th.

It can be seen from the figure that the average controllable load for all five MADE homes between 13:30 and 16:00 on this day was notably lower than surrounding days. The average controllable load on the 14th peaked at 1.6kW, compared to between 2.6kW and 3.7kW on the surrounding days. However it can also be observed that controllable load in advance of this restricted period is now higher than on any other day, demonstrating that maximum power limits should be carefully applied in order to avoid simply shifting demand peaks earlier.

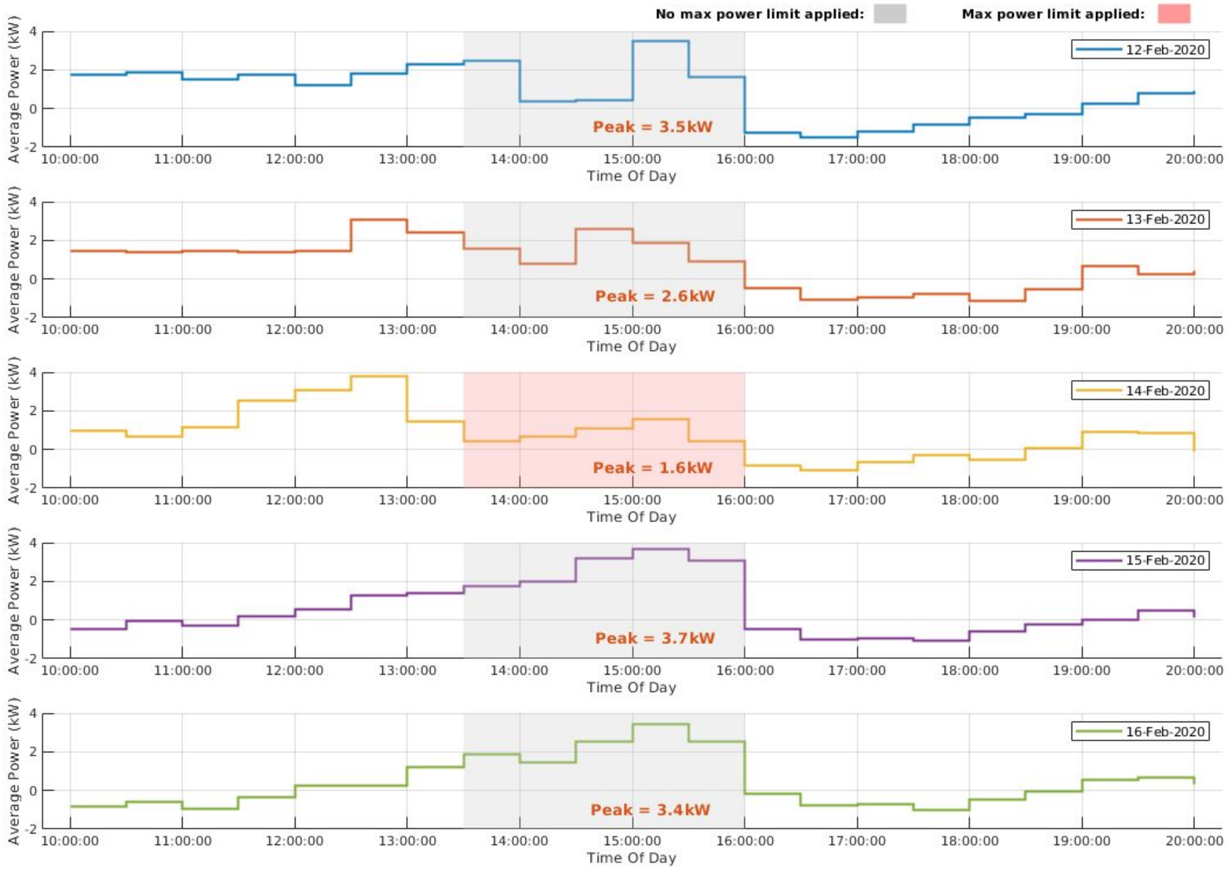

Figure 3.21 - Average controllable load (heat pump + battery load) over all MADE homes on Octopus Agile tariff *(All homes, 12/02/2020 - 16/02/2020)*

3.5.1.2 Octopus Go tariff

The Octopus Go tariff has a cheap overnight rate between 00:30 and 04:30. As seen earlier in this section, with smart controlled assets there is likely to be high demand during these four hours. This is particularly true during the winter, with the heat pump, battery and electric vehicle all taking advantage of the cheap overnight rate.

A maximum power limit can be applied to the controllable loads during this cheap overnight period. Again fully coordinated control is particularly useful in this scenario to ensure that this maximum power limit is honoured in the most efficient way possible, allowing for priorisation on which energy assets should be operated and when during the limited power period.

Figure 3.22 demonstrates this maximum power limit in action during an EV charge session under the Octopus Go tariff. This example is taken from Phase 3 of the trial therefore the heat pump, battery and EV are all controllable loads. A maximum power limit of 5kW is applied to the controllable load during the cheap tariff period (00:30 - 00:40).

The following can be observed from the figure:

- This example was during summer therefore there is no heating demand.
- On day one, the battery charges during the cheap overnight tariff rate as the system correctly predicts that there will not be enough solar during the day to charge the battery. The battery is then topped up using excess solar generation during the day.
- The EV is plugged in at 15:00 with an end time of 15:00 the following day requested. The EV charging rate is changed dynamically throughout the 24 hours the EV is plugged in. Without a maximum power limit in place, the EV is expected to charge at full rate (7.3kW) during the cheap tariff period. However with this maximum power limit in place, the EV only reaches a peak power of around 5kW during this period.
- The battery does not charge at all during this period as the system correctly recognises that it is better to directly use the 5kW to charge the battery than store it in the battery which introduces additional inefficiency if later used to charge the EV from the battery. Instead, it discharges its remaining energy to balance out household consumption while allowing the EV to charge at 5kW.

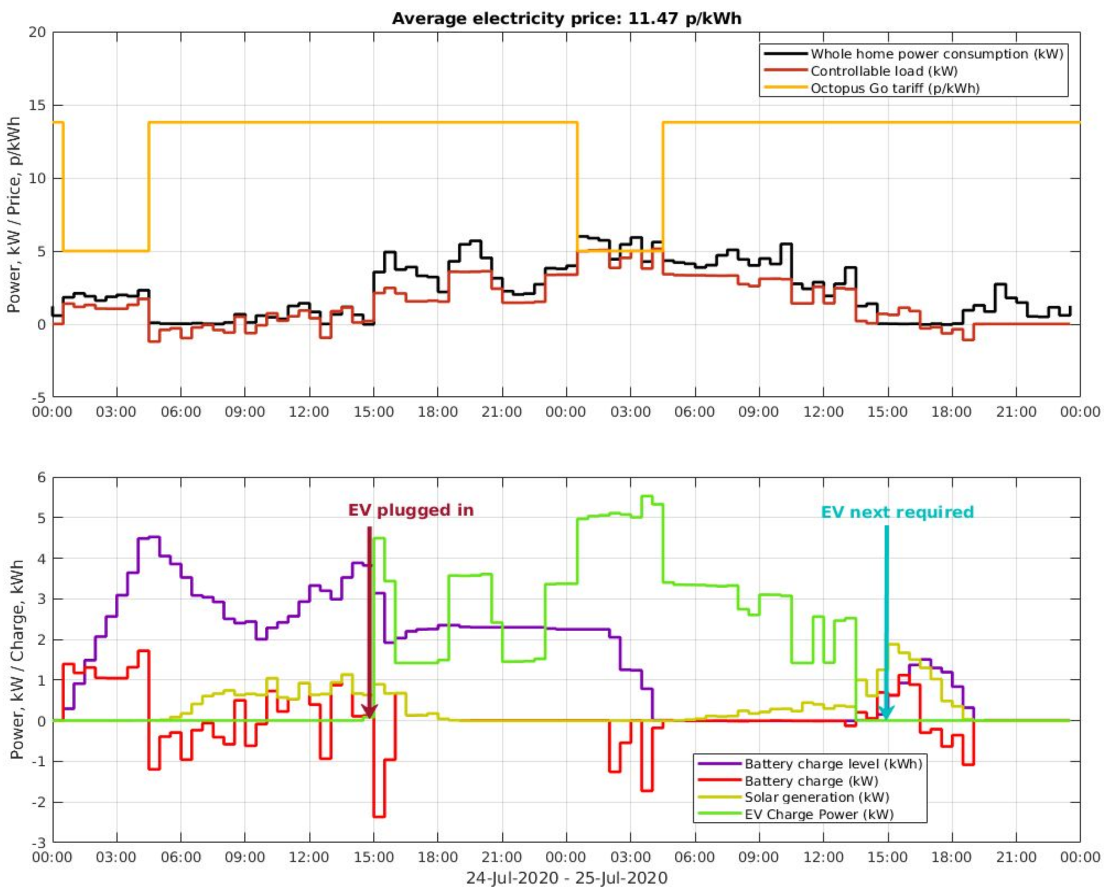

Figure 3.22 - Controlling load during cheap overnight tariff period on Octopus Go tariff ***(Home 04, 24/07/2020 - 25/07/2020). Here controllable load consists of heat pump, battery and EV power.***

3.5.2 Flexible Power interventions

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 preemptively 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. The cost of preparing for such a request is discussed in Section 4.3.

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 3.1 outlines the Flexible Power inventions that were tested over the course of the MADE field trial, in order to provide examples of how domestic DSR 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 (3 hrs)	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 3.1 - List of Flexible Power interventions carried out over the MADE field trial

3.5.2.1 Secure

Figure 3.23 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.

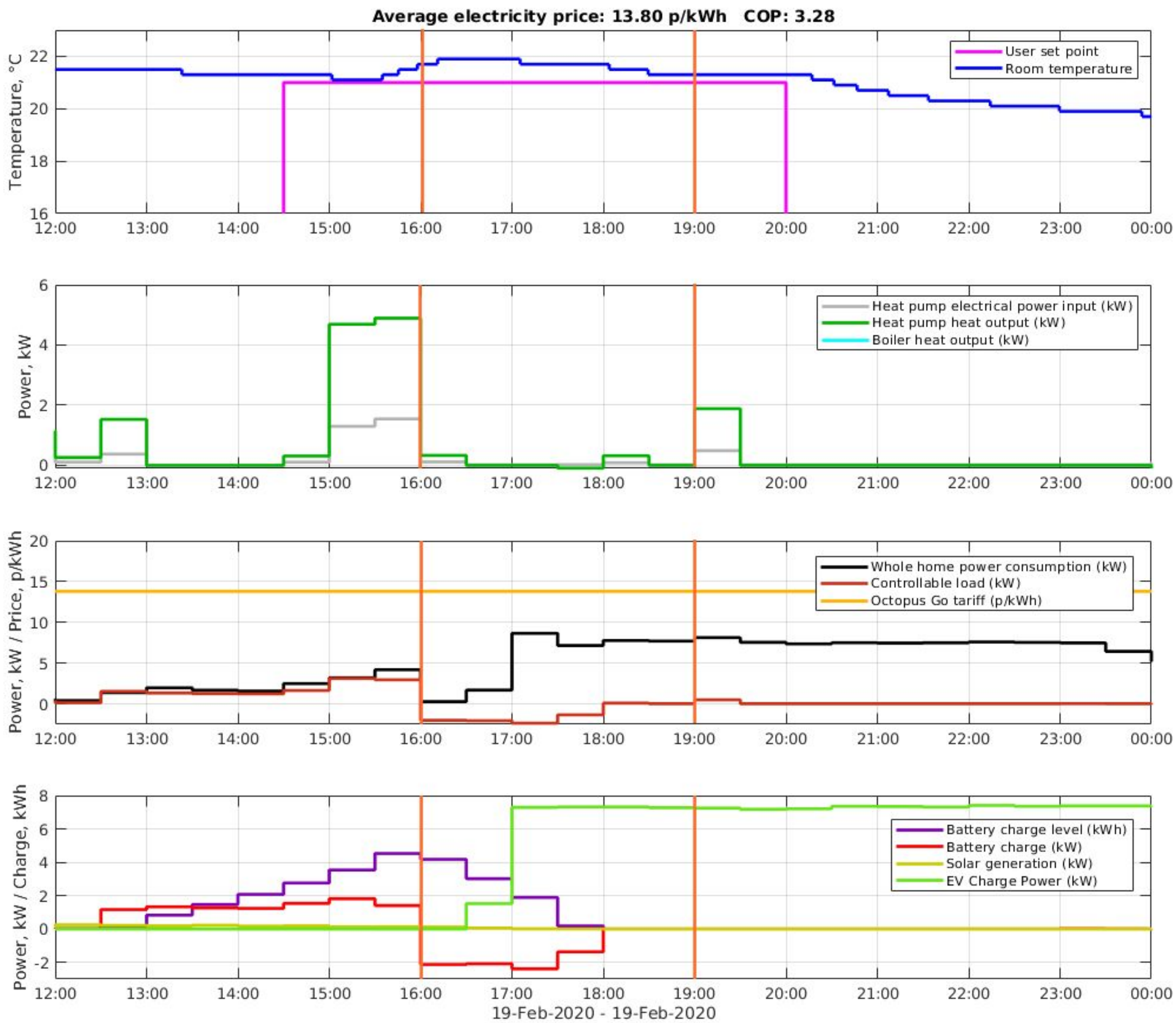

Figure 3.23 - Secure Flexible Power intervention *(Home 2, 19/02/2020)* . Controllable load is the combination of heat pump and battery in this case.

Figure 3.24 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 honoring 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.

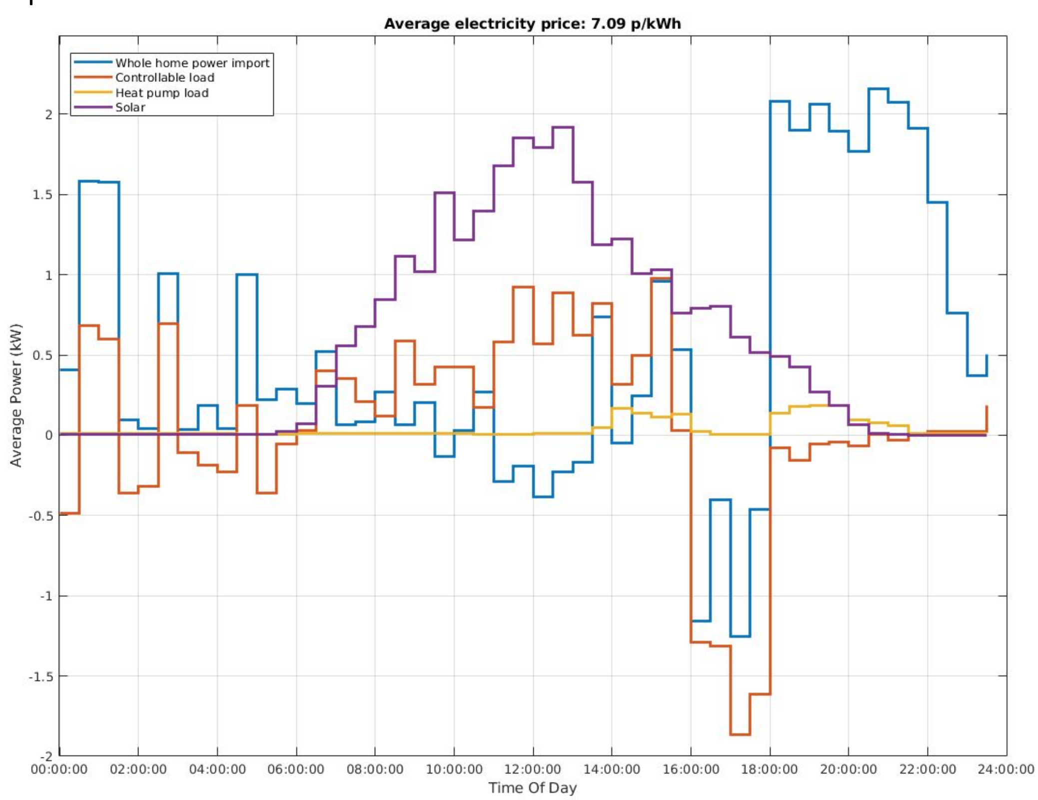

Figure 3.24 - Average load profiles during Secure Flexible Power intervention *(All homes, 08/06/2020)*. Controllable load is the combination of heat pump, battery and EV in this case.

3.5.2.2 Dynamic

Figure 3.25 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.

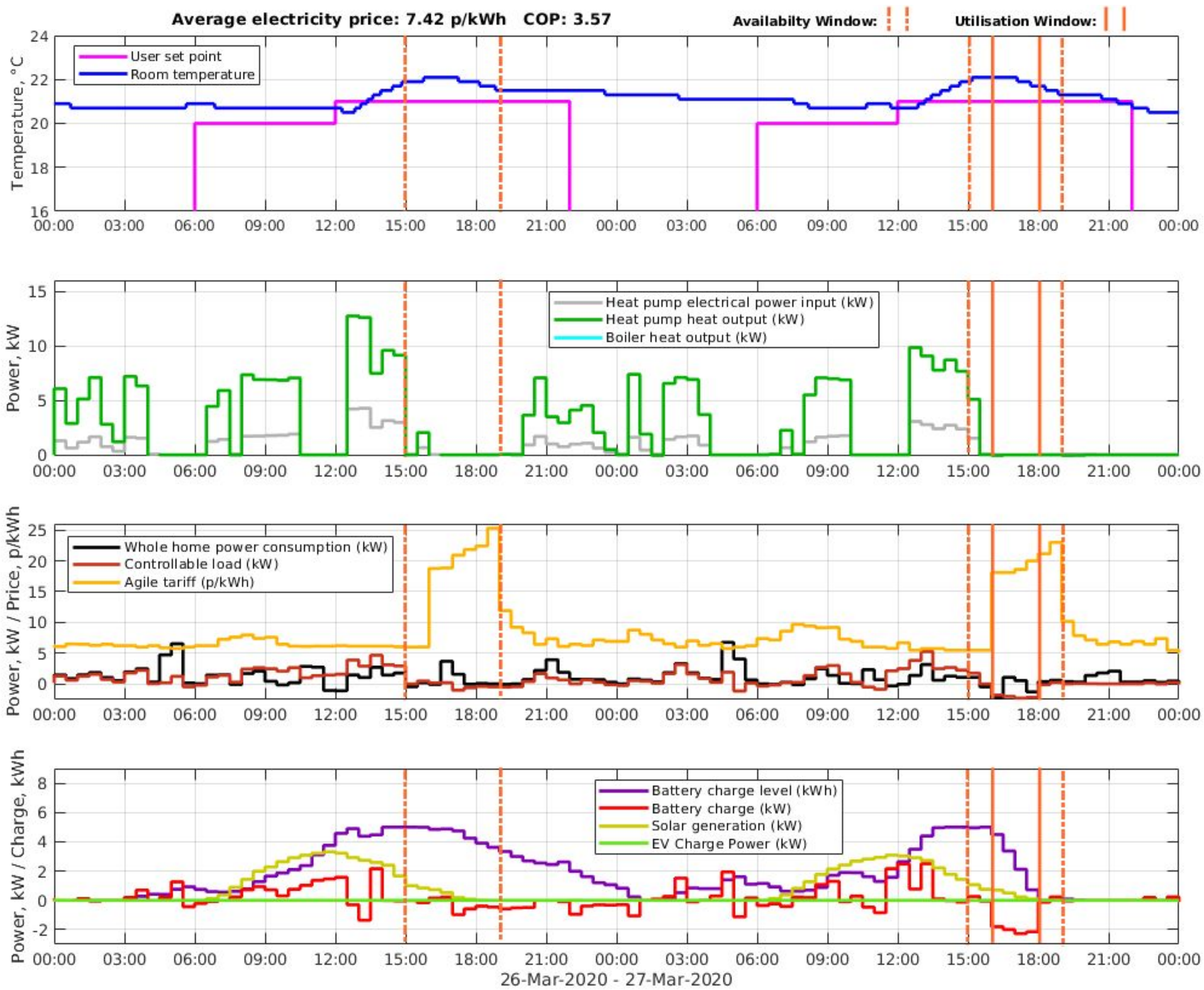

Figure 3.25 - Dynamic Flexible Power intervention ***(Home 3, 26/03/2020)*****. Controllable load is the combination of heat pump and battery in this case.**

3.6 Summary

In this section we draw out some of the key interesting findings that were observed during the field trial. We focus generally on the behaviour of fully coordinated assets (except where there are contrasts between non-coordinated and coordinated behaviour). Everything described here has been successfully demonstrated for real in the course of the MADE field trial.

Winter operation under Agile tariff:

- Note that during winter, asset behaviour is dominated by the heat pump heating load, and the solar PV has little role to play.
- Heating load can be significantly shifted under the Agile tariff, moving demand from the peak early evening period to beforehand, delivering significant consumer running cost savings.
- Coordinating heat pump operation with the battery increases heat pump efficiency as energy can be stored in the battery instead of the thermal fabric of the home (see simulation results in Section 4 for a quantified comparison).
- It is often possible to keep the home completely "off grid" during the Agile peak period.
- Optimised battery behaviour on the Agile tariff exhibits two cycles per day (one to store cheap overnight electricity, and one to avoid the peak period). Battery lifetime is usually quoted on an assumption of one cycle per day.
- Agile tariff patterns often have alternating prices between half hour periods, which the Passiv optimised battery control system manages to exploit through arbitrage: alternately charging and discharging, so that the consumer pays the lowest electricity price on offer over a period several hours long.
- Demand profiles on Agile can be very spiky as the combination of coordinated assets exploit slight variations in electricity price.

Winter operation under cheap overnight tariff (Octopus Go):

- In contrast to Agile, optimal behaviour is one battery cycle per day.
- Demand peaks very heavily during the cheap tariff period as all assets exploit the cheap electricity.
- There is a key trade-off between storing the cheap electricity in the battery versus the thermal fabric of the home (via the heat pump). The battery is more efficient but generally does not have enough capacity to serve the whole of a winter day. Predictive smart controls are essential to get the most of the assets (which becomes even more important as more solar PV is available in the shoulder seasons).

Electric vehicle charging under a time of use tariff:

- Without a time of use tariff, MADE homes exhibited the same typical baseline EV charging pattern (when not under smart control) seen in the Electric Nation project, with a significantly higher demand in the early evening period. This implies there are likely to be problems for the grid (which is already constrained at this time) unless there is smart EV charging control.
- With a time-of use tariff, the primary benefit of smart controls is delaying EV charge to make the most of the cheap overnight rate, or to avoid the Agile peak tariff period
- Under Agile, when the EV is coordinated with the domestic battery, the battery charges up fully in advance of the Agile peak period in order to serve EV demand. Where the EV needs to charge during expensive tariff periods, the coordinated controls then ensure that the EV charge rate (normally 7kW) is reduced to less than the battery discharge rate (maximum 2.5kW), and the battery itself can then dynamically adjust in "automatic mode" to balance other baseload consumption and any solar PV generation.
- Under Go, clearly the EV charges at full rate during the cheap period, but often 4 hours is insufficient to fully charge the EV (providing about 75% of a full Leaf battery). The smart controls then coordinate the operation of the domestic battery for the remaining charge, with two different modes possible: either (a) discharging before midnight if there is sufficient charge remaining, or (b) charging the battery with cheap rate electricity and then discharging after the cheap rate period. In both scenarios the EV charge rate is limited to match battery discharge. There is a clear benefit to the predictive smart controls (as solar availability and future baseload affect the trade-offs) and the net effect is the whole EV charge is provided at 5p/kWh (or cheaper).

Summer operation:

- Note that during summer, solar PV is dominant (and homes produced significantly more than could be stored in the battery), with no heat pump heating load. (The heat pumps do not contribute to domestic hot water in these hybrid deployments).
- The dominance of PV generation means that optimised batteries under an Agile tariff return to one cycle per day (charging up with free solar and then avoiding the peak period). The smart system determines that it is rarely worth charging with much cheap overnight electricity.
- Similarly with the Octopus Go tariff, the smart controls make the key trade-off between night time battery charging and waiting for solar. In many cases it is not worthwhile charging with cheap rate electricity as long as there is sufficient battery charge to bridge the gap until the sun comes up.
- The overall demand shape on Agile is fairly flat apart from significant export in the afternoon, but with Go there is an additional significant peak in the early hours.

- **Overheating.** A key finding during summer operation was the need to manage overheating. When there is negative Agile pricing, or spare PV generation in the shoulder season, it is theoretically worthwhile to turn on the heat pump to reduce running costs, even if that means heating the house significantly above setpoint. However, feedback from trialists indicated this was unacceptable in excess. As a mitigation, a maximum increase of 2℃ was enforced in the optimisation algorithms. This was found acceptable by all trialists and quantifies the flexibility offered by storing heat in the thermal fabric of a home: it will be a crucial component of smart controls when responding to demand side response or Flexible Power requests.

Interventions to limit peak demand:

- Time of use tariffs introduce significant peaks in demand when assets are optimised: immediately after the start of an overnight cheap period, or immediately before an early evening peak period. These peaks can be dominated by EV charging due to the high power levels involved.
- These peaks can be mitigated by smart controls by applying a maximum demand cap to the controllable assets in the optimisation calculation. This requires sophisticated controls where EV charging is involved to (a) best utilise the domestic battery to balance demand and (b) ensure that sufficient charge is delivered to the EV by the time required.

Flexible Power interventions:

- Smart controls can effectively deliver both Secure and Dynamic Flexible Power services using the MADE assets (see also simulation results in Section 4.3 for quantified comparisons).
- 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).

4 SIMULATION RESULTS

The focus of Section 3 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** (*Section 4.1*): these focus on the predictive optimisation calculation within the Passiv 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** (*Section 4.2*): 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** (*Section 4.3*): 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** (*Section 4.4*): these were performed to investigate demand peaks introduced by time of use tariffs and how they can be managed by a smart coordination system.

Note that:

- Savings figures are still anecdotal as they apply only to the individual days analysed and should not be extrapolated to annual figures, but they will give a broad indication of the savings possible.
- Some randomisation is still present in the simulations (particularly for solar irradiation and electrical baseload) which gives some underlying variability.

4.1 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 4.1 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°.
- 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.

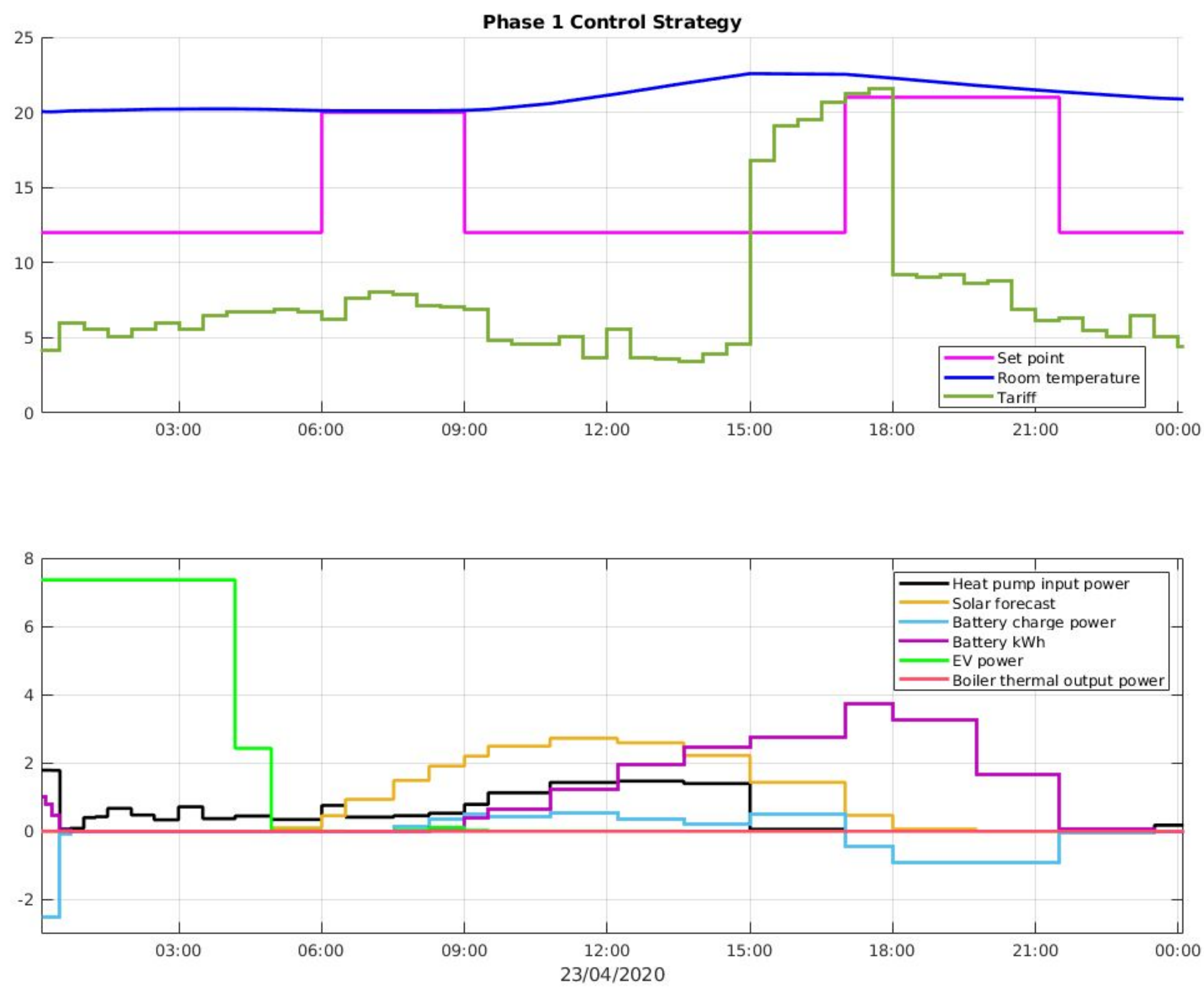

Figure 4.1- Optimisation output under Phase 1 control (Digital twin of Home 5, 23/04/2020)

Figure 4.2 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° vs 22.6° 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.

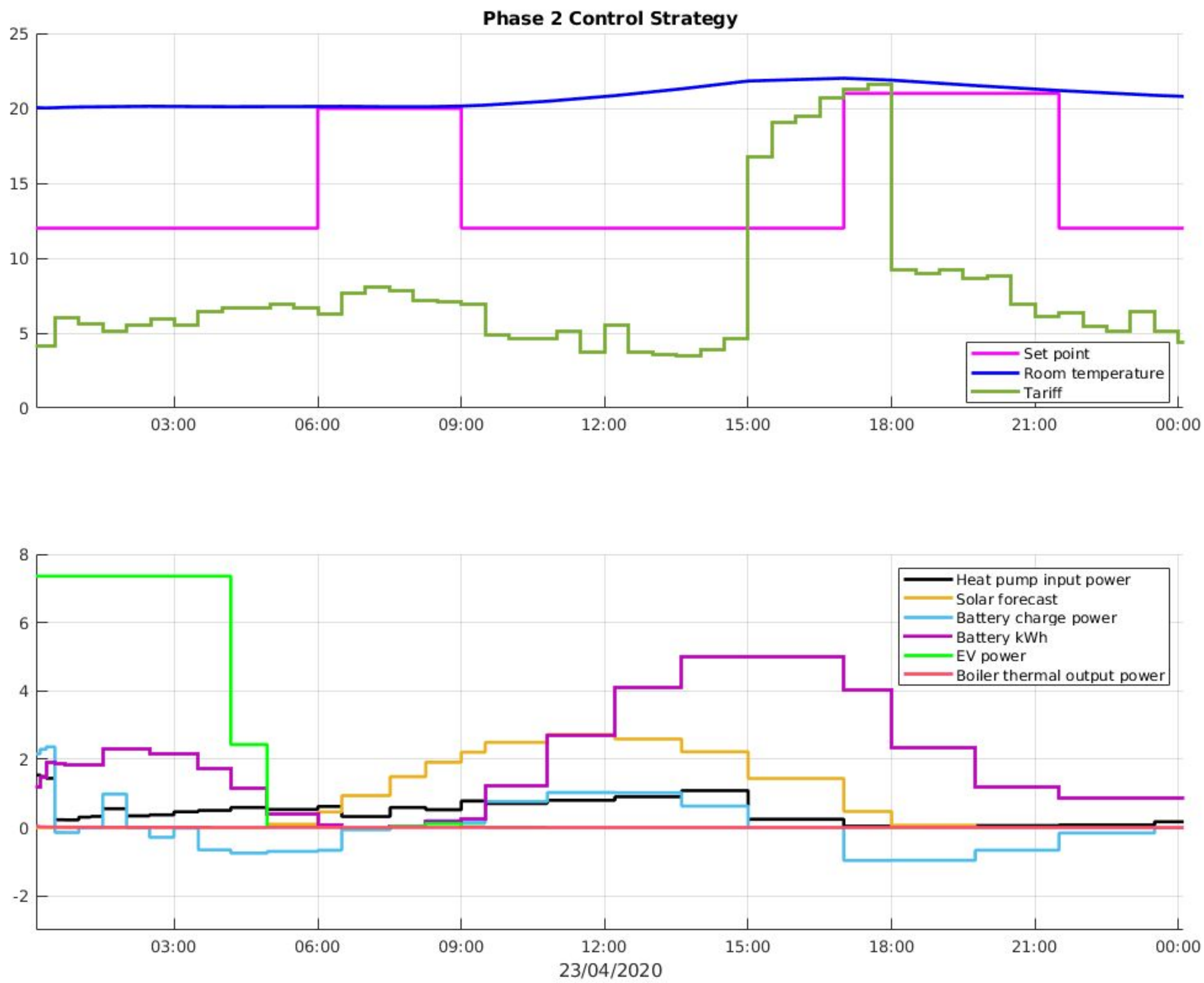

Figure 4.2 - Optimisation output under Phase 2 control (Digital twin of Home 5, 23/04/2020)

Figure 4.3 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.

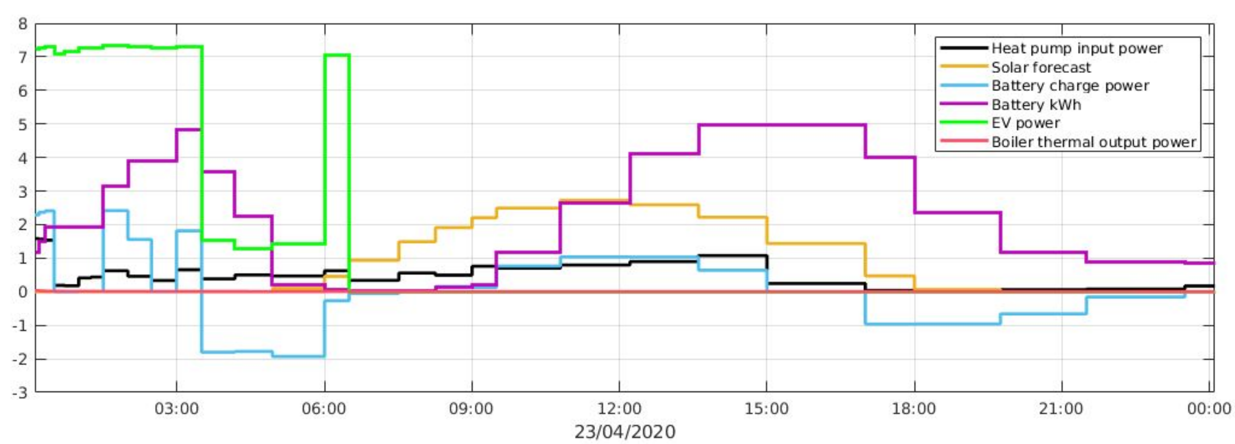

Figure 4.3 - Optimisation output under Phase 3 control (Digital twin of Home 5, 23/04/2020)

4.2 Benefits of coordination - Full simulation runs

This section presents the results of using a digital twin of one of the MADE homes to investigate the benefits of asset coordination. These simulations used more detailed modelling than the previous section and were run over a longer time period (2 days). Comparative evaluations were made of householder running costs as the level of asset coordination within the home increases.

- The digital twin was of MADE Home 2;
- The home was assumed to be on the Octopus Agile tariff;
- The EV is assumed to be plugged in at 18:00 on the first day, requiring a full charge by 07:00 the following morning;
- Simulations were run for Winter, March, and Summer scenarios;
- A maximum room temperature increase of 2°C was assumed for heating (c.f. Section 3.4.2).

Supporting simulation analysis can be found in Annex A, which focuses on the March simulation runs since at this time of year there is involvement from all assets considered under the MADE concept, including both heating and solar.

Winter, March and Summer simulation runs were performed with both uncontrolled and smart EV charging. In the uncontrolled case the EV was assumed to charge as soon as it was plugged in, whereas in the smart case the EV charging was assumed to be delayed until midnight.

Table 4.1 shows the total cost over the two day period considered for each of these simulation runs.

	Winter	**March**	**Summer**
Baseline Control	8.76	5.82	4.21
Baseline Control, Smart EV Charging	6.92	4.09	3.21
Phase 2 Control	8.00	5.26	4.05
Phase 2 Control, Smart EV Charging	6.21	3.95	3.12
Phase 3 Control	5.95	3.72	2.92

Table 4.1 - Total electricity cost on the Octopus Agile tariff across a two day period under various control strategies (£)

In summary:

- There is value in full coordination between all assets in the home, throughout the year. These results indicated that there may be more value from full coordination during the Winter than during the Summer however the variation is small and this may simply be due to the tariff on the particular days selected or due to randomisation in the simulation runs.
- There is notable value from EV charging control, particularly during the Winter simulation runs.
- There is much less benefit from Phase 2 control over Phase 1 control during the summer. This is expected largely due to the fact that there is unlikely to be heating demand during the summer and so there is no benefit to coordination between the heat pump and battery. This is also expected since, as observed in the field trial results presented in Section 3, during the summer the battery is generally fully charged entirely using free solar and thus this will happen whether or not additional demand is expected in the evening.

4.2.1 Comparison with Everoze modelling

The example electricity cost savings presented in Table 4.1 have been compared against Everoze's MADE modelling results. The "baseline control with smart EV charging" case most closely matches Everoze's base case scenario, with the "Phase 3 control" results used for the fully optimised scenario. Focussing on these two cases, the assumed daily cost saving from full coordination at various times of the year is assumed to be as follows (Table 4.2):

Winter	**Shoulder season**	**Summer**
48.5p	18.5p	14.5p

Table 4.2 - Simulated daily cost saving from fully optimised control compared to the baseline scenario with smart EV charging

Based on these daily cost savings, the estimated annual import electricity cost savings through implementation of fully coordinated control is £91.25. This is notably higher than the £28.66 of import cost savings calculated in the Everoze medium demand commuter case, which most closely matches the simulated example. This cost difference is largely due to the fact that in the simulated results, a full EV charge (40kWh) was modelled over a 2 day period and thus extrapolating these results assumes 140kWh of EV charging is performed each week. Conversely, in the Everoze scenario the commuter EV profile assumed a total of 49.5kWh which is notably lower, thus providing much less scope for flexibility. This highlights that the figures presented in this section should be treated with caution as they represent short anecdotal examples rather than annual averages with typical EV usage patterns. Despite this, both sets of results suggest that there is good value to be obtained through fully coordinated control.

4.3 Flexible Power

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 (Table 4.3):

	Secure:	Dynamic:
Arming Fee:	£125/MW/h	N/A
Availability Fee:	N/A	£5/MW/h
Utilisation Fee:	£175/MWh	£300/MWh

Table 4.3 - Flexible power payment amounts for both Secure and Dynamic

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.

4.3.1 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. More detailed analysis of these simulation runs can be found in Annex B.

- When preparing for a flexible power request the home was heated to a maximum temperature of 19.8° (compared to 19.2° 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.

4.3.2 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. More detailed analysis of these simulation runs can be found in Annex B.

- When preparing for a Flexible Power request the home was heated to a maximum temperature of 19.7° (compared to 19.4° 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.

4.3.3 Summary

Table 4.4 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**	**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 4.4 - Flexible Power simulation results for the Octopus Agile and Octopus Go tariffs with various Flexible Power windows

Table 4.5 summarises the results presented in Table 4.4 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.

Tariff	Flexible Power Window	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 householder 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 4.5 - Total net cost vs benefit to the householder of Flexible Power style interventions

4.4 Managing ToU tariff peaks

Time of use tariffs such as those considered in the MADE project can bring substantial benefits to customers who can exploit the cheap electricity prices, but can bring challenges for the electricity networks when peaks in demand are introduced around the times electricity prices change. This can happen at the start of a cheap tariff period (which can be demonstrated using the Octopus Go tariff) or just before a peak tariff period (as is seen with Octopus Agile).

This section of the report presents simulated optimisation outputs to investigate these peaks and how they can be managed by a smart coordination system. We show how maximum power limits can be successfully applied, and use the simulations to evaluate the householder costs which may be incurred as a result of this.

- A Winter scenario only is consider as demand is highest;
- The EV is assumed to be plugged in with an end time set for 07:00 the following morning;
- Both Octopus Go and Octopus Agile tariffs are included.

4.4.1 Octopus Agile Tariff

It has been observed during the MADE field trial that fully coordinated control against the Octopus Agile tariff can result in high demand in advance of the 16:00 - 19:00 peak Agile tariff period, where the battery is charging in preparation for keeping the home off grid during this time and the heat pump is pre-warming the home to minimise the need to heat during this expensive period.

Figure 4.4 shows the simulated controllable load with a variety of maximum power limits between 13:00 - 16:00 in order to limit controllable load in advance of the expensive evening tariff period. This figure illustrates how controllable load can be successfully reduced through implementation of such limits. The figure also shows that there is in fact a significantly larger peak overnight which is attributed to the EV charging once the tariff is lowest.

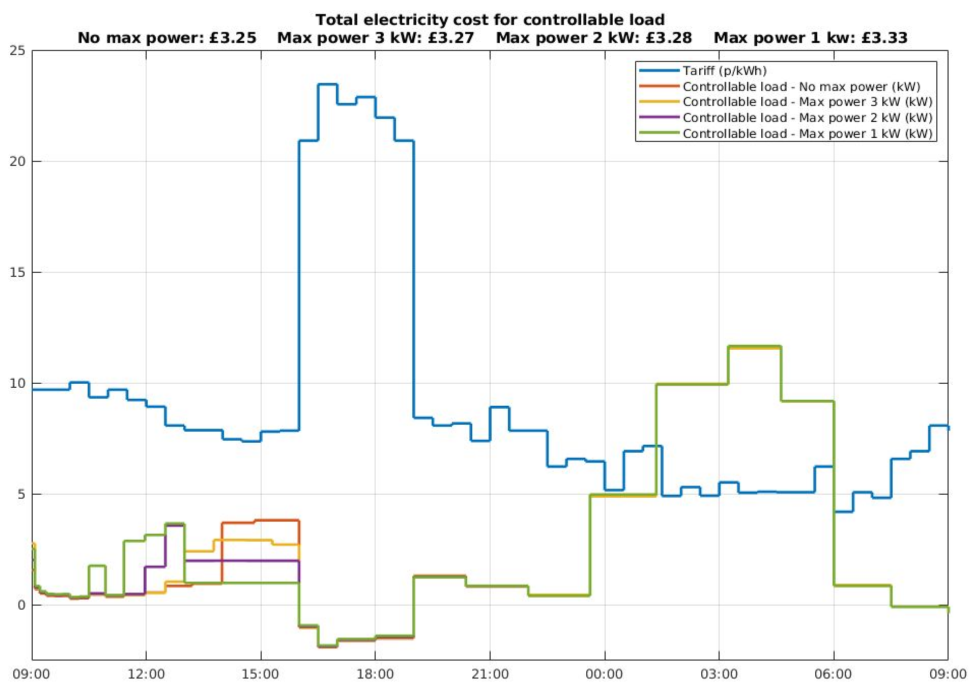

Figure 4.4 - Simulated controllable load on the Octopus Agile tariff with a range of maximum power limits between 13:00 - 16:00 (Digital twin of Home 5, 03/01/2020 - 04/01/2020)

Table 4.6 provides a summary of key information extracted from Figure 4.4. Whilst controllable load is successfully limited via various maximum power limits between 13:00 - 16:00, if this limit is too severe it can result in the demand peak simply moving earlier. It can also be seen that the cost increases associated with the maximum power limits applied in these examples are not significant.

Max Power Limit	**Peak controllable load 13:00 - 16:00**	**Pre 16:00 peak controllable load**	**Total householder cost attributed to controllable load**	**Cost increase from baseline**
Baseline	3.8kW	3.8kW	£3.25	N/A
Max power 3kW between 13:00 - 16:00	3kW	3kW	£3.27	£0.02
Max power 2kW between 13:00 - 16:00	2kW	3.6kW	£3.28	£0.03
Max power 1kW between 13:00 - 16:00	1kW	3.7kW	£3.33	£0.08

Table 4.6 - Summary of simulation results on the Octopus Agile tariff with a range of maximum power limits.

4.4.2 Octopus Go Tariff

It has also been observed during the MADE field trial that fully coordinated control against the Octopus Go tariff can result in very high demand during the four hours of cheap overnight electricity where the cost of electricity is 5p/kWh compared to a day rate of 13.8p/kWh. During the winter, the EV, battery and heat pump are all likely to attempt to make use of the cheap tariff period in the absence of any peak management.

Figure 4.5 shows the simulated controllable load with a variety of maximum power limits implemented between 00:30 - 04:30 in order to limit controllable load during this cheap overnight period.

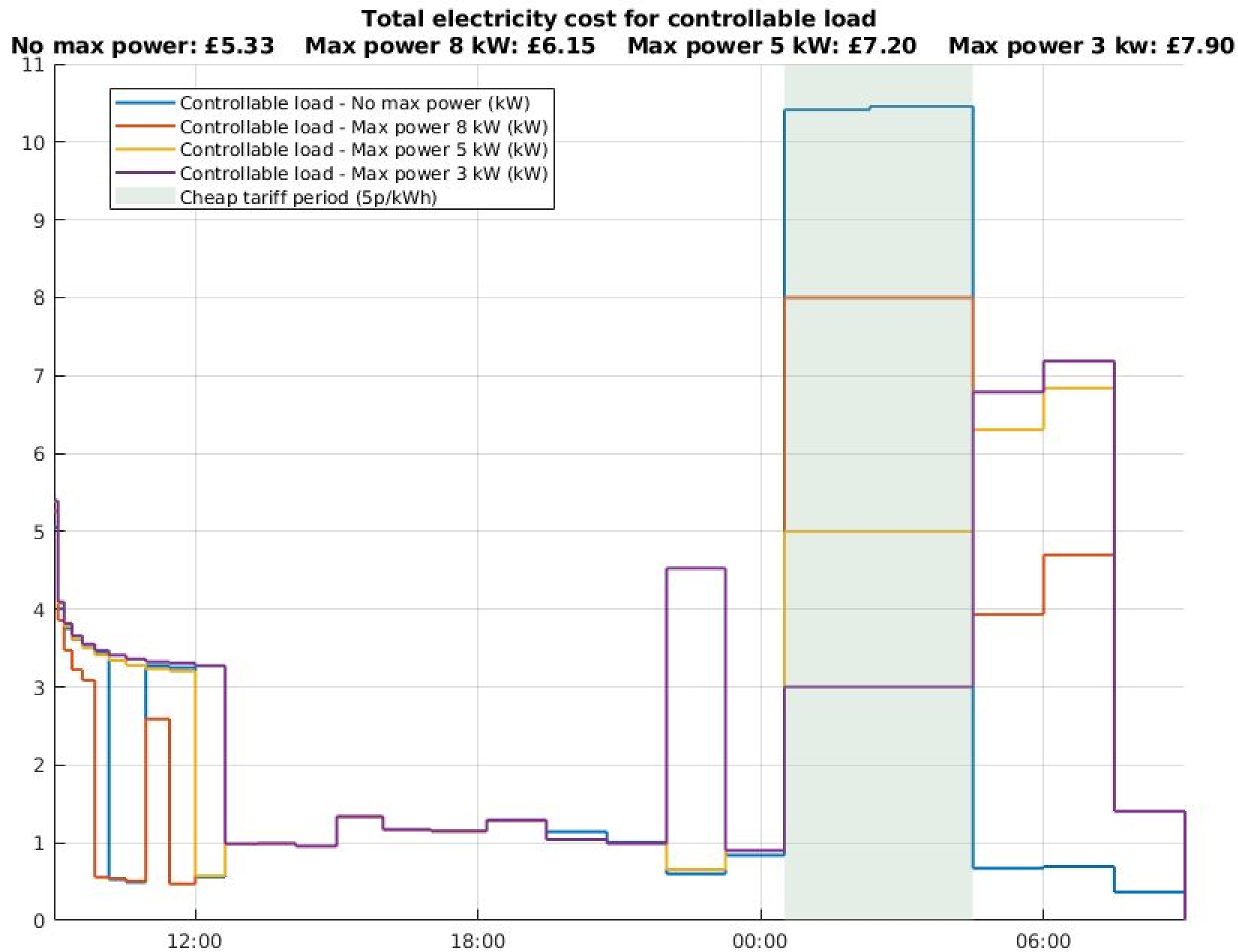

Figure 4.5 - Simulated controllable load on the Octopus Go tariff with a range of maximum power limits between 00:30 - 04:30 (Digital twin of Home 5, 03/01/2020 - 04/01/2020). Day tariff rate is 13.8p/kWh with a cheap overnight tariff rate of 5p/kWh as indicated on the figure.

Table 4.7 provides a summary of key information extracted from Figure 4.5. As for Agile, whilst controllable load is successfully limited, if this limit is too severe it can result in the demand peak simply moving earlier/later. The cost increases associated with the maximum power limits applied in these examples are more substantial than in the Octopus Agile tariff examples, due to the fact the ability of the home to make the most of cheap electricity is being directly restricted.

This demonstrates that the management of demand peaks caused by time of use tariffs must be carefully executed with awareness of associated householder cost increases.

Max Power Limit	Peak controllable load 00:30 - 04:30	Overall peak controllable load	Total householder cost attributed to controllable load	Cost increase from baseline

Baseline	10.5kW	10.5kW	£5.33	N/A
Max power 8kW between 00:30 - 04:00	8kW	8kW	£6.15	£0.82
Max power 5kW between 00:30 - 04:00	5kW	6.8kW	£7.20	£1.87
Max power 3kW between 00:30 - 04:00	3kW	7.2kW	£7.90	£2.57

Table 4.7 - Summary of simulation results on the Octopus Go tariff with a range of maximum power limits.

4.4.3 Summary

These simulation results suggest that management of ToU tariff peaks will need to be performed with careful consideration of how this may affect householder costs and any additional peaks that may be introduced as a result, however the Agile scenario in particular demonstrates that under the right circumstances ToU tariff peaks can be successfully managed with little additional cost to the consumer.

4.5 Summary

PassivSystems predictive smart controls are based on automatically constructed simulation models of the house and low carbon assets. In this section we utilised these simulation models to quantitatively compare scenarios that were not possible in the real world.

- By comparing the figures in Section 3 and Section 8 it can be seen that the simulation models are providing a qualitatively good match to real world behaviour.

Asset coordination. Smart coordinated control of low carbon assets can significantly reduce consumer running costs:

- Coordinating heat pump and battery operation enables more efficient behaviour on a time of use tariff, as a quantified decision can be made about how much energy should be stored in the battery vs the fabric of the building.
- Smart control of the battery and EV charging can deliver savings by shifting electricity import to the cheapest times.
- The simulations were used to calculate quantitative savings for short example periods, on the Agile tariff. Separate comparisons are provided with and without EV smart charging (whether the EV charger is able to independently respond to time of use tariffs,

which is not within the capability of off-the-shelf EV chargers, but dominates the results and is somewhat separate to asset coordination)

- **Baseline without EV smart charging:** Compared to the baseline control scenario (without smart EV charging), full asset coordination reduced running costs by 32% in winter and 30% in summer, but these figures are dominated by EV charging (as the highest power asset). Adding battery coordination to heat pump controls saved 9% in winter and 4% in summer.

- **Baseline with EV smart charging:** Compared to the baseline control with smart EV charging scenario, adding battery control reduced running costs by 10% in the Winter and 3% in the Summer, whilst full asset coordination reduced running costs by 14% in the Winter and 9% in the summer.

- These figures should be treated with caution as they represent short anecdotal examples rather than annual averages with typical EV usage patterns.

Flexible Power interventions. The simulated scenarios demonstrated net benefits to customers with MADE assets participating in the Flexible Power service (but it is not clear how representative these are).

- In the scenarios studied, the "availability payment" for preparing for a Flexible Power intervention was less than the cost to householder, although the costs are quite small, and the difference is very marginal in the case of an Agile tariff because the home would have been prepared for the peak period in any case. The costs to the householder for making the home "available" are greater later in the evening (under a Go tariff), where it has an impact on the capacity to store upcoming cheap rate electricity.

- In the scenarios studied, the cost to the householder for dispatching a Flexible Power intervention is about half of the payment they would receive from WPD, so it would certainly be beneficial to participate. The net benefit to the householder was very approximately 60p/day (assuming good utilisation in the case of the Dynamic service).

Managing peak demand due to ToU tariffs. Where peak demand limits directly affect availability of cheap electricity, there can be significant cost impact on consumers.

- Applying maximum demand limits can have an effect of shifting peaks earlier: in some cases restrictions need to be applied more than 4 hours in advance of the tariff change.

- On the Octopus Agile tariff the cost to the householder of avoiding peak demand can be quite little (2%), although this is dependent on the tariff being fairly flat in the run up to the peak period.

- The opposite is true for the Octopus Go tariff: as the peak load restriction directly limits the amount of cheap electricity that can be consumed, there is a big cost impact on the consumer (33% in the most extreme case considered here).

5 HOW COORDINATION AFFECTS THE DEMAND PROFILE

This section of the report draws out and pulls together various themes from the previous sections, in order to address the following research questions which the MADE project aimed to answer:

- How does real-world overall household demand shape (and balance between the assets) change depending on time-of-use tariffs, level of asset coordination, and over the seasons? *(See Section 5.1)*
- What happens to the peak demand as we move between each scenario? *(See Section 5.2)*
- How can the demand shape be influenced by interventions? *(See Section 5.3)*

5.1 Patterns of demand shape

This section of the report addresses how real-world overall householder demand shape (and balance between the assets) changes depending on time-of-use tariffs, level of asset coordination, and over the seasons.

5.1.1 Time-of-use tariffs

It can be observed through both the field trial results and simulated results that time-of-use tariffs heavily affect the shape of demand. Particular examples of this are as follows:

- On a flat tariff, demand is generally highest when heating or EV charging is required, with no advantage to shifting this demand around.
- On the Octopus Agile tariff, there is generally very low demand between 16:00 - 19:00 when the tariff is considerably more expensive. To allow for this, demand is generally reasonably high in advance of this period with energy assets preparing to minimise import whilst the tariff is expensive. High demand can also be seen during particular low or negative Agile tariff periods.
- On cheap overnight tariffs such as Octopus Go or Economy 7, very high demand can typically be observed during the cheap overnight period.

5.1.2 Level of asset coordination

It can be observed through both the field trial results and simulated results that increasing the level of asset coordination can affect the shape of demand. Particular examples of this are as follows:

- Under the Phase 1 control strategy the heat pump typically operates whilst the electricity price is cheap or when there is excess solar generation. Often, the home is overheated in order to make use of free solar generation or cheap tariffs rates which occur in advance of the evening set point, since lack of coordination between the heat pump and the battery means that the system cannot rely on the ability to run the heat pump using cheap electricity stored in the battery closer to the time it is actually required.

- Under the Phase 1 control strategy the battery is not used at all in the absence of excess solar generation. This limits the ability of the battery to smooth out demand or lower demand during high tariff periods.

- Under the Phase 1 control strategy the EV charges as soon as it is plugged in with no awareness of tariff or demand from other energy assets in the home. This has the potential to produce large demand spikes or high demand during expensive tariff periods on time of use tariffs which is more likely to align with periods of high demand on the network. However the simulation runs performed under MADE showed that these demand spikes could be mitigated if required, through the use of smart controls, where EV charging was delayed until midnight when demand is likely to be lower.

- Under the Phase 2 control strategy, there is coordination between the heat pump and the battery. Thus excess solar and cheap electricity can be stored in the battery and the heat pump can then operate when required using this stored cheap energy. Thus a decrease in maximum room temperature during the day can generally be observed, with the battery allowing for more efficient heating of the home. Additionally the heat pump will have a lower overall demand. Under the Phase 2 control strategy the battery is also able to take advantage of cheap tariff rates, charging during these periods to meet the demands of the heat pump at a later period. This means that heating can be performed at a cheaper rate when it is actually required, lowering householder costs.

- Under the Phase 2 control strategy the EV still charges as soon as it is plugged in with no awareness of tariff or demand from other energy assets in the home. This again has the potential to produce large demand spikes or high demand during expensive tariff periods on time of use tariffs which is more likely to align with periods of high demand on the network. However once again this was shown to be mitigated in the simulation runs performed under MADE, where EV charging was delayed until midnight when demand is likely to be lower.

- Under Phase 3 control, all energy assets within the home are coordinated. In particular, the EV charging is now optimised to take advantage of cheap electricity tariff periods and excess solar generation. Additionally, coordination between assets allows for assets power rates to be matched during expensive tariff periods such that EV plus heat pump demand is matched to excess solar plus battery discharge power in order to minimise import during expensive tariff periods and save the householder money.

5.1.3 Seasonal changes

Seasonal changes can also be observed in both the field trial results and simulated results. Particular examples of this are as follows:

- As expected, there is a large amount of heat pump operation during the winter months which decreases during the spring. Heat pump use is then very limited or not observed at all during the summer with the exception of during the occurrence of a negative Agile tariff period when the heat pump may run in order to financially benefit the householder providing that upper comfort limits are honored. During the winter months, additional heating support from the boiler is often required during especially cold periods or short notice requests for heat. This reduces upon moving into spring and the boiler is not generally used at all for heating during the summer months.
- During the winter in the absence of solar the battery charges during cheap tariff periods in order to meet demand during more expensive tariff periods. As solar generation increases upon moving towards summer, battery charge patterns may change as follows:
    - On a flat tariff the battery is unlikely to be used at all during winter. Moving towards summer, the battery is likely to exhibit one cycle per day, charging using excess solar generation and then discharging over the course of the evening.
    - As solar generation increases and heating demand reduces upon moving towards summer, depending on household demand, the battery may charge less during the cheap overnight period, particularly if there is limited demand between the end of the cheap tariff period and the solar window, in order to save space for excess solar generation which is free.
    - On the Octopus Agile tariff during winter the battery typically exhibits two battery cycles a day. Cycle one involves the battery charging overnight to make use of cheap overnight Agile tariff prices, before discharging to meet morning heating demand. The second involves the battery charging in advance of the evening peak Agile tariff period before discharging over this period to keep the home off grid. Moving towards shoulder season with increased solar generation but heating demand still required, the battery is expected to maintain two daily cycles, however the second cycle is likely to involve the battery charging from

excess solar generation where available. During summer under the Agile tariff, in the absence of morning heating demand the battery typically moves to one cycle per day as there is no advantage to charging from cheap overnight electricity over free solar generation since there is no longer any heating demand in the morning in advance of the solar period. However, in the presence of negative agile tariff periods the battery.

    - On a cheap overnight tariff such as Octopus Go or Economy 7 during winter the battery can be expected to charge over the cheap overnight period and then to discharge once the tariff increases to meet excess demand. Once the battery is empty, it is not generally used until it charges during the next cheap overnight period. As solar generation increases during shoulder season but there is still heating demand, the battery is expected to exhibit two battery cycles per day. Similarly to the behaviour on the Agile tariff during this time of year, the battery is expected to charge during the cheap overnight rate to meet morning heating demand. The battery is then likely to charge from excess solar generation, depending on household demand, which will be discharged over the course of the evening. Upon moving into summer depending on solar availability and household demand the battery is likely to move to one cycle per day should solar generation be sufficient to charge the battery and cover household demand. This may differ in the presence of a negative agile tariff period where the system recognises that being paid to charge the battery is of greater advantage than charging from free excess solar generation.

- During the winter the EV is likely to charge during cheap tariff periods, making use of coordination between the heat pump and battery when charging is required outside of these periods. As solar generation increases throughout the year, depending on when the EV is plugged in, the charge pattern may alter such that EV charging takes place when there is sufficient excess solar.

5.2 Consequences for peak demand

This section of the report addresses what happens to the peak demand when moving between each scenario.

5.2.1 Time-of-use tariffs

It can be observed through both the field trial results and simulated results that time-of-use tariffs heavily affect the presence of demand peaks. Particular examples of this are as follows:

- Demand typically peaks during periods of cheap electricity. This is particularly prominent during negative tariff periods on the Octopus Agile tariff periods.
- Additionally, on the Octopus Agile tariff high demand can often be observed in advance of the expensive evening tariff period where the assets are preparing to minimise import whilst the tariff is expensive.
- When the domestic battery is optimised, variations in the Agile price half-hour to half-hour can lead to surprisingly large demand peaks as the battery carries out arbitrage (storing electricity in a cheap half-hour then discharging the following half hour). This is particularly true when the EV is also being optimised, as typically both the battery and EV will charge at full power during the cheap periods, with the battery then offsetting EV load during the more expensive tariff periods.

5.2.2 Level of asset coordination

It can be observed through both the field trial results and simulated results that increasing the level of asset coordination can affect demand peaks. With multiple assets optimised to the same time-of-use tariff, this may lead to notable demand peaks during cheap electricity periods. This is especially evident from field trial results and simulated results when optimisation is performed against a cheap overnight period. However optimisation between multiple assets allows for peak management to be applied to all assets in order to ensure that maximum power limits are honoured in the most effective way possible, as demonstrated in both the field trial results and simulation runs. Additionally, the battery can act to smooth out demand which may help to reduce demand peaks.

With a high power compared to the other assets considered under the MADE concept, the EV in particular can be seen to drive demand peaks. Coordinating EV charging with other assets for example reducing EV charge power to meet excess solar generation or to match available battery power can notably reduce the EV charging demand, thus having an effect on the peak demand of the home.

5.2.3 Seasonal changes

In the winter, demand is likely to be highest during the morning and evening aligning with times that the heat pump is required, or during cheap tariff periods when cheap electricity is stored to run the heat pump at a later time period. Demand is typically much lower during the summer, primarily due to increased solar generation and reduced heating demand, thus demand peaks are generally likely to be higher during the Winter. However as mentioned previously the EV charge power is notably higher than the power rating of other energy assets within the home, therefore EV charging is likely to drive peak demand during the summer months and will also have a large contribution during the winter months.

5.3 Influence of interventions

This section of the report addressed how the demand shape can be influenced by interventions.

It can be seen from the field trial results in Section 3.5.1 and simulated results in Section 4.3 that demand peaks introduced through optimisation of multiple assets against a time of use tariff can be successfully mitigated through the application of maximum power limits. However it can be observed that maximum power limits should be carefully selected in order to avoid additional undesirable demand peaks as demand is shifted to alternative time periods. Section 4.3 in particular considers the magnitude of additional costs incurred to the householder through management of ToU tariff peaks, which demonstrates that any maximum power limits should also be selected with a good understanding of these additional costs.

It can be seen from the field trial results in Section 3.5.2 and simulated results in Section 4.2 that demand can be altered in order to lower demand during a specified time in order to benefit the network. This is shown in both the Secure and Dynamic style interventions that have been performed under the MADE trial.

6 FIELD TRIAL FINDINGS

This section of the report summarises a number of key findings which have been observed over the course of the MADE field trial, relating to the specific assets considered under the MADE concept.

6.1 Heating

- **Hybrid boiler utilisation.** Homes were primarily heated using the heat pump with some support from the boiler for (a) short notice requests for heat, (b) during expensive tariff periods, and (c) during particularly cold weather.
- **Overheating.** During negative agile tariff periods and times with an abundance of excess solar there may be financial incentive for the control system to deliberately heat the home more than required. However feedback from MADE trialists indicated that they did not want unlimited overheating to occur, even if it was financially advantageous, as homes became uncomfortable warm. It has been demonstrated during the MADE field trial that overheating can be successfully managed through the introduction of upper comfort limits. Generally an overheating limit of 2°C above the householders usual heating setpoint appeared to be sufficient to keep the occupants comfortable and also provided a sufficient buffer for demand flexibility.

6.2 Solar and battery

- **Two cycles per day in winter under Agile.** During the Winter, under the Octopus Agile tariff batteries typically exhibited two cycles per day; charge overnight when cheap to meet morning demand and charge in advance of the evening peak tariff period to minimise import during this time. This is an interesting project finding given that batteries are typically designed with one cycle per day in mind. Moving towards summer, batteries moved to one cycle per day; charging from excess solar during the day and discharging over the course of the evening.
- **Battery performance at extreme temperatures.** Examples were observed where the battery cell temperature was too low resulting in the battery charging at a lower rate than requested were observed during the field trial.
- **Hybrid complexity.** For the hybrid battery system, manual mode charge and discharge requests correspond to requested inverter power, rather than actual battery charge/discharge as had been initially expected.
    - This adds complexity where there is PV generation happening, as the specified inverter power includes PV.

    - The hybrid battery system actually has four different power ratings: (a) the maximum amount of PV power entering from the panels (b) the maximum charge rate of the battery (c) the maximum discharge rate of the battery and (d) the maximum inverter power. PV power can bypass the battery (in DC) to the inverter.

    - There is currently a software bug in the Sonnen system which limits the manually-specified inverter discharge to 2.5kW, whereas its actual rating is 4.6kW (2.5kW battery discharge plus 2.1kW PV export). This is due to the hybrid case not being properly accounted for. This limited some MADE use case experiments.

- **Battery efficiency.** There were advantages to factoring round trip battery efficiency into the optimisation calculations.

    - This avoided some small spurious charge/discharge cycles.

    - During scenarios where maximum power limits were applied and the system had to prioritise asset operation during cheap tariff periods, the system correctly identified that it was better to run assets directly during this period rather than store this electricity in the battery and run the assets from the battery later which would introduce additional losses.

    - The system was able to make a more informed decision about whether to store excess solar generation in the form of heat in the home or electricity in the battery, factoring in the relevant inefficiencies in each case.

- **Automatic/manual mode trade off.** There are many different use cases for battery control, depending on the relative levels of solar generation, baseload consumption and controllable asset consumption, as well as future requirements. This can lead to tricky trade-offs between automatic battery control (which is best for real time balancing of solar PV or whole home usage) and manual control (where the third party specifies a fixed charge/discharge rage). Usually our approach was to always use automatic mode to discharge the battery, but there are some edge cases (such as deliberate export or partial discharge) where explicit discharge was advantageous.

6.3 Electric vehicle

- **Next day tariff publication time.** In practice, we found that the Octopus Agile pricing for the following day was at times delayed (even though it is nominally available from 4pm), and so on MADE the tariff was updated at 8pm each day. This was found to be too late for some EV smart charging use cases: for example if the EV is plugged in at 5pm, the system has to decide whether to charge or wait for cheap night-time electricity. This may prove to have been the wrong decision after the new information when the Agile tariff is published at 8pm. This advance knowledge is particularly important for EVs that charge at a lower rate and can take 12 hours to fully charge.

- **Tesla sleep mode terminates charge.** Tesla vehicles appear to have a limitation where if the charge rate is reduced to below 6A, they enter sleep mode and permanently stop charging. This is a scenario where smart charging could have severe consequences: holding back charge for a few hours means that at the end of the night the EV is not charged at all. Within MADE we mitigated this issue by ensuring Tesla charge rates were not reduced below 6A.

- **Immaturity of smart charging.** Smart charging where a third party remotely influences the behaviour of an EV charge point (e.g. by limiting the charge rate within MADE) is a relatively immature technology.

  - Multiple technical difficulties were encountered in integrating and configuring the interfaces. Nevertheless both NewMotion and Alfen charge points were able to participate fully in the MADE system by the end of the trial.

  - Connectivity issues have been experienced with all three NewMotion charge points in the MADE homes, meaning that householders needed to manually power cycle the charge point to allow charging to be controlled.

- **Knowledge of current EV charge level** on plugging in. The key barrier to seamless provision of smart EV charging services is that there is no easy way of determining the current state of charge of an EV with typical current domestic charging technology.

  - Within MADE, our approach was to ask the user to specify the current state of charge using their smartphone App, and then allow a charge buffer of 5 - 10% of the EV capacity to ensure that charge level was over- rather than under-provided. It was then possible to detect the end of the cycle by spotting the EV stopping drawing power from the charge point (in practice this tails off in a curve as the battery is trickle charged when nearly full). This needed careful treatment in the optimisation algorithms.

  - In future this would likely be resolved by two way communications on the EV charge cable (such as CHADEMO).

- **EV prewarming.** EVs have a prewarming function where mains electricity can be used to de-ice and warm the vehicle on winter mornings. Smart control systems need to allow for this and not prevent it happening. Within MADE the control system reset the charge point limit back to maximum when the EV was detected as full, which enabled unrestricted prewarming.

- **Missed charge point notifications.** Notifications from the charge points in the MADE trial could easily be missed in circumstances of intermittent connectivity (EV start and end of session notifications are only sent once by the charge point, and it is not possible to poll their status). This needs to be handled by careful logic and use of periodic reports from the charge points, to ensure that charge sessions are appropriately started and terminated.

- **The combination of high power assets** like those on the MADE trial can lead to unexpected consequences for ordinary domestic electrical components. One MADE home had a circuit breaker (RCD) trip whenever the battery and EV charged simultaneously (combined load of ~10kW, likely to happen at the start of cheap tariff periods). This was resolved by replacing the RCD with a more suitably specified component.

- **Longer than day-ahead EV usage.** The MADE EV App enabled the user to select an EV end time for the next day, but some users would have liked to set it further in advance (e.g. commuting return on Friday and knowing the vehicle wasn't needed until Monday morning).

7 Conclusions

7.1 Summary

The MADE project carried out a field trial where four low-carbon technologies (hybrid heat pump, solar panels, battery and electric vehicle charger) were installed in five properties, together with a PassivSystems smart control system to coordinate their operation. The aim of the project was to explore the behaviour of these assets when operating together in an optimum fashion, and the consequent electrical demand shape which has an impact on the electricity grid. This report presents results from the field trial from analysis of the real monitoring data from the homes, together with the use of simulation tools to make some additional quantitative comparisons.

The key factors affecting the behaviour of the assets which were explored during the field trial were:

- **Time-of-use tariffs**: The project focused mainly on (1) “Agile” tariffs (which follow wholesale market price plus early evening peak charges) and (2) cheap nighttime tariffs (which are increasingly being offered to EV owners).
- **Level of asset coordination**: As the project progressed, the system was able to coordinate more of the assets together, and the benefits could be assessed.
- **Seasonality:** The project covered the very different circumstances of winter (where heat pump demand dominates the picture) and summer (where PV generation dominates).
- **Interventions**: Optimising assets to reduce consumer running costs is not necessarily in the best interests of the grid, so the project explored interventions crafted to directly mitigate negative impacts on the local electricity network.

The key findings from the field trial were:

- **Asset coordination.** Increasing the level of coordination between the low carbon assets brings additional benefits in terms of reduced consumer electricity costs. We have been able to quantify benefits in some scenarios using simulations but the field trial is not of sufficient scale to provide statistically significant savings figures overall.

- **Agile behaviour patterns**. The Agile tariff has the potential to offer considerable running cost benefits to consumers, 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, using which it is generally possible to take homes “off-grid” throughout the three hour evening peak period. Optimised batteries can also deliver arbitrage to exploit short term price variations, but this can lead to “spiky” demand profiles and increases in peak demand for the grid.

- With a **cheap overnight tariff** like Octopus Go, performance is driven by making the right trade-offs between (a) storing cheap electricity in the battery (b) storing it as heat in the thermal fabric of the home and (c) waiting for free solar generation later in the day.

- **Seasonal variations.** Patterns of asset behaviour changes very significantly through the seasons, being dominated by heat pump heating load in the winter and PV generation in the summer. On the Agile tariff, optimised batteries are incentivised to charge twice a day in winter but once a day in summer. PV export can also be controlled (turned down) as required, either with a suitable inverter or via a "hybrid" battery as in the case of MADE.

- **Electric vehicle charging** by default occurs at the worst time of day for the grid (early evening, as seen in the Electric Nation project), but the demand can in most cases be significantly delayed to other times, either to avoid the peak Octopus Agile tariff period or to pick up cheap overnight rates, offering considerable consumer cost savings. Coordinating battery operation with the EV can offer significant benefits, as more cheap rate electricity can be captured and utilised, but only if the systems operate properly in tandem.

- **EV user interface.** The MADE approach of allowing a user to specify in an App when they next needed to use their EV and the level of charge required worked very well. Smart EV control is currently limited by the slight immaturity of chargepoint connectivity and the challenge with determining the actual EV charge level without EV communications.

- Significant **peaks in demand** can be introduced by time of use tariffs, particularly where EV charging is involved (due to the high load), either at the start of a cheap rate period or immediately before a peak rate period (e.g. 4pm on Octopus Agile). These peaks can easily be mitigated by a smart control system, but if demand limits restrict the availability of cheap electricity there may be considerable cost implications for consumers.

- 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. This enables the heat pump to turn off, the battery to discharge, and PV generation to be exported to service the command.

Predictive controls are the key enabling technology for all of the above benefits of tariff optimisation and asset coordination. Under the MADE project PassivSystems has developed 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.

7.2 Next steps

The most valuable follow-on project would be a **larger scale field trial**. With a sample of five homes, it is not possible to make statistically meaningful conclusions about the impact on typical demand profiles, particularly when electric vehicle charging is involved (it can dominate the profiles due to the high power consumption, and yet usage patterns are often inconsistent day to day so many samples are needed to understand typical behaviour and its variability). A larger scale field trial would enable:

- Quantitative determination of **demand profiles** affecting the network under different scenarios (ToU tariff, or different asset operational modes), as well as the statistical variability and insight into diversity assumptions

- Utilisation of **aggregated control** across multiple homes, for example to apply a multi-home max power limit perhaps tuned to capacity in the local grid.

Annual forecast simulations. Some of the insight from a larger scale field trial would be achievable at much lower cost by extending the simulation work from the MADE project. These could be based on digital twins of homes which don't currently have any of the MADE assets, and would produce predictions of the demand profiles within a range of asset deployment and control scenarios, over the course of a full calendar year (rather than the anecdotal examples in this report). Simulations can provide quantitative assessments of householder costs and network impact with direct comparisons of scenarios.

Individual transformer/substation focus. An alternative direction would be a more intensive field trial focused strongly on the local grid impact (perhaps looking at rural scenarios with small transformers shared among small numbers of homes, which are likely to decarbonise to heat pumps earlier as they are off the gas grid). This trial could combine actual measurements from a transformer or substation together with multi-home control to limit the effect of combined low-carbon assets to be less than the original capacity, thus helping avoid unnecessary grid-reinforcement to support the roll-out of these low-carbon technologies.

Off-the-shelf tariff-aware assets. One limitation of MADE is that it has been hard to separate tariff optimisation from asset-coordination, as domestic batteries and EV charge points do not yet come with tariff optimisation out of the box -- so the service offered by PassivSystems includes both of these at the same time. This could be addressed by trialling more advanced batteries and EV charge points which are tariff aware, and tracking the likely progression (from simple assets, to tariff-aware assets, to coordinated assets) in a more commercially market-focused way.

Another limitation of MADE was that **V2G chargers** (where EVs could discharge to the grid) were not available for the project timescale -- these could be investigated in a future project. Such a project could also look at the benefits of being able to read the EV charge level automatically (this is likely to happen at the same time due to the CHAdeMO charge interface).

8 ANNEX A - SUPPORTING SIMULATION RESULTS, FULL SIMULATION RUNS

This section provides supporting analysis of the simulation runs discussed in Section 4.2. This section focuses on the results from the March simulation runs, as at this time of year there is involvement from all assets considered under the MADE concept, including both heating and solar.

8.0.1 Phase 1 control - Baseline

Figure 8.1 below shows the March simulation output under Phase 1 control. For this simulation run, the EV is assumed to charge in a smart manner, where charging is delayed until midnight, in order to understand additional benefits of coordinating the EV with other assets when comparing with the fully optimised scenario.

The following can be observed from the figure:

- Since there is no coordination between the heat pump and the battery, the system cannot rely on the ability to use the battery to heat the home during the expensive tariff period. The home is therefore notably overheated to 21.0° which, at 2° greater than set point, is the hottest the home is allowed to heat to as per the maximum room temperature limit in place during the simulation run.
- As most of the solar is consumed by the heat pump and other uncontrollable demand within the home, the battery does little charging on day one and therefore the home is required to import electricity from the grid during the expensive evening Agile tariff period. On day two, there is more solar available and the battery reaches a maximum state of charge of 45%, which is sufficient to keep the home off grid during the evening peak tariff period. There is no battery activity overnight.
- The EV starts charging at midnight and charging has completed by 04:00.

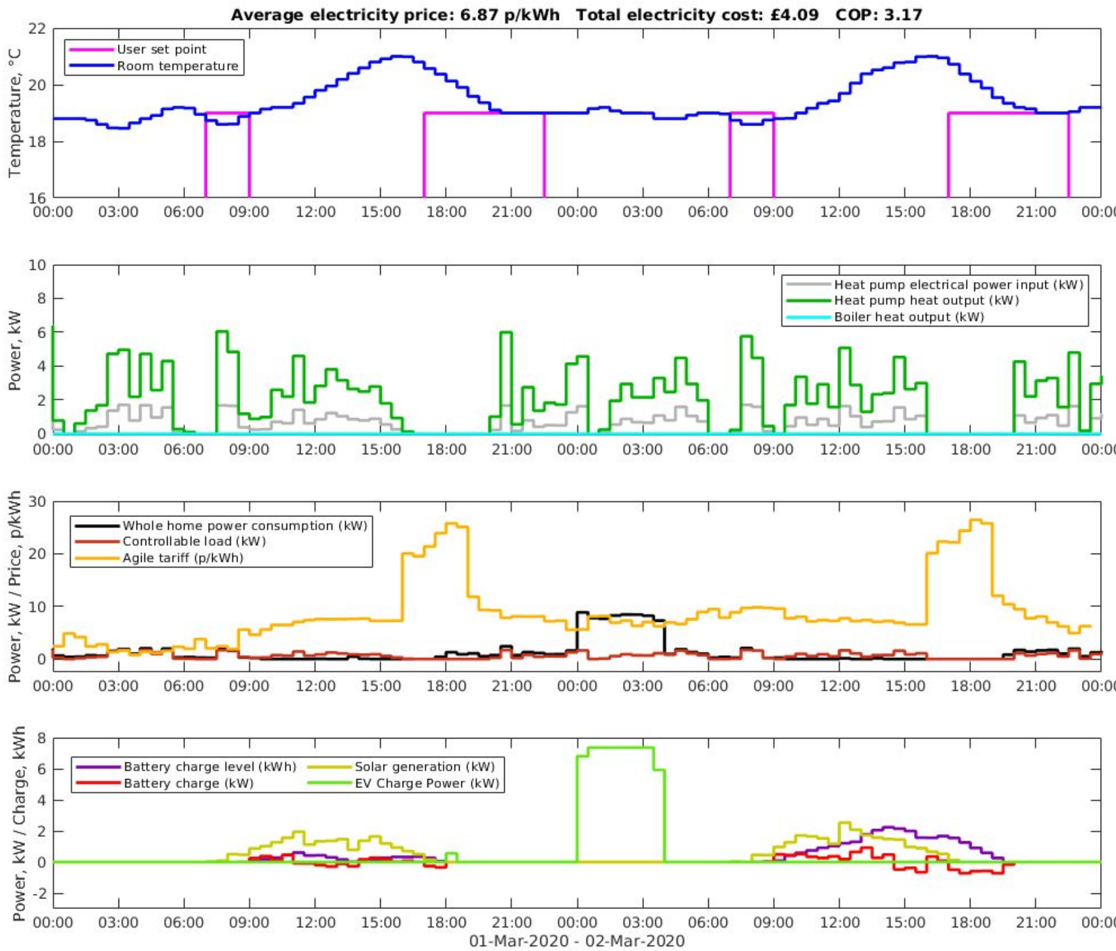

Figure 8.1 - Full simulation run under Phase 1 control with smart EV charging (Digital twin of Home 2, 01/03/2020 - 02/03/2020)

8.0.2 Phase 2 control - Some coordination

Figure 8.2 shows the March simulation output under Phase 2 control. For this simulation run, the EV is assumed to charge in a smart manner, where charging is delayed until midnight, in order to understand additional benefits of coordinating the EV with other assets when comparing with the fully optimised scenario. The following can be observed from the figure:

- As there is now coordination between the heat pump and the battery, the system has more confidence in the ability to use the battery to heat the home during the expensive tariff period. Thus the home is only heated to a maximum temperature of 20.4° and the heat pump is operated during the evening peak tariff period using electricity stored in the battery, preventing the need to import from the grid during this expensive period.

- The battery now does additional charging using cheap overnight electricity in order to meet the morning heating demand once the tariff is notably more expensive. During the EV charge session, the battery does a mixture of charging and discharging. Since there is no coordination between the EV and the battery at this point, this only occurs since the battery charges to take advantage of the cheap rate, the battery then detects high consumption and thus discharges to meet this in automatic mode, and once empty again the battery once again decides to charge with a view to offsetting heating and baseload demand once the tariff price increases. Although this indirectly helps to lower the cost of the EV charge session, without coordination between the EV and the battery, the EV charging cannot be reduced to match the power that the battery is able to discharge during the expensive tariff periods which would allow for further cost savings to be achieved.

- The EV starts charging at midnight and charging has completed by 04:00.

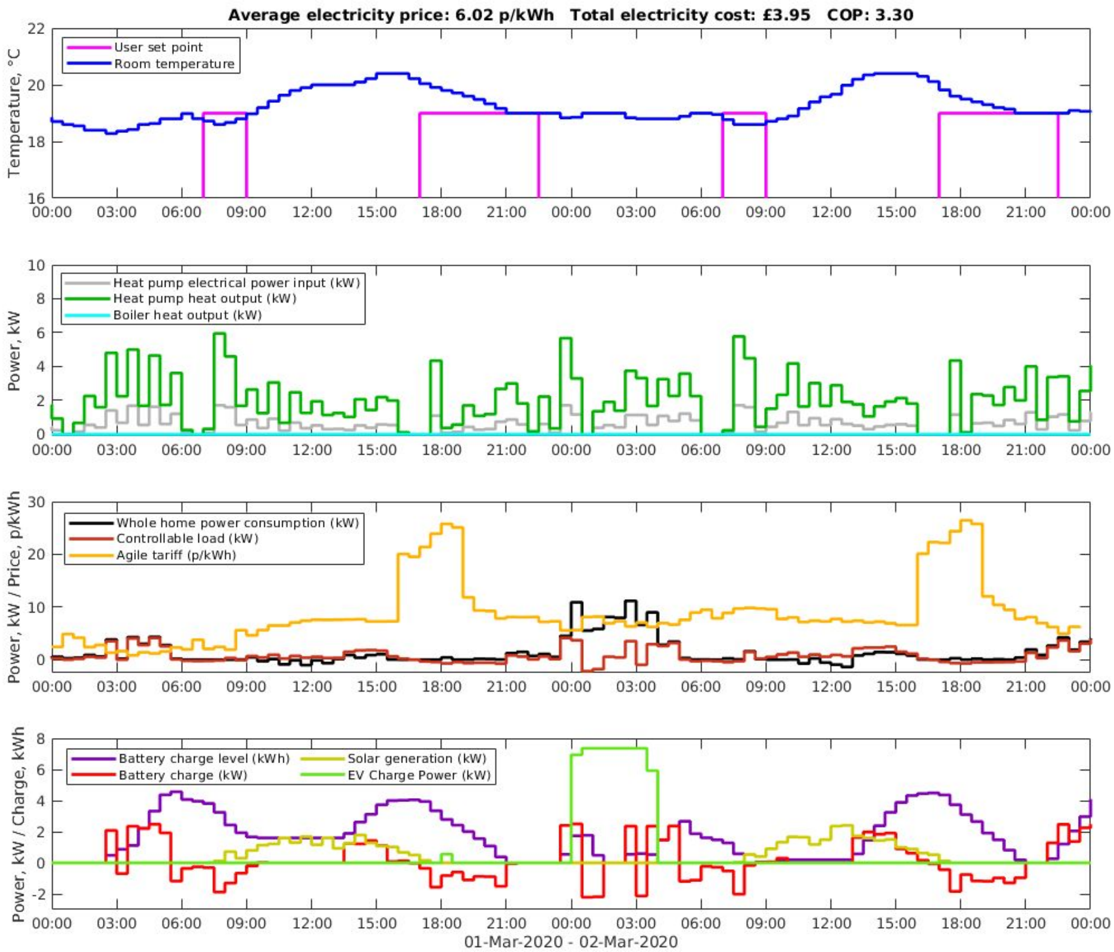

Figure 8.2 - Full simulation run under Phase 2 control with smart EV charging (Digital twin of Home 2, 01/03/2020 - 02/03/2020)

8.0.3 Phase 3 control - Full coordination

Figure 8.3 below shows the March simulation output under Phase 2 control. The following can be observed from the figure:

- As there is coordination between the heat pump and the battery, the system again has confidence in the ability to use the battery to heat the home during the expensive tariff period. Thus the home is only heated to a maximum temperature of 20.4° and the heat pump is operated during the evening peak tariff period using electricity stored in the battery, preventing the need to import from the grid during this expensive period.
- The battery again does additional charging using cheap overnight electricity in order to meet the morning heating demand once the tariff is notably more expensive. During the EV charge session, the battery does a mixture of charging and discharging. This is no longer coincidental charge and discharging but planned with full awareness of the upcoming EV demand. As a result, during the most expensive overnight tariff period the EV power is matched to the power that the battery is able to discharge in order to prevent the need for import during this hour.

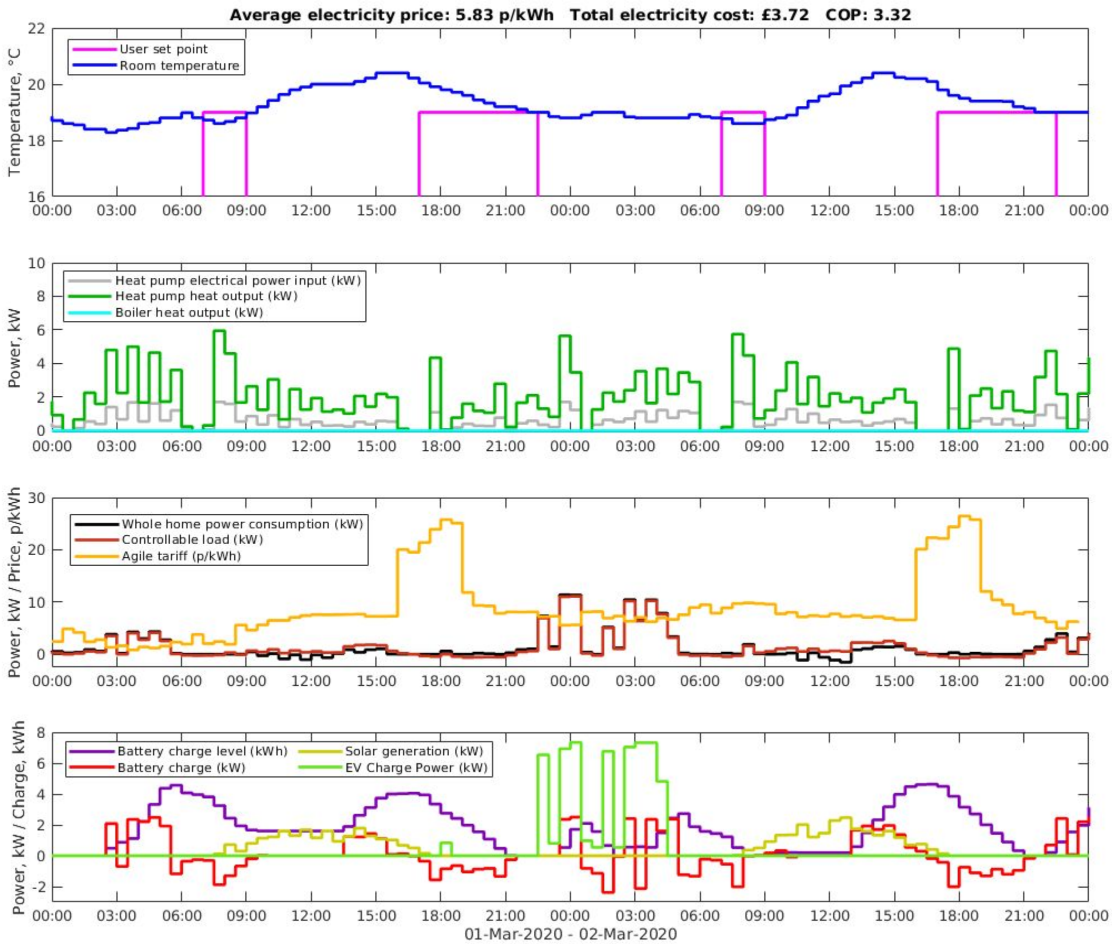

Figure 8.3 - Full simulation run under Phase 3 control (Digital twin of Home 2, 01/03/2020 - 02/03/2020)

9 ANNEX B - SUPPORTING SIMULATION RESULTS, FLEXIBLE POWER

This section provides supporting analysis of the simulation runs discussed in Section 4.3. This section focuses on the results from the simulation runs with a Flexible Power window of 16:00 - 18:00, since demand is typically expected to be highest at this time.

9.0.1 Octopus Agile Tariff

Figure 9.1 shows the baseline simulation run with no Flexible Power request on the Octopus Agile tariff. The following can be noted from the figure:

- Room temperature is consistent throughout the day with a maximum temperature of 19.2° and a minimum of 18.6°. The heat pump is operated during the evening peak Agile tariff period however this demand is met by the battery.
- The battery charges up using cheap electricity overnight before discharging to meet household consumption over the morning once the tariff becomes more expensive. The battery then charges up again in advance of the evening Agile peak tariff period.
- No household import is required during the evening peak Agile tariff period.

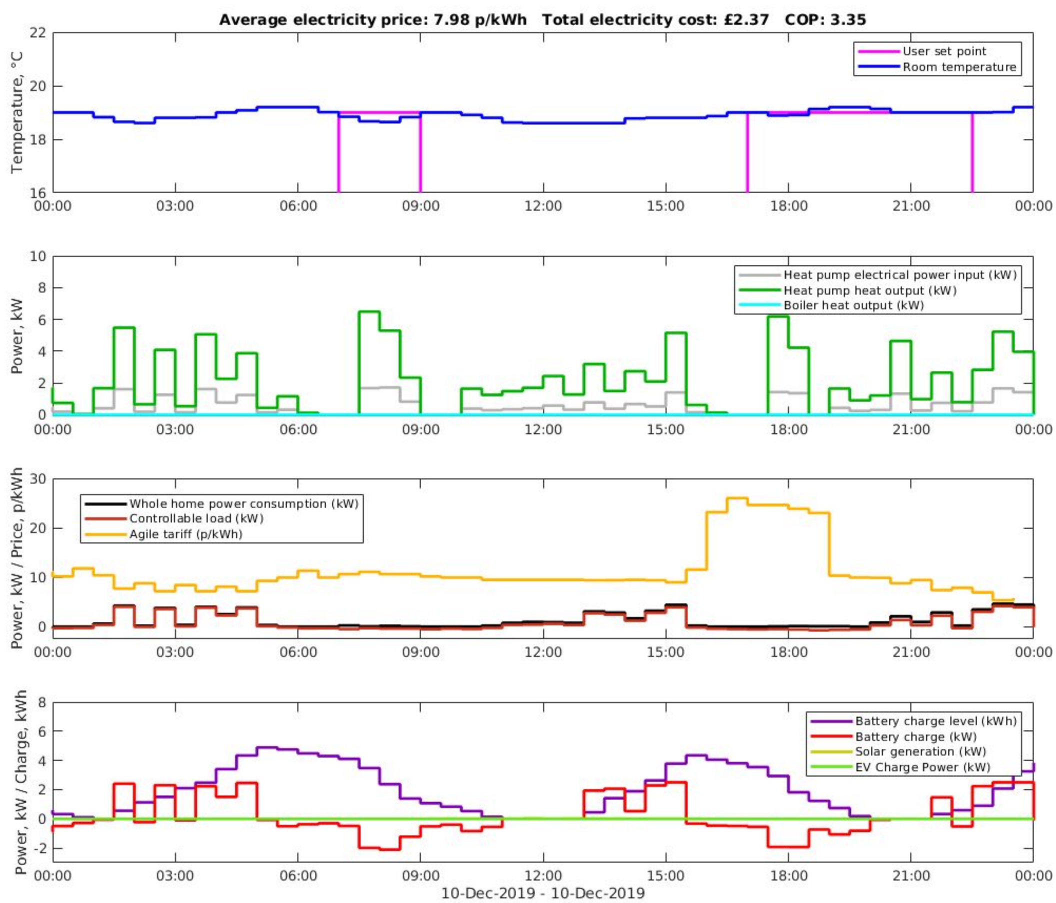

Figure 9.1 - Full baseline simulation run on the Octopus Agile tariff (Digital twin of Home 2, 10/12/2019)

Figure 9.2 shows the simulation where the home is prepared for a 16:00 - 18:00 Flexible Power request but this request is not utilised. The following can be noted from the figure:

- The home is now overheated to 19.8° in advance of the potential Flexible Power request window, to ensure that comfort levels could be maintained without the need to run the heat pump during this period should a request come in.

- Due to the similarities of preparing for the peak Agile tariff period and preparing for a Flexible Power request kicking in at the same time, the total electricity cost for the day has not changed significantly, with a total increase of £0.08. Additionally, this is offset by a Flexible Power availability payment of £0.02 leading to a total net cost of only £0.06 incurred by the householder.

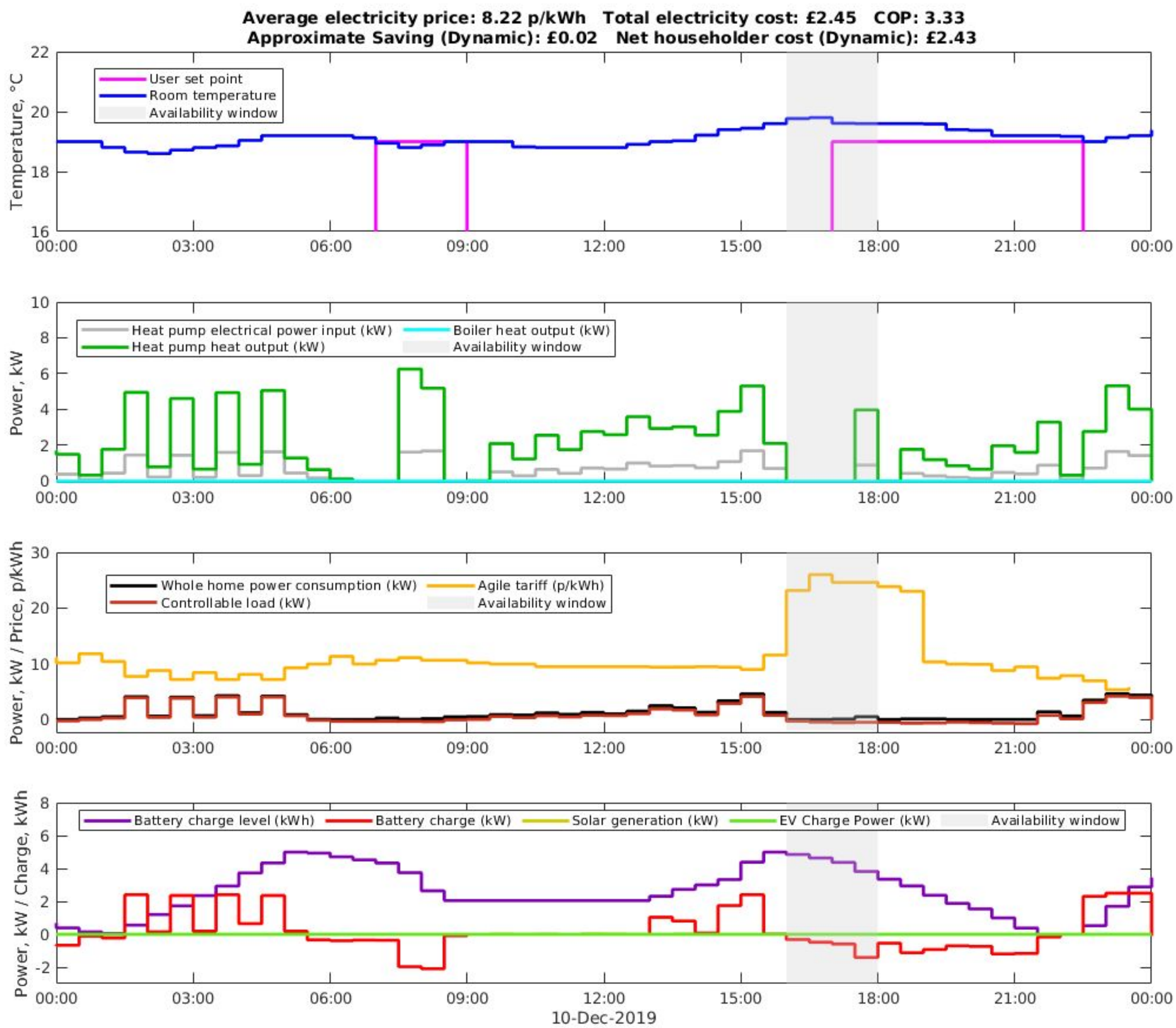

Figure 9.2 - Full simulation run, available for 16:00 - 18:00 but request is not utilised on the Octopus Agile tariff (Digital twin of Home 2, 10/12/2019)

Figure 9.3 shows the simulation where a Flexible Power request is utilised between 16:00 - 18:00. The following can be noted from the figure:

- The battery charge pattern is very similar to before however the battery now fully discharges between 16:00 and 18:00 in order to ensure that demand is sufficiently lowered during this interval. Some import is thus required during the last hour of the peak Agile tariff period whilst the tariff is still very expensive.

- The total electricity cost for the day has increased by £0.49 compared to the baseline case. However the Flexible Power cost benefit paid to the householder is 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 is very similar.

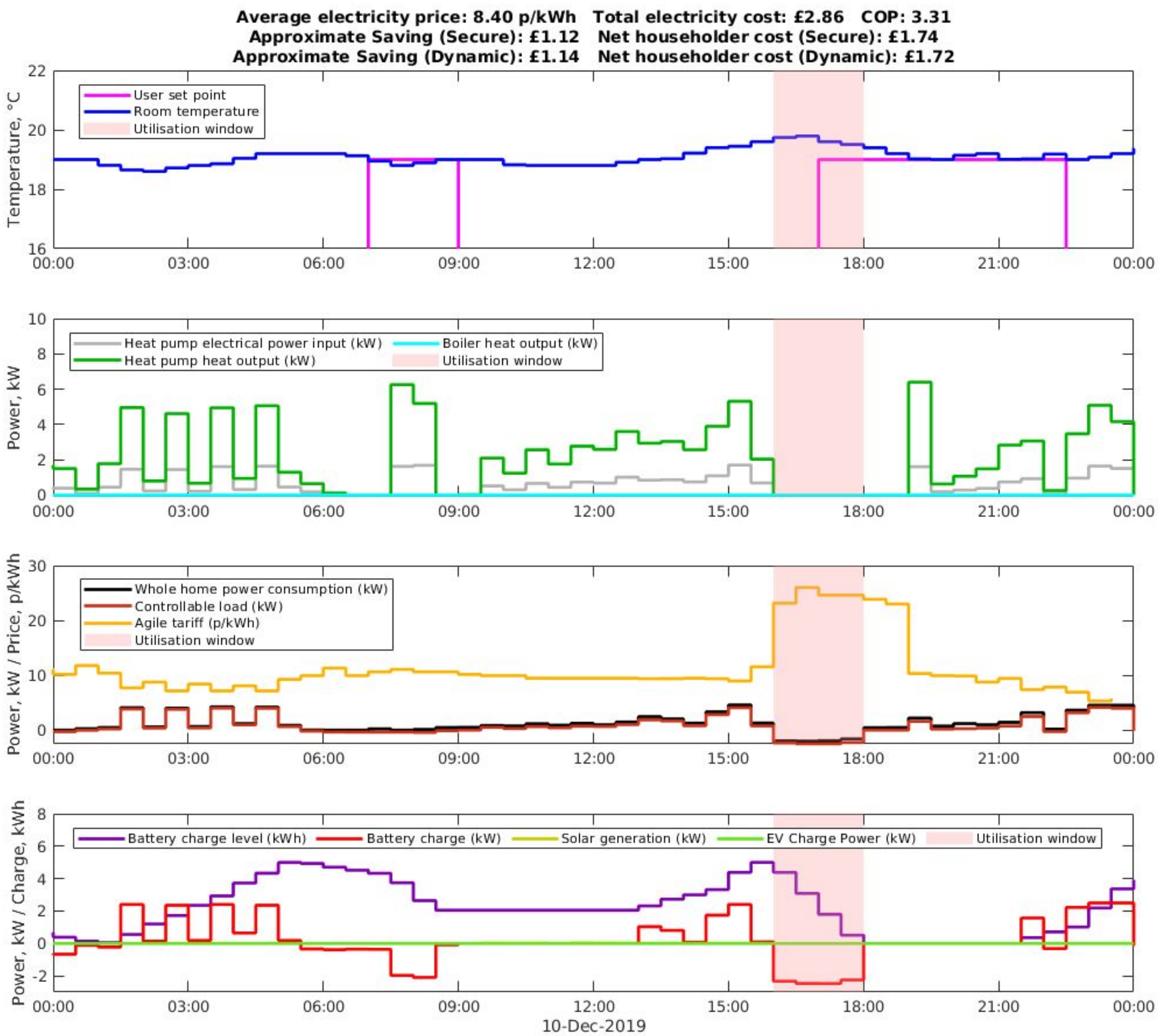

Figure 9.3 - Full simulation run, 16:00 - 18:00 request utilised on the Octopus Agile tariff (Digital twin of Home 2, 10/12/2019)

9.0.2 Octopus Go Tariff

Figure 9.4 shows the baseline simulation run with no Flexible Power request on the Octopus Go tariff. The following can be noted from the figure:

- The home is overheated slightly to 19.4° during the cheap overnight period.
- The battery completes a full charge during the cheap electricity period overnight and discharges over the course of the morning to meet household consumption including heating demand.

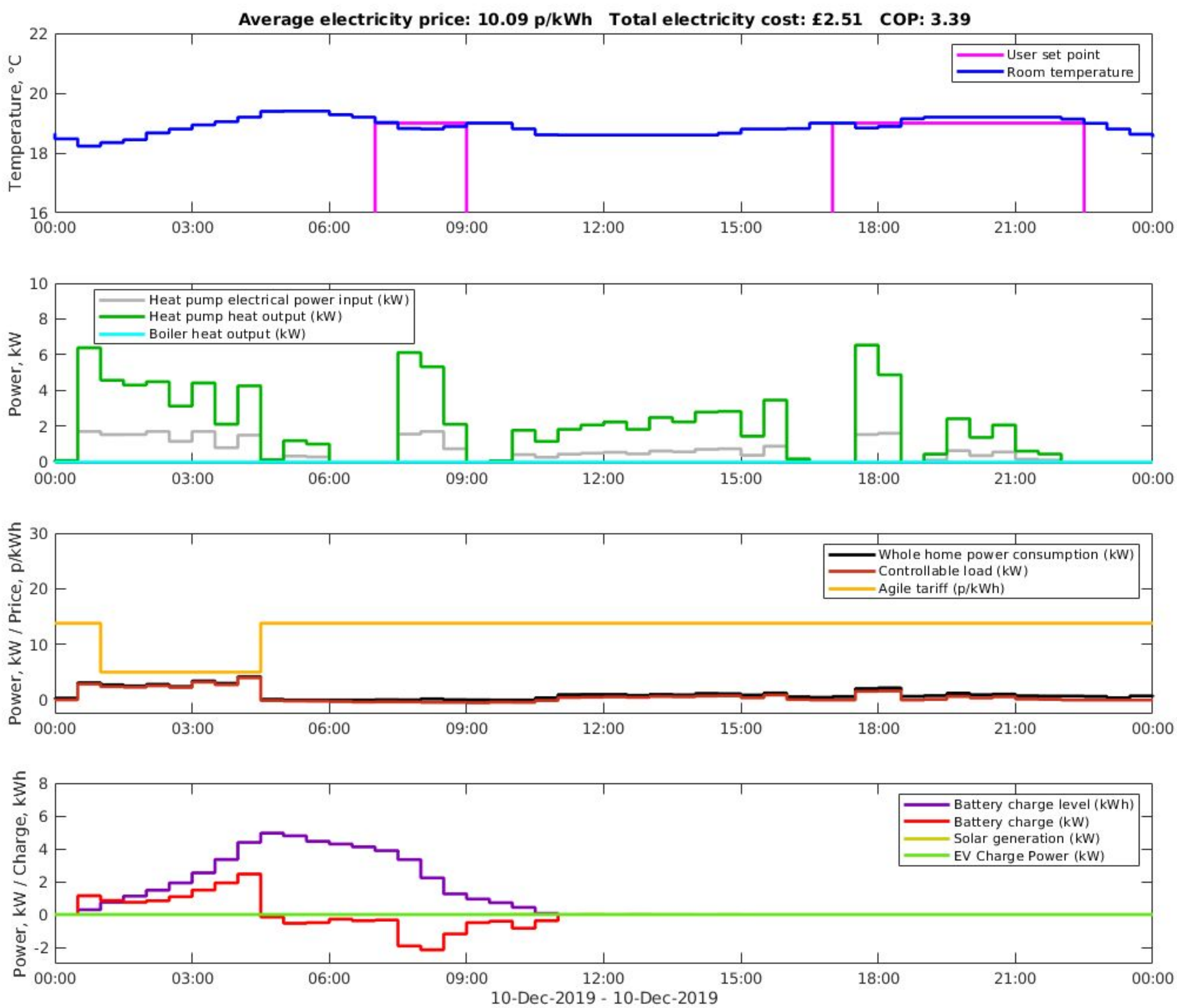

Figure 9.4 - Full baseline simulation run on the Octopus Go tariff (Digital twin of Home 2, 10/12/2019)

Figure 9.5 shows the simulation where the home is prepared for a 16:00 - 18:00 Flexible Power request but this request is not utilised. The following can be noted from the figure:

- The home is again overheated slightly during the cheap overnight period, however this time it is heated to a slightly higher to 19.7°.
- The battery completes a full charge during the cheap electricity period overnight, however this charge is now held until the potential Flexible Power window so that a request could be met using cheap electricity. In the absence of a request, the battery then begins to discharge to meet household demand.

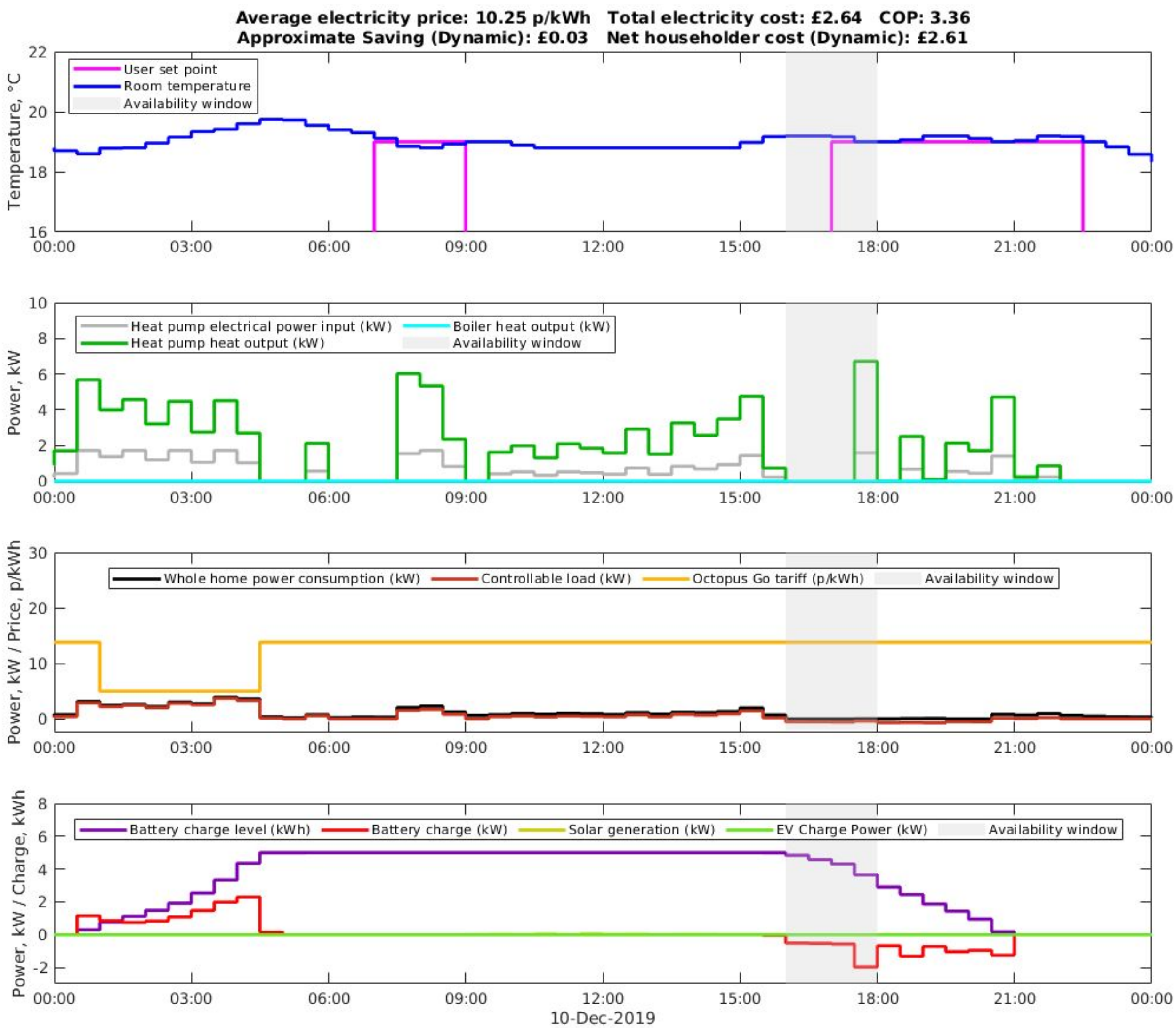

Figure 9.5 - Full simulation run, available for 16:00 - 18:00 but request is not utilised on the Octopus Go tariff (Digital twin of Home 2, 10/12/2019)

Figure 9.6 shows the simulation where a Flexible Power request is utilised between 16:00 - 18:00. The following can be noted from the figure:

- The home is again overheated to 19.7° during the cheap overnight period.
- The battery completes a full charge during the cheap electricity period overnight, however this charge is now held until the potential Flexible Power window and the battery then discharges at full rate over the request period.

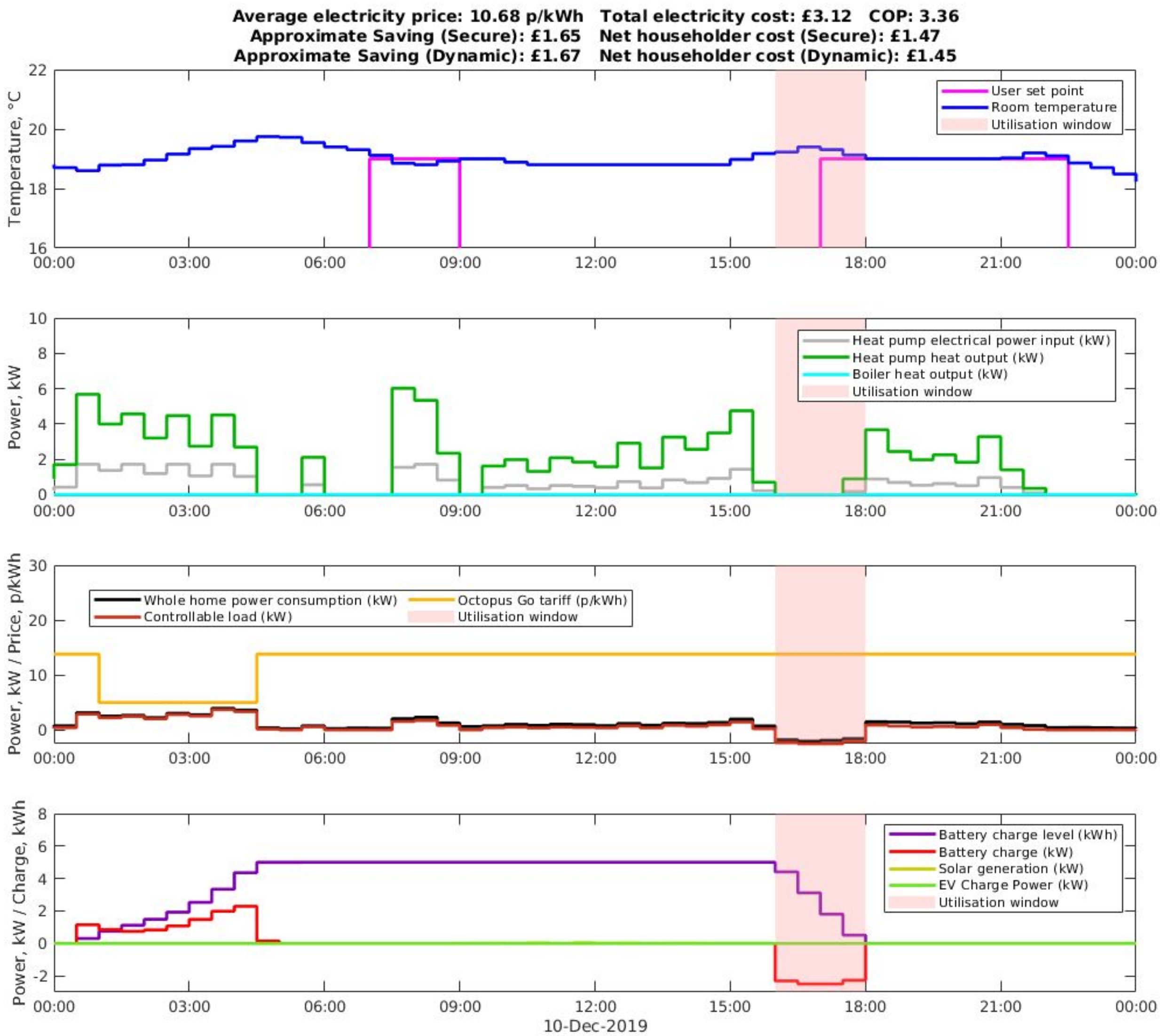

Figure 9.6 - Full simulation run, 16:00 - 18:00 request utilised on the Octopus Go tariff (Digital twin of Home 2, 10/12/2019)

10 ANNEX C - SUPPLEMENTARY FIELD TRIAL RESULTS

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 thus some of the key examples of fully coordination control were conducted slightly later in the year during summer, resulting in lower heating demand than originally anticipated. In light of this, the MADE field trial was extended into winter 2020/2021 to allow for examples of fully coordinated control with notable heating demand to be explored.

During this additional stage of the project, interventions were also carried out to explore how the heat pump could be used to contribute to hot water, alongside the fossil fuel boiler. The ability to heat hot water using either fuel source would provide increased flexibility and allow the hot water tank to act as an additional storage asset, storing electricity when the tariff is sufficiently cheap or when it is beneficial for the grid.

10.1 Fully Coordinated Control

This section of the report covers examples of fully coordinated control with notable heating demand. During this stage of the project the homes were operating until a Phase 3 control approach, 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 Passiv's EV control algorithm, based on user information inputted via the Passiv 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.

The homes were optimised to two different tariffs:

- **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.
- **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.

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**.

10.1.1 Octopus Go tariff

Figure 10.1 shows typical operation under the coordinated control strategy implemented in Phase 3 of the trial during a winter scenario, 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 heat pump operating and the battery and EV (where plugged in) charging during this time.
- Thermal comfort is maintained across the two day period, with heating demand primarily met using the heat pump. The heat pump runs at full power during the cheap overnight tariff period in order to heat the home at the lowest possible cost. During the late afternoon of day 1 the room temperature dips 0.3°C below set point (likely due to a door/window being left open) and the boiler kicks in briefly to bring it back up to temperature quickly.
- The battery undergoes a full charge during the cheap overnight tariff period and then discharges over the course of the day.
- The EV is plugged in at 16:30 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. The EV charges at a reduced rate until the cheap tariff period when it charges at maximum power.

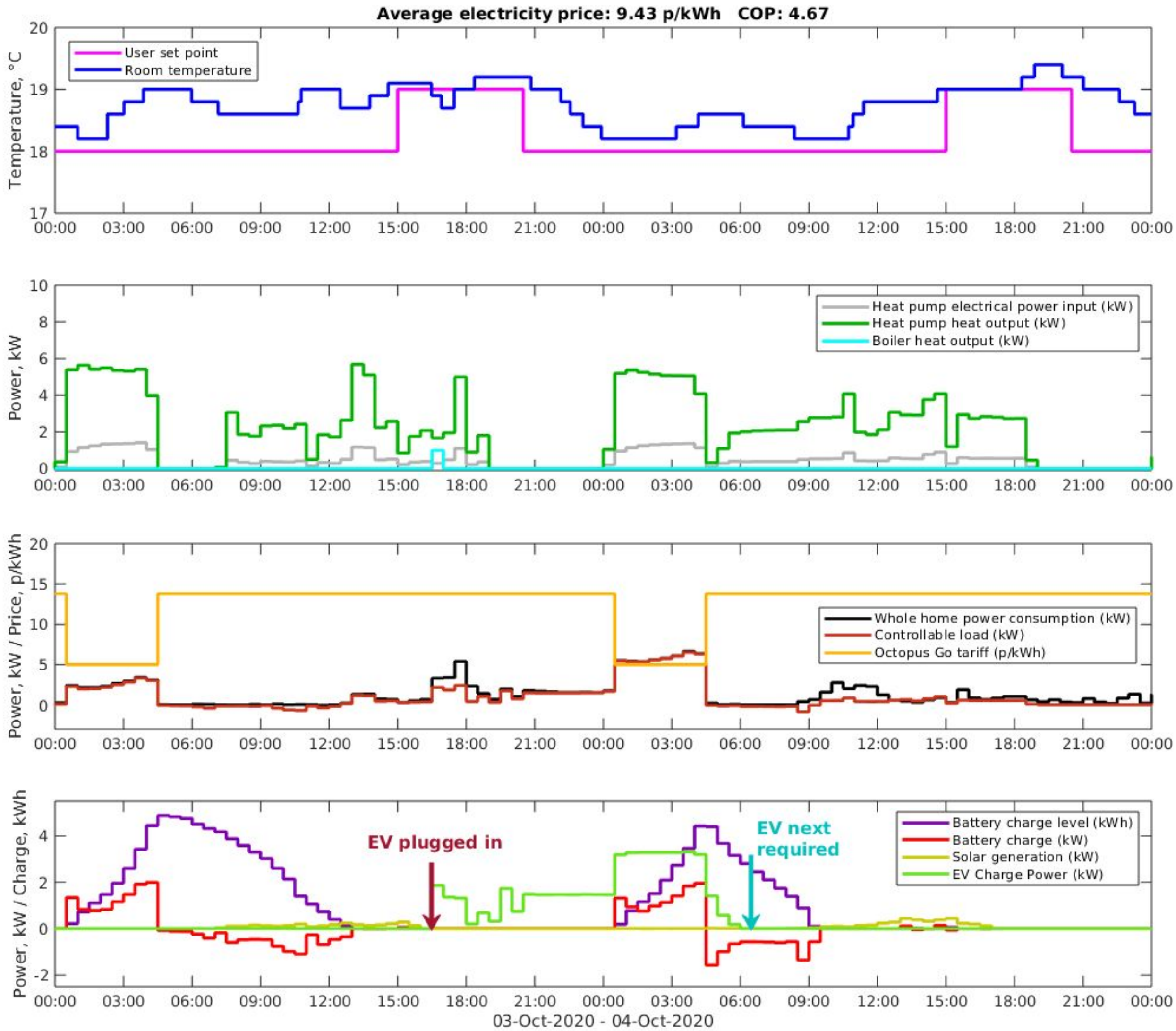

Figure 10.1 - Fully coordinated control on the Octopus Go tariff *(Home 1, 03/10/2020 - 04/10/2020)*

10.1.2 Fully Coordinated Control - Agile tariff

Figure 10.2 below shows typical operation under the coordinated control strategy implemented in Phase 3 of the trial during a winter scenario, against the Octopus Agile tariff. The following can be observed from the figure:

- Thermal comfort is maintained, with heating demand met entirely by the heat pump. Coordination with the battery allows the heat pump to operate during the peak Agile tariff period, with the battery discharging to meet heat demand during this period avoiding the need to import electricity.

- One day one, the battery charges in advance of the peak Agile tariff period from a combination of excess solar generation and cheap electricity. The battery then discharges over the peak tariff period to meet demand within the home, including demand from the heat pump. On day two the battery also charges overnight when electricity is sufficiently cheap in addition to charging from excess solar generation, again offsetting demand during the peak tariff period.

- The EV is plugged in at 11:30 on day one, with the user requesting full charge by 10:00 the following morning. The maximum charge rate for this particular EV is 3.6kW.

    - At the beginning of the charge session, the EV charges from a combination of excess solar generation and cheap electricity.

    - The EV stops charging entirely during the peak Agile tariff period, and for the few hours following this period where electricity is still relatively expensive.

    - Once electricity becomes sufficiently cheap overnight the EV begins to charge at full rate and is fully charged by the requested time.

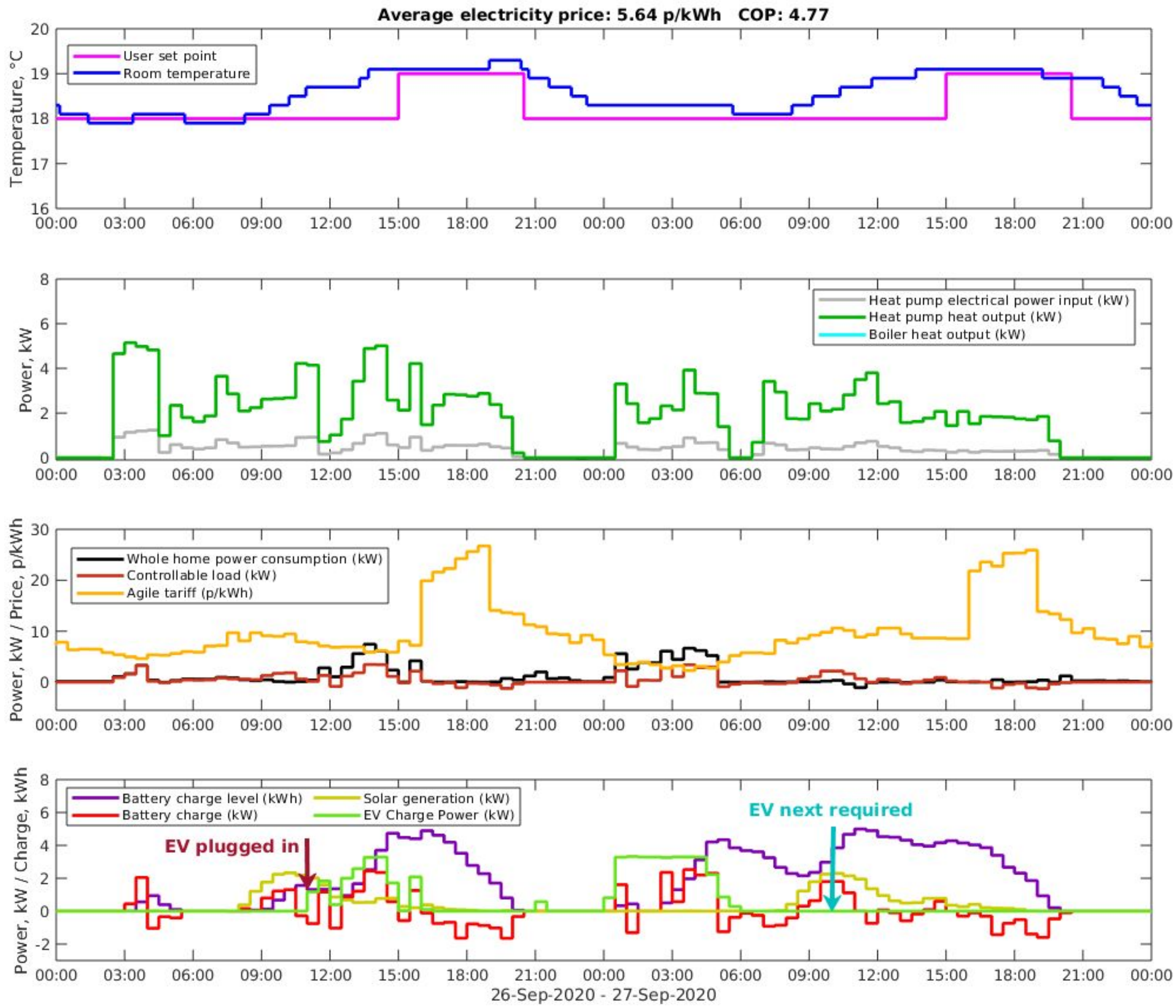

Figure 10.2 - Fully coordinated control on the Octopus Agile tariff *(Home 01, 26/09/2020 - 27/10/2020)*

10.2 Hot Water

This section of the report covers interventions that were carried out to explore how the heat pump could be used to contribute to domestic hot water (DHW) production, with a view to utilising the hot water cylinder as an additional energy storage vector (in addition to the thermal fabric of the house, the battery, and the EV battery), which can offer additional flexibility to balance the grid. The interventions carried out under MADE demonstrate heat pump hot water capability in action and provide insight into the heat contribution from the heat pump as well as future flexibility potential.

Usually with a hybrid heat pump, hot water production is carried out solely by the fossil fuel boiler. Using the heat pump to contribute is not trivial due to the complexity of the plumbing configuration and the fact that the hot water cylinder is designed to be heated only by a high temperature fossil fuel boiler system (heat pumps typically require a dedicated hot water cylinder with a much larger area coil).

Figure 10.3 shows a hybrid hot water intervention for MADE Home 05. During this intervention, the hot water preheat period was set to 90 minutes in advance of a hot water requirement, and the system was instructed to use the heat pump for the first 60 minutes of this. From Figure 10.3 it can be observed that the heat pump alone meets the entire space heating requirement of the home, which is as expected since there is relatively low demand for heat and there are no user set point changes during this period. The hot water is heated up initially by the heat pump, and then the boiler fires next to bring the tank fully up to temperature. From the heat output figures, the heat pump can be seen to be providing the majority of the hot water energy, and demonstrating good scope for additional flexibility.

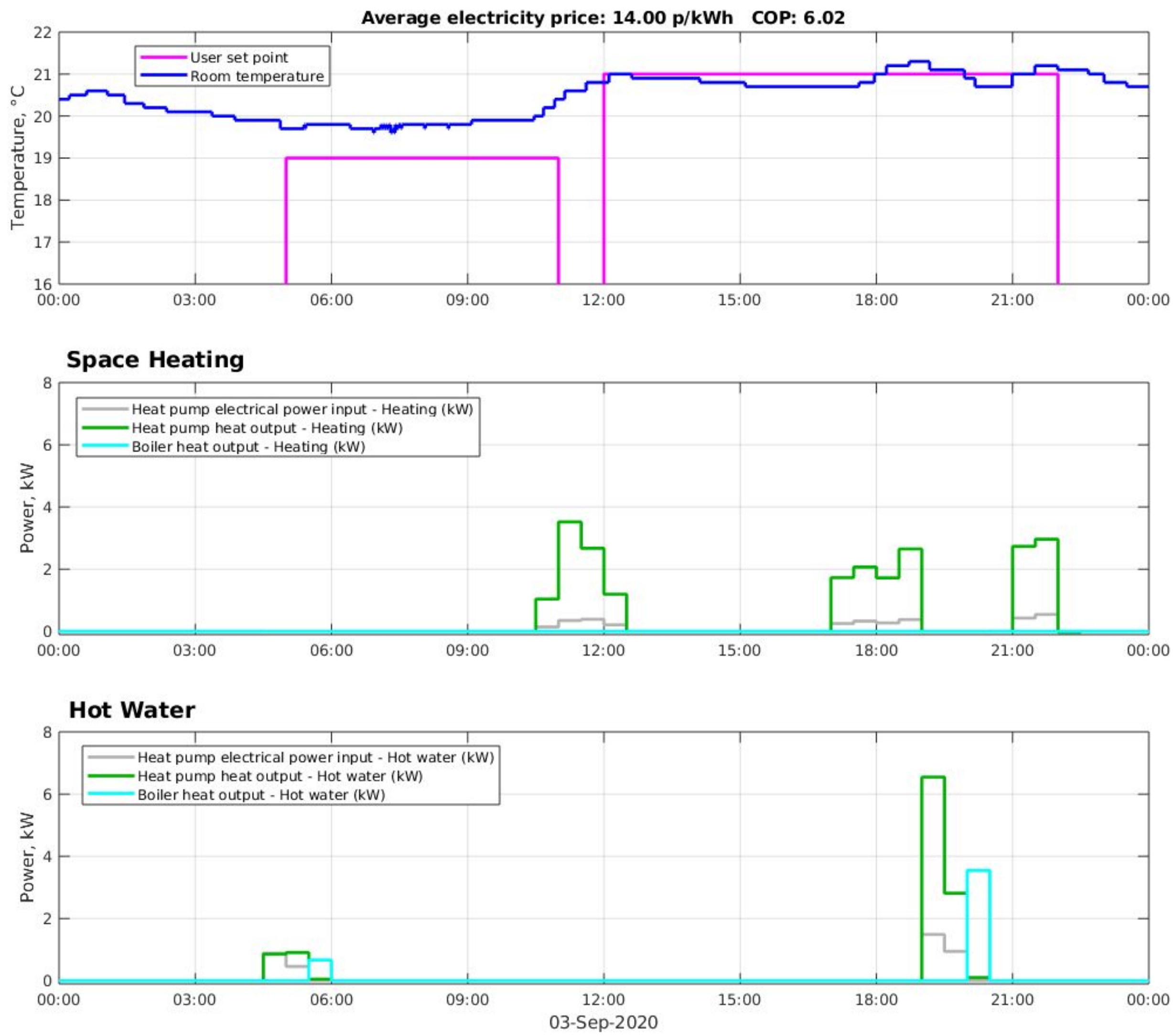

Figure 10.3 - Hot water intervention *(Home 05, 03/09/2020)*

Figure 10.4 shows a hybrid hot water intervention for MADE Home 03. During this intervention, the hot water preheat period was set to 90 minutes in advance of a hot water requirement, and the system was instructed to use the heat pump for the first 60 minutes of this. From Figure 10.4 it can be observed that again the heat pump alone meets the entire space heating requirement of the home, which is as expected since there is relatively low demand for heat and there are no user set point changes during this period. Additionally it can be seen that both the heat pump and the boiler are used for hot water, as planned. Again the heat pump contribution to hot water generally meets or exceeds that of the boiler, demonstrating good scope for additional flexibility.

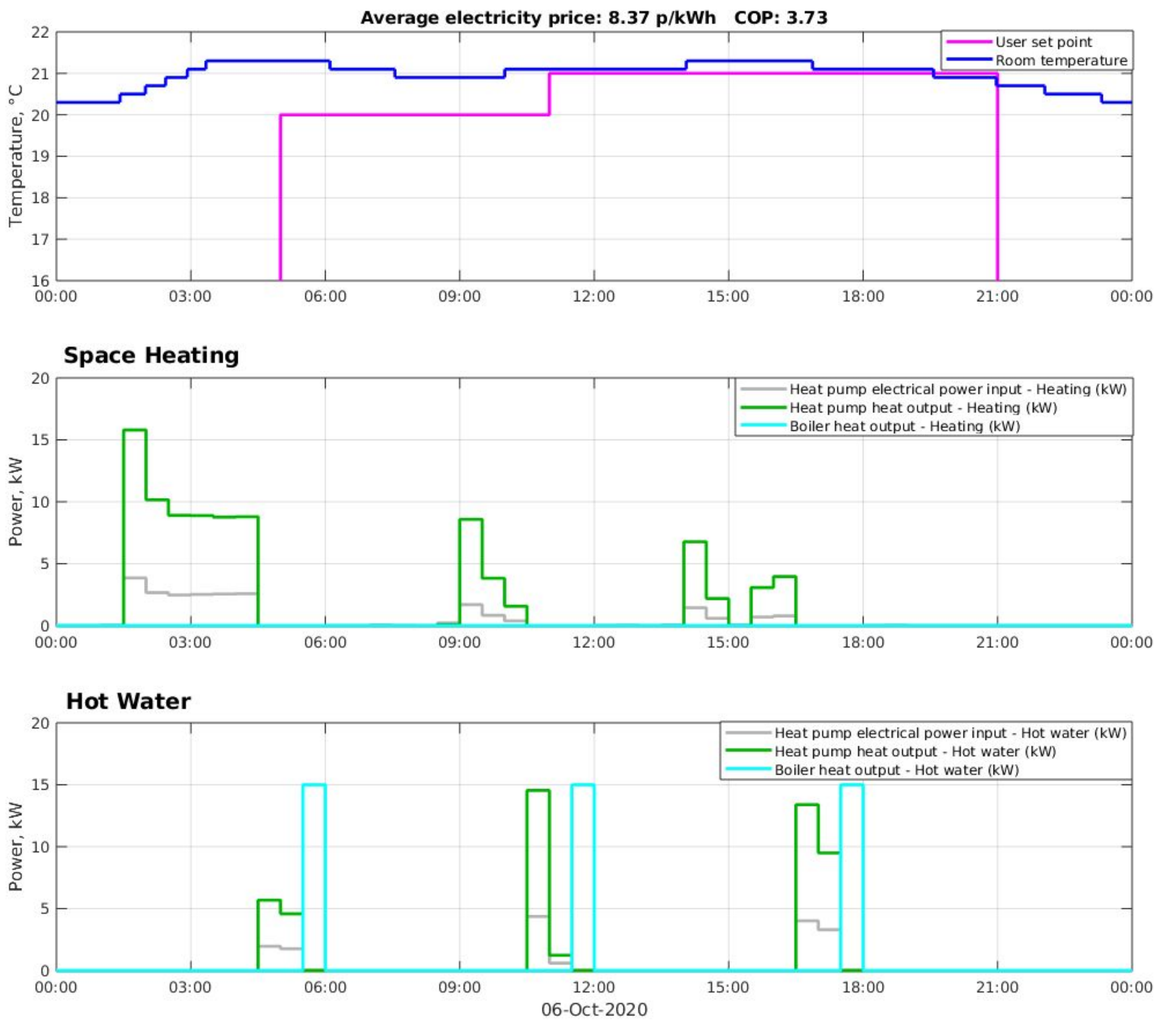

Figure 10.4 - Hot water intervention *(Home 03, 06/10/2020). Note that the boiler heat output is estimated as this home does not have a boiler heat meter.*

10.3 Summary

10.3.1 Fully Coordinated Control

The benefits of fully coordinated control can continue to be observed when moving towards winter when increased heating demand is observed. As demand for heat increases, the heat pump generally runs at full power during cheap tariff periods, allowing heat demand to be met at the lowest cost. In addition, coordination between the heat pump and the battery allows thermal comfort to be maintained whilst avoiding grid import during expensive tariff periods.

Whilst solar generation generally reduces as heat demand increases, Section 10.1.2 demonstrates a scenario where both solar generation and heat pump demand are at notable levels, providing a good example of all four assets considered under the MADE concept being actively coordinated at once. As solar generation becomes negligible battery optimisation becomes increasingly important, with the battery charging during cheap tariff periods and discharging during expensive tariff periods.

10.3.2 Hot Water

The hot water interventions presented in this section demonstrate that combined heat pump and boiler operation can successfully be used to meet hot water demand, and these examples provide evidence that the heat pump contribution can be significant enough to offer worthwhile cost and carbon savings as well as additional electricity demand flexibility. The next step is to incorporate heat pump and boiler hot water operation fully within the optimisation calculations. This would allow the hot water tank to act as an additional storage block for cheap electricity, in addition to offering additional flexibility to meet the needs of the grid, in an automated way that ensures the hot water requirements of the household are fully met.