Energy
Superhub
Oxford

Energy Superhub Oxford

Final Report

APRIL 2023

Environmental Change Institute eci

DEPARTMENT OF ENGINEERING SCIENCE

UNIVERSITY OF OXFORD

Contents

Suggested citation:

Hampton, S., Azzouz, L., Fawcett, T., Grunewald, P., Howey, D., Kumtepeli, V., Mould, T., Rose, T. (2023). Energy Superhub Oxford: Final report. Available: **energysuperhuboxford.org**

Executive Summary

Energy Superhub Oxford (ESO) is a £41m demonstration project delivering innovation in smart local energy systems. As countries around the world embark on energy transitions to decarbonise their economies, decentralised and digitised solutions are increasingly important in delivering power, heat and mobility to users. Exploring options for smart local energy systems is a key UK priority.

ESO is one of three large demonstrator projects part-funded by the UK government under its "Prospering from the Energy Revolution" (PFER) programme. Work began in April 2019 and ran until March 2023. ESO's main focus has been on investment in infrastructure for energy storage, electric vehicle charging, low carbon home heating and developing innovative, smart ways of generating benefits from these for users, investors and society at large.

This report has been produced by the University of Oxford team and draws on their research findings spanning each of the major work packages: transport (including private wire and Superhub construction), decarbonising heat, and the transmission grid connected battery, its operation and carbon impact. It also includes a chapter on consortium working practices and concludes with overall learnings from the project.

Project Partners.
ESO is a consortium of six partners led by EDF Renewables (formerly Pivot Power) and including Oxford City Council, Habitat Energy, Kensa Contracting, Invinity Energy Systems and the University of Oxford.

Transport

ESO set out to accelerate a smooth and just transition to EVs in and around Oxford. The project supported a wide range of activities that have implications for the economic, social, and environmental sustainability of the transition.

Oxford's Hackney taxis

ESO has accelerated the transition to EVs in the Hackney taxi community. Oxford's Zero Emissions Zone will ban diesel taxis in the city centre from 2025, and through ESO, Oxford City Council was able to offer licenced drivers a £5,000 grant towards the purchase of ultra-low emission vehicles (ULEV). These factors led to higher-than-expected take-up of ULEV taxis during the project. Currently, around 26 out of the 107 licenced Hackney taxis in Oxford are electric.

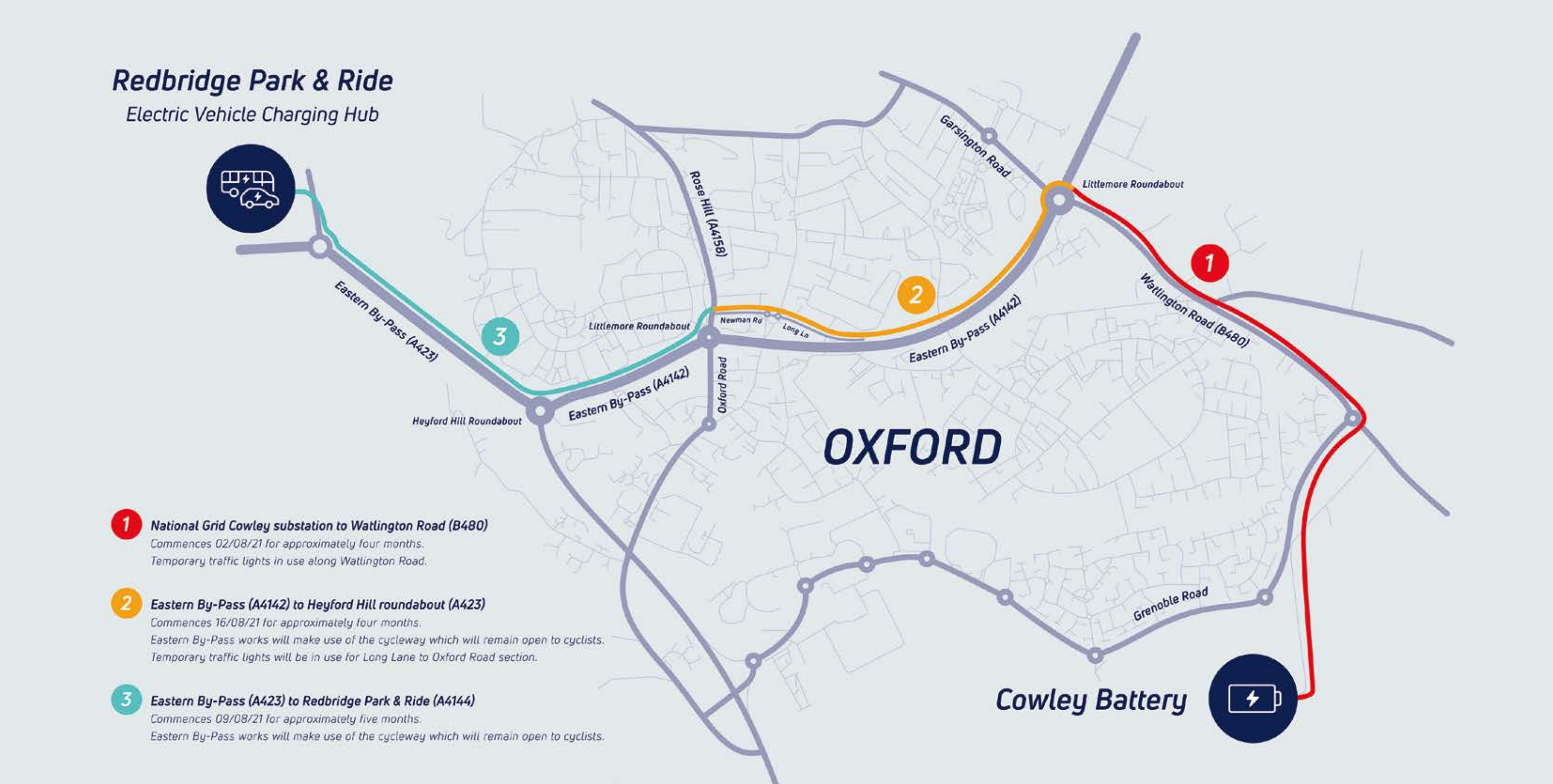
Taxi drivers are generally satisfied with the transition. They reported financial savings on fuel costs, satisfaction with the available charging infrastructure, a quiet and pleasant driving experience, and happy customers. Environmentally, the EV taxis reduced CO_2 emissions by a minimum of 60 tonnes in 2022 alone, plus reductions in other pollutants and noise levels.

However, the EV taxis' high upfront cost, the lack of local EV-specialised technicians, and the taxis' new technology constituted notable concerns to some drivers. Future grants, incentives, and training will be necessary to guarantee a just, inclusive, and smooth transition.

Private Wire and Superhub Construction

A key element of the ESO project is a 6.9 km 'private wire' cable running from the National Grid Connection at Cowley to the Redbridge Park and Ride. Due to being directly connected to the transmission network, the private wire provides large amounts of power and offers an affordable and timely alternative to distribution network connections for public and fleet EV customers. This infrastructure was constructed and is owned by EDF Renewables, whose business model is to offer capacity for large amounts of power to customers on the route.

The private wire enables the Redbridge Superhub to be the first transmission-connected charging hub in the UK, offering up to 10 MW for ultra-rapid charging. In total it currently offers 42 charging points at what is the UK's largest and Europe's most powerful charging hub, with the capacity to extend to hundreds more.



1 National Grid Cowley substation to Watlington Road (B480)
Commences 02/08/21 for approximately four months.
Temporary traffic lights in use along Watlington Road.

2 Eastern By-Pass (A4142) to Heyford Hill roundabout (A423)
Commences 16/08/21 for approximately four months.
Eastern By-Pass works will make use of the cycleway which will remain open to cyclists.
Temporary traffic lights will be in use for Long Lane to Oxford Road section.

3 Eastern By-Pass (A423) to Redbridge Park & Ride (A4144)
Commences 09/08/21 for approximately five months.
Eastern By-Pass works will make use of the cycleway which will remain open to cyclists.

The Oxford Bus Company is committed to using the private wire to enable ultra-rapid charging of its 104 buses which will be electrified under a national scheme, with buses beginning to arrive in the autumn of 2023, contributing to Oxford's air quality objectives as well as net zero plans.

Key lessons in developing and delivering the private wire have included the need for a new and progressive charging structure to make such transmission-connected EV charging projects viable; clarifying metering arrangements for transmission connections; and many planning and construction-related learnings which can be applied in future projects.

User experiences at the Superhub

The Superhub's strategic location and its proximity to major roads plus offering rapid charging were found to be key factors that attract users of different journey purposes, distances, and socio-economic backgrounds. A significant proportion of users come from outside Oxfordshire and are familiar with other public charging stations. Overall, charging experiences at the Superhub exceeded users' expectations, including ease of payment, finding and accessing the Superhub, and the availability of rapid, fully operational chargers.

Surveys found that the Superhub had not influenced users' decisions to drive or own an EV. However, it influenced how they planned their trip routes and boosted their ability to fulfil obligatory and desired trips. The Superhub's impact on accelerating the transition to EV in and around Oxfordshire may be more evident in coming years.

Oxford Direct Services fleet electrification

ESO has accelerated the electrification of the Oxford Direct Service fleet. ESO's contribution of over £1.1m enabled the procurement of 40 additional EVs across a full range of vehicles. These EVs reduced the fleet's carbon footprint by at least 56 tonnes in 2022, plus reductions in other pollutants and noise levels. Further, the per-mile charging cost of around £0.10 was significantly lower than the per-mile petrol/diesel fuel cost of almost £0.29.

Data collection and analysis and strategic planning are essential for electrification. Fleet data collection is a resource-intensive process but will help to optimise the fleet performance in the long term and will maximise fuel cost savings and emission reductions. The availability of EV large vehicle types remains limited, hindering progress in this sector.

ESO's contribution of over £1.1m enabled the procurement of 40 additional EVs across a full range of vehicles.

Heat

ESO set out to demonstrate and test smart heat pump operation combined with time-of-use pricing to reduce running costs. Ground source heat pumps (GSHPs) were installed by Kensa Contracting in 57 social housing properties in Blackbird Leys, an Oxford suburb. A further five GSHPs coupled with heat-batteries were trialled in Sonning Common, South Oxfordshire.

User experiences

Most tenants were dissatisfied with their previous heating systems (electric storage heaters) in terms of both cost and comfort, used pre-payment meters and were on low incomes. Overall, tenants expressed high levels of satisfaction with their new heating and hot water systems, the installation process, and customer support. Several tenants reported saving up to 50% on their energy bills. General satisfaction with the systems has not been affected by the energy price crisis of 2022-23.

Funding and policy support

Heat pumps were part-funded by ESO, and partly by the Non-Domestic Renewable Heat Incentive (RHI). The cost per property was around £13,100, including drilling boreholes, full plumbing and installation, and some fabric insulation upgrades.

The business case for investing in ground-source heat pumps remains dependent on subsidy, and public funding became less reliable during the project. For instance, installations did not qualify for Energy Company Obligation funding, and the RHI ended during the project. This influenced uptake by social housing providers, and the project fell short of its initial target of 320 installations.

Flexibility

Market turmoil and technological barriers prevented real-world testing of flexibility through the retail market. There remains only one time-of-use tariff with half-hourly price settlements in the UK, and this became uncompetitive during the project. Two trials were implemented using simulated costs. These demonstrated the technical capabilities of dynamic heating, and lessons were used to improve the tenant experience.

GSHPs with heat-batteries were effectively optimised using price signals, and delivered reliable, responsive heating and hot water to tenants in Sonning Common. These units, known as ‘Kombi’ systems, do not require hot water tanks and are therefore smaller than conventional GSHPs. The success of the ESO demonstration has led Kensa to incorporate Kombi units into its strategic growth plans.

Two trials were implemented using simulated costs. These demonstrated the technical capabilities of dynamic heating, and lessons were used to improve the tenant experience.

Battery storage

Battery storage is essential for the future operation of a distributed grid. Through the ESO project EDF Renewables installed the UK's first transmission-connected battery energy storage system, opening up the transmission network to other battery storage developers, who are now applying to National Grid for similar connections.

The battery is the world's first grid-scale 'hybrid' battery, combining 50 MW/50 MWh of lithium-ion storage with 2 MW/5 MWh of a new vanadium redox flow product. By operating these two batteries together it was hoped their complementary efficiency and degradation characteristics would provide better overall performance. Unfortunately, combining the lithium-ion and vanadium flow batteries could not be fully achieved during the timescale of the project, and exploring the benefits of hybrid batteries remains a work in progress.

Battery modelling

The University of Oxford created a digital twin of the battery and undertook degradation modelling to better understand the drivers of degradation and how these can be managed. The study revealed that trading mode, while resulting in shorter battery life, offers high utilisation of the battery (i.e., energy throughput), whereas grid services mode extends battery life but leads to under-utilisation of the available battery cycles. Employing a mixed dispatch mode that combines both trading and frequency response allows for efficient use of the asset whilst maintaining a reasonable lifespan, making the most of the battery's potential under various operating conditions. It also provides an optimal return to shareholders. Grid services have been shown to be particularly profitable under current UK market arrangements and also result in lower battery cycling degradation. However, they do deliver less directly attributable energy-related carbon benefits, and arguably the battery is over-engineered for this purpose.

Battery storage represents a viable investment case for investors who understand and are willing to take the risks involved with energy trading.

Dual mode operation

The lithium-ion battery operates in two modes, both supported by a new machine learning-based Optimisation and Trading Engine, developed by Habitat Energy, which makes automated decisions as to which mode and market each element of the battery is placed in.

1. Grid services mode:
Provides balancing services such as frequency response to National Grid, enabling improved flexibility of the electricity system and ultimately greater amounts of distributed renewable generation on the grid of the future.

2. Trading mode:
The battery is used to import and export at different times of the day to optimise revenues from the spread of energy prices.

The lithium-ion battery has demonstrated strong financial returns over its first 18 months of operation, as well as insights into carbon savings associated with the different modes.

CO_2 savings from battery operation

The CO_2 impacts of the battery system have been analysed for different operation modes and carbon metrics. When applying simple 'average grid emission factors' to all power flows to and from the system, auxiliary loads and other losses appear to result in a 450 tonne CO_2/year increase in emissions. The reasons include insufficient variability in average emission factors and poor alignment between the market signals and the emission factors.

Battery operation in frequency response markets (70-80% of battery activity to date) provides valuable system services, but the carbon attributed to traded volumes is small and has not made up for the emissions attributed to auxiliary loads and losses. However, when operating in this mode, storage can displace inefficient part-loaded 'spinning reserve' gas turbine plant, giving considerable carbon benefits not included in these calculations. Inclusion of this effect shows that the battery system reduces emissions by over 15,000 tonnes CO_2/year when devoting as little as 40% of capacity to frequency response, hugely outweighing the carbon increases calculated above.

Calculating carbon savings from battery operation is complex and contested; methods for doing so require further investigation and improvement. ESO has resulted in follow-on funding for research to explore the impact on carbon emissions of the temporal and locational aspects of storage on the grid.

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Consortium working

The ESO consortium has faced myriad challenges since the start of the project in 2019, including COVID-19 and consequent working practice restrictions and global supply chain shortages, the energy price crisis, changing government and Ofgem rules and support, planning permission delays, changing ownerships of private-sector partners and delays due to fundraising exercises. Despite this, partners have worked positively and effectively together to find new solutions.

Overall impact and potential for replication

A smart, local energy system in Oxford

ESO has delivered a range of innovations, spanning power, heat, transport and storage. It has helped to demonstrate and accelerate the smart, sustainable energy transition at a local level, and many of the activities initiated by ESO will continue to grow beyond the timescale of the project. A smart, local energy system can be achieved in different ways. Compared with some **other projects** funded by the PFER programme, ESO involves greater investments in infrastructure and large-scale technology. It has exploited the synergies involved with the co-deployment of storage, power and transport innovations, although its renewable heat activities were less well integrated.

While the infrastructure and technologies deployed by ESO are geographically concentrated in and around the city of Oxford, its impact spans geographical scales: from national energy markets, to EV chargers for drivers from across the region, to electric taxis across the city, and low carbon heating in one Oxford suburb.

Routes to replication

Many of the innovations pioneered by the project are already being replicated elsewhere. EDF Renewables has already committed almost £200m of investment funding to replicate the transmission-connected model at five other sites in the UK, while Invinity is deploying the flow battery in other projects both in the UK and internationally.

ESO has demonstrated the benefits of delivering high-powered EV charging in the city of Oxford and further instances of this model, including public and fleet charging, are being sought alongside the the new EDF Renewables battery storage sites. Whilst limited to specific transmission-connection opportunities, these will be especially suitable at locations where local grid constraints hinder the roll out of high-powered EV chargers. Oxford has leveraged ESO funding to become a leader in the electrification of local authority and taxi fleets.

Lastly, the project has demonstrated the technical viability of smart-controlled heat pumps, although their deployment continues to rely on public subsidy and barriers remain to the implementation of dynamic heating in social housing.

About the authors

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David Howey is a Professor of Engineering Science, University of Oxford. His research interests are focused on modelling and managing energy storage systems, for electric vehicles as well as grid and off-grid power systems. He led Oxford's battery research.

Volkan Kumtepeli is a postdoctoral researcher in the Department of Engineering Science focused on modelling and optimisation of grid-scale battery energy storage systems, mathematical optimisation techniques, and safe machine learning approaches.

Tina Mould works for Oxford City Council as a Project Manager and oversaw ESO's work on the private wire, Superhub construction, fleet migration, and taxi electrification.

Tim Rose works for EDF Renewables (previously Pivot Power) and was ESO Programme Manager with overall responsibility for the success of each work package.

Acknowledgments

Thank you to all those contributing to this report including Matthew Boulton, Nicole Gilbert, Andrew Elliot, Mim Norvell, Ed Porter, Amy Featherstone, Lisa Treseder, Matthew Trewella, Liza Lebedev and Andrew Luers. Maryam Altaf and Zhaoqi Zhou assisted Labib Azzouz with data gathering. We are also grateful for the insights provided by all research participants.

Partners:

EDF renewables

Kensa Contracting
A KENSA GROUP COMPANY

OXFORD CITY COUNCIL

HABITAT ENERGY

INVINITY ENERGY SYSTEMS

Funders:

UK Research and Innovation

Chapter 1

Introduction

Energy Superhub Oxford (ESO) is a £41m demonstration project delivering innovation in smart local energy systems. As countries around the world embark on energy transitions to decarbonise their economies, decentralised and digitised solutions are increasingly important in delivering power, heat and mobility to users. Exploring options for smart local energy systems is a key UK priority.

ESO is one of three large projects part-funded by the UK government under its "Prospering from the Energy Revolution" (PFER) programme. Work began in April 2019 and ran until March 2023 (Figure 1.1). ESO's main focus has been on investment in infrastructure for energy storage, electric vehicle charging and low carbon home heating and developing innovative, smart ways of generating benefits from these for users, investors and society at large.

ESO has trialled innovations with strategic importance for achieving a more sustainable and affordable energy system.

This report has been produced by the University of Oxford team and may not represent the views of other project partners or the consortium as a whole. As researchers embedded in the project, we work alongside other partners to assess overall impact.

Our work is guided by six objectives which map broadly onto ESO work packages:

1

Evaluating the impact of the Energy Superhub on transport in Oxford.

2

Evaluating the implications of the ESO project for the decarbonisation of heat in Oxford.

3

Monitor the functioning of the consortium as a whole, identifying key barriers and obstacles encountered and strategies for overcoming these.

4

Developing insights for policy, governance and regulation for the development of smart, local energy systems.

5

Tracking the technical performance of a large-scale hybrid battery system.

6

Analysing the CO_2 savings of the grid energy storage system.

The report is structured into five main chapters, which map on to these objectives. Policy insights (the 4th objective) are incorporated into the other sections. It highlights the obstacles and challenges faced by the consortium; highlights successes and lessons learned; and outlines and justifies where the scope of work has deviated from the original project plan.

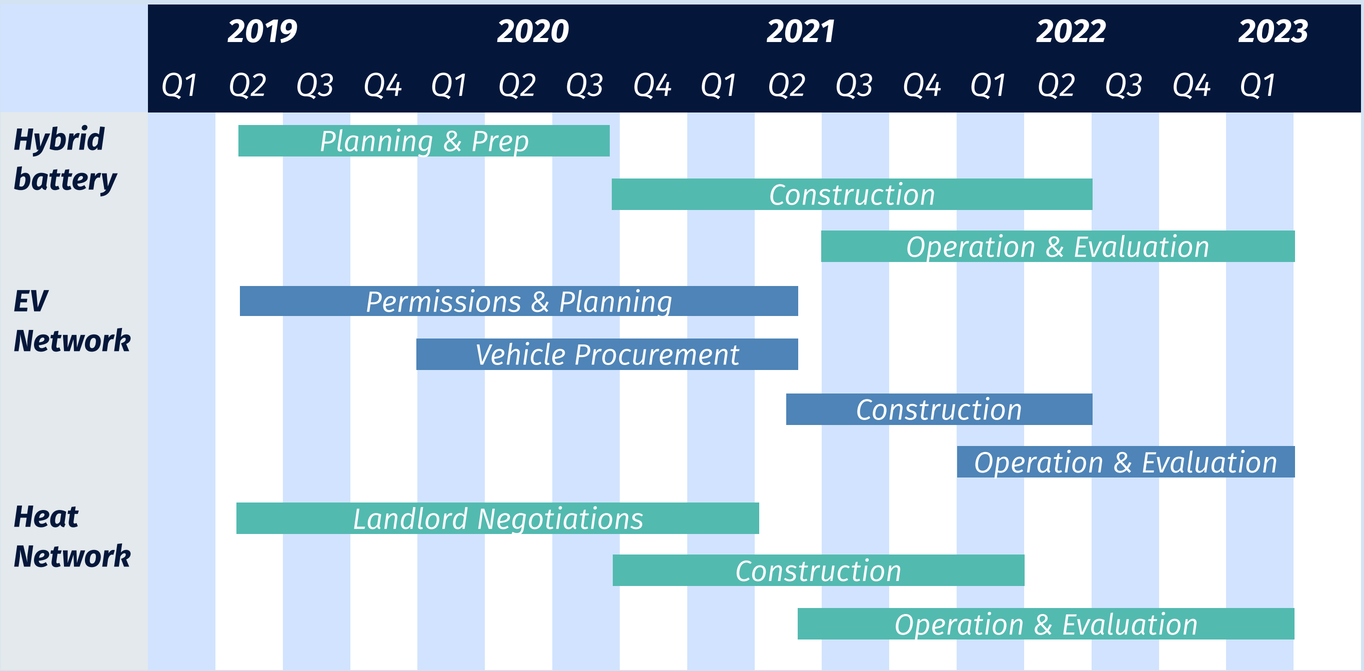


Figure 1.1: Project timeline

Who is this report for?

This report has been written for those involved in energy innovation, including investors, technology developers, researchers and policy makers.

In addition to this report, a wide range of outputs are available. The project website can be found at **energysuperhuboxford.org**, and the University of Oxford's **Environmental Change Institute website** includes the Interim Report, and other academic articles reporting on findings from ESO.

Other reports and documents relating to the Prospering from the Energy Revolution programme can be found on the **EnergyRev consortium website**.

Chapter 2

Transport

This section focuses on ESO's work on decarbonising transport in Oxford. This is reported in five themes:

- The electrification of Oxford's Hackney taxis
- The private wire and Superhub
- User experience at the Redbridge EV charging hub
- Oxford Direct Services' fleet electrification
- Oxford City Council's EV strategy and transitioning to a sustainable future.

Each section contains:

- *Its own summary*
- *Key achievements*
- *Lessons learned*

The Transition to EVs from the Perspective of Electric Hackney Taxi Drivers in Oxford

Summary

The study aims to understand and gather insights into motivations, opportunities, concerns, and challenges of the transition to EVs as perceived by Hackney taxi drivers in the city of Oxford. The study started with informal discussions with Hackney taxi drivers, then a list of questions was prepared and tested through several interviews. Formal interviews took place between June and August 2022. A total of 24 interviews were conducted, each lasting between 25 and 60 minutes.

All participants drove the LEVC TX electric Hackney taxi: a plug-in vehicle with a battery range of around 78 miles and an integrated petrol range extender. At the time of the interviews, around 30 out of 105 Hackney taxis were electric. Some interviewees owned the car, others were employed by the original owner to work on it. The study also included those who rented a car under the Try-Before-You-Buy Scheme. The council commissioned Electric Blue (EB) to run the scheme. EB operates several charging stations in Oxford. Each interview comprised 33 questions reflecting on different aspects: background and vehicle ownership, parking and charging habits, working patterns, and the overall EV taxi experience.

Motivational factors for switching to the E-Hackney cabs

In March 2019 the City Council set new emission standards to facilitate faster adoption of electric Hackney taxis. Hackney taxis, also known as Hackney carriages, cabs or 'black cabs', are a characteristic, traditional vehicle type which can be hired on the street. They are distinct from other taxis, which must be pre-booked, and they are separately regulated. This text relates to Hackney taxis only, unless otherwise noted.

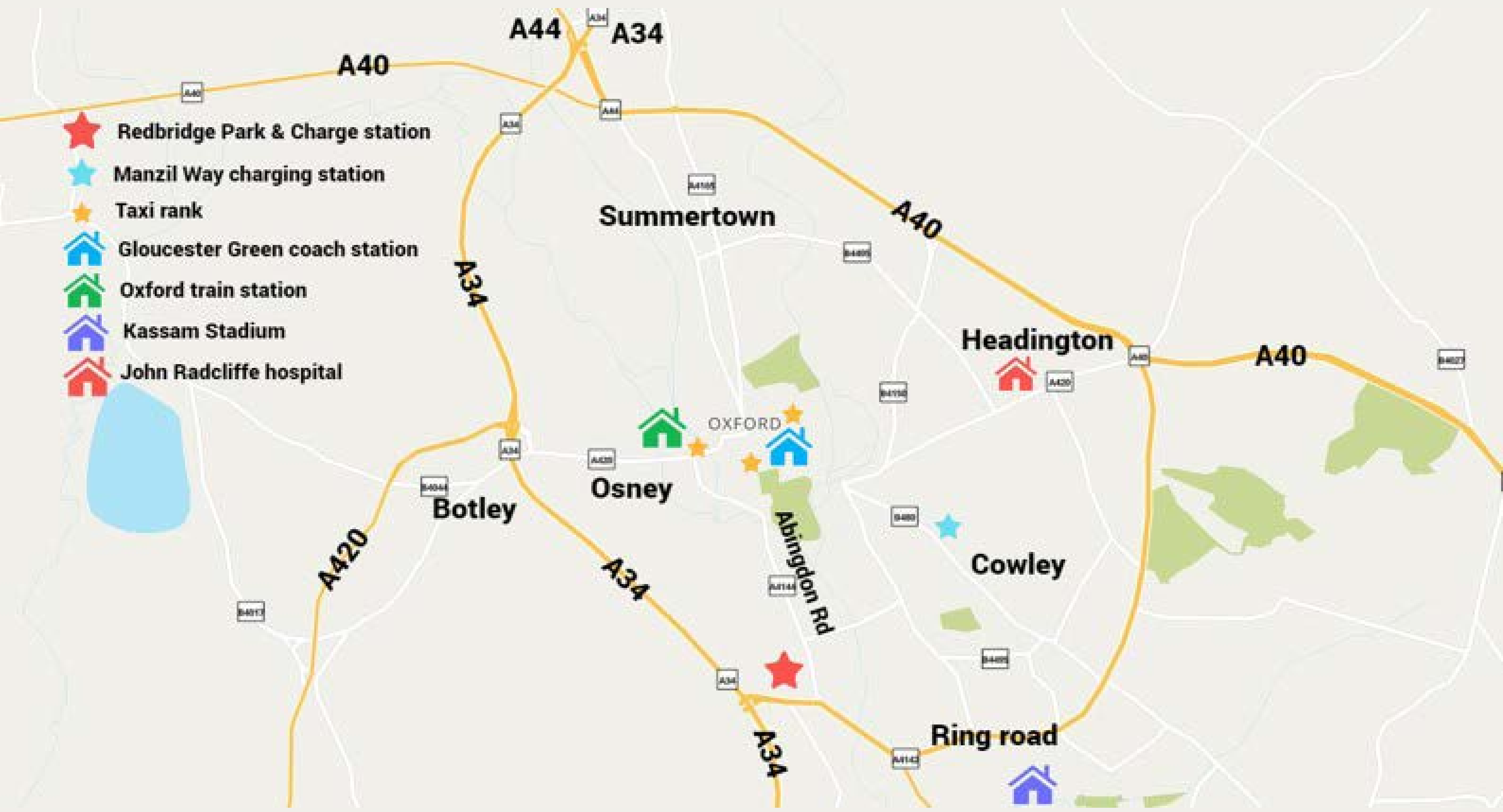


Figure 2.1: Map of taxi ranks, charging points and other locations in Oxford

Oxford City Council stipulated that all 107 registered Hackney taxis must be upgraded to ULEV by 2025. With all cabs having a minimum of a Euro 4 compliant engine by 2020. At the time over 50% of cabs in Oxford were over 18 years old, providing extremely high levels of emissions, over 1000 tonnes of CO_2 emissions and 4500 kg NO_x per year. The transition of these vehicles to electric would have a huge impact on emissions in Oxford.

Interviewees were asked about factors that influenced their decision to switch to an electric ‘e-Hackney’ taxis. Responses revealed mixed opinions and for most drivers, a combination of factors influenced their final decision. Oxford City Council’s (OCC’s) 2025 policy was a pivotal factor and at the core of most drivers’ decision. Some drivers having driven diesel taxis for 10-15 years, were already considering renewing their vehicles. A minority of drivers further mentioned regional/national EV transition policies and restrictions.

Due to OCC’s policy, drivers explained that it was more sensible to buy a new vehicle that would comply with the council’s laws and regulations, as this would give them ‘peace of mind’ over the longer term. The council’s £5000 grant was found to be another influential factor, particularly for drivers whose internal combustion engine (ICE) taxis were technically and operationally capable of staying in service until 2025. The grant encouraged those drivers and prompted an earlier accelerated transition to EVs.

Though to a lesser extent, factors like discounted licensing, subsidised charging, and the ZEZ were also mentioned by a minority of interviewees. From a cost perspective, some drivers were also motivated by the idea that operating an EV would generate fuel savings. Neither the availability/accelerated deployment of charging infrastructure nor Oxford’s built environment had a notable influence on drivers’ motivations.

Interestingly, the decision to buy/drive the e-Hackney was not only dictated by rational choices based on the availability of grants, subsidies, policies, and regulations, but also by non-rational factors like social influence and self-esteem. Some drivers expressed that they were open to:

- change, trying something new,
- owning and driving a brand-new electric taxi that preserves the iconic traditional Hackney design,
- driving cutting-edge technology that represents the 'future' of driving.

Those who got satisfactory and informed answers from their EV-driving colleagues were more convinced/ relieved about switching to EVs, and some of them have, switched in the end. It is worth noting that the earliest e-Hackney adopters played a key role in this regard; they naturally acted as ambassadors not only to the car but also to the whole EV taxi driving experience in Oxford. Unfortunately, the first four adopters bought their cars before the council's schemes and hence they were not able to benefit from the £5000 grant. Still, they were generally satisfied with their EV driving experience and were able to promote it effectively and passionately within the taxi community.

> *"If you have a brand-new toolbox, with sharp tools, and brand-new hammers, your craftsmanship is much better. I think that's what it is like with the car. It is like a brand-new toolbox with lots of lovely tools in there that just want to make you go out there and drive".*

The influence of 'others' was also captured. Socially, the Hackney carriage drivers act as a community; they regularly and irregularly chat, share ideas, and news, and discuss work-related topics. These discussions occur during break times, waiting at the ranks, and waiting at the charging point. Most interviewees stated that they were often approached by 'curious' diesel taxi drivers who asked questions about the e-Hackney experience. These questions were mostly centred around:

- the range of the battery,
- the cost of purchase,
- the cost of operation and fuel savings,
- charging convenience, locations, and practicality,
- driving and charging behaviour,
- maintenance and charging problems.

A minority of drivers expressed their environmental awareness and explained how driving an EV taxi can minimise environmental damage. However, it was hard in a place to establish a significant association between environmental awareness and drivers' final decisions.

When asked about their plans regarding purchasing their own electric Hackney, drivers who did not own the car had a major concern; the car's significantly high purchase cost. They clarified that the cost may prevent them from owning their vehicles at least for the next 3-5 years. However, they did not disclose a reluctance to purchase an e-taxi in the longer term. Future grants, discounts, and incentives may motivate them to buy a car. Most importantly, some drivers – due to cultural/ religious considerations – suggested that an interest-free loan/repayment scheme could be particularly helpful and attractive.

> *"At the moment, what not encouraging is really the cost of the vehicle and the range of the battery".*

EB Try-Before-You-Buy (TBYB) Scheme Evaluation

ESO funded a TBYB scheme for Oxford's Hackney taxi drivers. It enabled drivers to trial one of two models – an all-electric Nissan Dynamo or a LEVC for a two or four-week period, intending to reduce barriers to adoption. OCC and EB administrated the scheme. As a part of the evaluation, EB conducted interviews with the Hackney drivers in Oxford.
10 participants were involved (Figure 2.2).

In 2022, switching to EVs Hackney taxis reduced relevant CO_2 emisssions by at least

60 tonnes

(based on charging at EB alone)

Key Findings

A full transition to EVs in the Hackney taxi business may reduce relevant CO_2 emissions

by 580 tonnes and direct fuel costs by £224,700 annually

Half of respondents shared their vehicle with other drivers (one or two additional drivers). Most of the time, taxis are used for business purposes. Fuelling behaviours revealed mixed responses; some drivers refuelled their vehicle before the shift, and others during or at the end of the shift. Seven out of 10 drivers stated that they usually park the taxi at home on a driveway (a similar pattern was found in the wider EV Hackney taxi interviews). Most drivers' annual mileage exceeds 30,000 miles a year, which equals at least 105 miles a day (assuming they work 5.5 days over 52 weeks). The implication is that since the battery's range is below 90 miles, they would need to either charge their battery at least once a day if they preferred to use the pure electric mode or to activate the petrol range extender (smart) mode. Further, most drivers stated that they would prefer to charge their car at home. Nine out of 10 drivers said that they would probably buy/lease an e-taxi in the next 2-3 years. Personal contract purchase and lease were the preferred ownership options, whereas the outright purchase was not selected. This may be related to the significantly high purchase cost. All drivers stated that they would buy the range-extended EV Hackney taxi. Most had limited experience of driving an EV taxi.

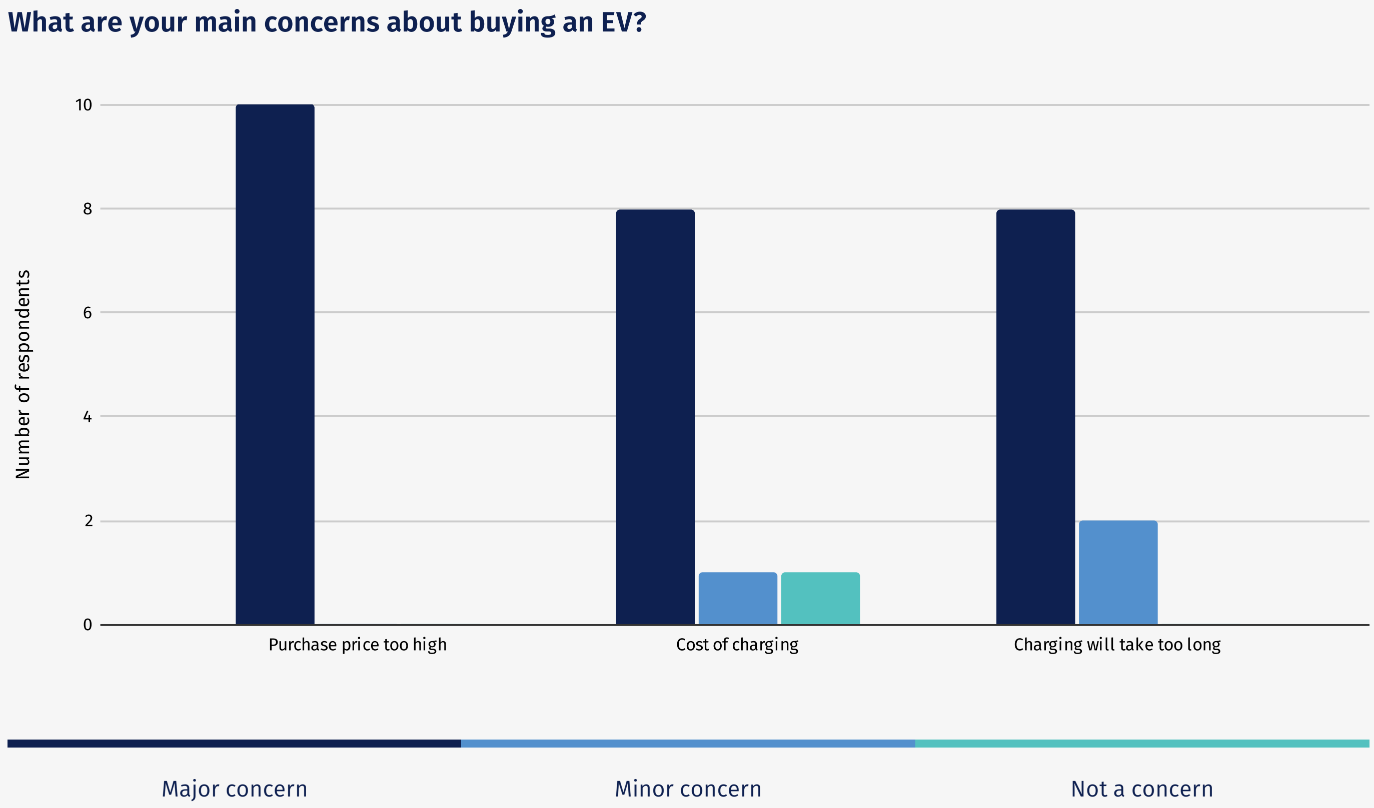


Figure 2.2: Try-before-you-buy user concerns about buying an EV

> *Most drivers revealed that they had a fixed schedule for when they are on a shift, and this was influenced by household and other duties. As a result, they had a fixed charging schedule.*

Journeys, Working Patterns, and Driving and Charging Behaviour

Most interviewees worked 5-6 days a week, 7-9 hours a day, and drove 50-90 miles a day. Most conducted trips were short-distance trips – inside the ring road – and with an average distance of 3-4 miles. Almost all drivers stated their willingness to conduct long-distance trips and some of them travelled to London, Reading, and other locations outside Oxfordshire. Most drivers revealed that they had a fixed schedule for when they are on a shift, and this was influenced by household and other duties. As a result, they had a fixed charging schedule. They usually charge their vehicles at the end of their shift at a public charging station. Drivers who did not own the car were usually responsible for charging the taxi before returning it to the owner, who usually started a shift with a fully-charged battery. Owners with a home charge point charged their taxis mostly at home at night and seldom used public stations. Drivers with longer EV driving experience charged their cars more frequently – almost on daily basis – compared to other drivers.

Drivers expressed their awareness of the available public charging stations in Oxford. However, their awareness seems to be limited since most drivers were able to mention – and use – only 2-3 stations, all of which were provided by Electric Blue. The most mentioned stations/ charging points were:

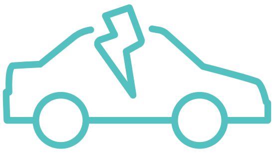
- Manzil Way station at Cowley Road, Cowley,
- Keble Road charging point, city centre,
- The Westgate charge point, city centre,
- The Waitrose car park charging point, Headington.

The popularity of these stations is because charging at them is currently much cheaper than elsewhere. In terms of popularity, the Manzil way station was by far the most popular and preferred station, due to several reasons. These include the station's proximity to shops, cafes, and restaurants along Cowley Road where most drivers live, and most importantly, its proximity to the local mosque. Drivers explained that they prefer to charge their cars at Manzil way since this allows them to visit the mosque and perform their regular praying duties while waiting for their cars to be charged.

While charging their taxis, drivers reported using this time to undertake a wide range of activities, mostly: grabbing food/drinks, sitting and relaxing, praying at the nearby mosque, chatting with other drivers, socialising via the phone, surfing the internet, cleaning the taxi, having a short walk, and exploring the taxi's features. For most drivers, the length of a normal charging session at a public charging station ranged from 40 to 60 minutes.

Some of the older drivers were somehow less accustomed to the cars' technology. They explained how a younger member of their family helped them to set up the navigator or explained the manual to them. Some drivers stated that they have always driven the car using the factory settings, without, for instance, changing or trying to change the driving mode. They were concerned that changing the driving mode would result in a flat battery. This was exacerbated by the fact that one of their colleagues ended up with an empty battery during his shift within the first week of his work.

Interviewees were asked about ways in which they adjust their driving behaviour to make sure that they can finish their shift and avoid getting stranded with a flat battery. Findings are summarised on the following page (Table 2.1).



Owners with a home charge point charged their taxis mostly at home at night and seldom used public stations.

Table 2.1: Characteristics of e-taxi driving and drivers, by length of experience

Taxi driver group by EV driving experience	Longest experience (years) + early adopters	Mixed, mostly moderate experience (months to a few years)	Short experience (weeks/months), late adopters
Representation and prevalence	Minority	Majority	Second majority
Taxi driver group by age	Most drivers are in their 30s and 40s	Mixed	Mixed
City driving (inside Oxford's ring road)	The 'Pure EV' mode is mostly used. Drivers start their shift with a full battery, and they switch to 'Smart' mode when the battery reaches low levels. They seek to recharge it shortly after.	The default 'Smart mode' is often used, whereas the 'Pure EV' is used at a lower frequency. Drivers will charge their cars randomly, mostly at the end of their shifts.	Both the 'Smart' and 'Save' modes are used, whereas the 'Pure EV' is mostly avoided. Attention is paid to having a full petrol tank on regular basis, whereas charging appears to be less important.
Frequency of charging	Frequent, almost daily	Less frequent, several times a week	Several times a week to several times a month
Intercity driving (long-distance trips)	Reliance on the 'Smart' mode during most of the journey, and only activate the 'Save' mode when the battery charging reaches low levels or when driving at high speeds.	Reliance on both the 'Smart' and 'Save' modes. Drivers usually switch from 'smart' to 'save' on motorways.	Drivers will mostly use the 'save' mode.
Competency and skills	Drivers are fully aware of different driving modes. They maximise the use of 'pure EV' and where possible avoid other modes. High speeds are avoided especially in the city, and brakes are used carefully. Battery charging levels are closely monitored during driving. Plus, Awareness of other car features.	Drivers are aware of different driving modes but are not fully confident/ bothered about switching between them, hence, the default factory mode is often preferred. Less attention is paid to battery charging levels.	Drivers have a basic to almost no understanding of the vehicle's different modes. They avoid using other features or technologies that did not exist in older models. Help is sometimes requested from family members/other drivers. In a sense, this group handles the e-Hackney almost in the same way they previously handled the diesel one.
Reported fuel savings	Significant, accurately monitored, and calculated	Significant/ moderate, somehow calculated	Moderate/ marginal/ not realised/ roughly or not calculated
EV taxi mode key (according to the manufacturer)	**Pure EV mode:** uses only electric power from the battery and disables the petrol-powered range extender. **Smart mode:** depletes the battery as much as possible before activating the range extender, which then recharge the battery. **Save mode:** activates the range extender to conserve the battery at its current levels.		

Best and worst aspects of the e-Taxi Experience

For almost all drivers, the best part of the e-Hackney taxi experience was centred around driving the vehicle. They stated that driving the electric Hackney car offered an elevated driving experience and was remarkably more comfortable than driving the old diesel models. They explained how before the e-Hackney, sitting behind the wheel for an extended period accompanied by the exposure to the noise of the diesel engine was an 'absolute nightmare'. In contrast, they described driving the EV Hackney as a smooth, quiet, clean, comfortable, and pleasant experience. Moreover, several drivers mentioned that the taxi's quietness allowed them to enjoy clear chats with customers who were equally happy with the e-taxi experience. It is worth noting that several customers wanted to ride only in an electric taxi, and sometimes they waited on the rank for an available one.

Finally, several drivers praised the healthy relationship between Oxford City Council and the Hackney taxi community and appreciated the swift and fruitful communications with relevant officers at the council.

Regarding the worst part of the e-taxi experience, drivers mostly referred to the high purchasing cost. Additionally, encountering a faulty or fully occupied charging station was frustrating, though this was seldom the case. Several drivers suggested deploying additional public charging points, especially at the taxi ranks at the train station, coach station, and city centre. They recommended that these could be mobile charging robots. Another difficult and disappointing part was the lack of local mechanics/ garages that could deal with the car's technology and relevant issues. Sometimes, a simple fault forced the driver to send the vehicle to the manufacturer. A minority of drivers mentioned lengthy delays in their home charging point applications, these were related to communication and technical issues.

> *"The whole experience includes a lot of positivity for me, and for customers as well. They really enjoy it... Maybe those guys who care about the environment don't feel so bad about getting an electric taxi".*

Financial issues

Most drivers reported financial savings; operating an EV taxi was relatively cheaper than operating a diesel one. However, early adopters, younger drivers, and those with a more extensive EV driving experience reported higher savings, when compared with others. These drivers were more confident about and well-accustomed to switching between different driving modes in a way that; reduced dependency on petrol; maximised the use of electrical power; slowed down the drainage of the battery.

Interviewees were asked whether it was a good investment to switch to EVs. Answers were mixed combining positive and negative economic aspects in one answer, mostly referring to two points: fuel savings (positive) and purchase costs (negative). Regarding the purchase cost, most drivers explained that from a purely economic perspective, the high purchasing cost cannot be justified, at least for now. They added that in the long term, the fuel savings may offset the initial cost, but this will also depend on other factors like the cost of maintenance and repairs.

The council's £5k grant and the government £7.5k plug-in grant helped most drivers, however, some of them struggled with the initial payment. Some interviewees explained how their income remarkably dropped during the COVID-19 pandemic years. So, they were not able to save for a new vehicle, despite initially having the idea of purchasing it. Instead, they were spending from their earlier savings, plus focusing on other financial commitments like paying house mortgages. So, purchasing the e-taxi was postponed as a result. This may be the case for other drivers who are currently operating a diesel Hackney taxi.

If you knew what you know now about driving an EV taxi, would you still make the decision to switch to an EV taxi? Why?

Since most interviewees were generally satisfied with the electric taxi experience, their answer to the above question was "yes", re-mentioning the smooth driving experience, the availability of charging infrastructure, fuel savings, and satisfied customers. However, some drivers kept referring to the fact that besides the above benefits, the council's ULEV 2025 deadline meant that they had relatively limited options, and in a way, they were 'gently' forced to purchase electric Hackney despite its high upfront cost. Only a couple of drivers expressed that if they were given the choice, they would wait a couple of years when they can purchase a less expensive taxi or at least a taxi with better technical specifications i.e., longer battery range.

Based on their satisfaction with the electric Hackney taxi experience, most drivers suggested that they would recommend EV taxis to other drivers.

> *"Yes, I would recommend EVs. We are in 2022 and they are the way forward".*

Drivers’ concerns

Some of the drivers’ concerns related to potential future costs, in particular maintenance and operational costs. A couple of drivers reported that their cars had technical issues where they were forced to send the cars back to the manufacturer, as local garages/ mechanics could not swiftly fix the issue. The process required days for collection, fixing, and delivery during which drivers would not be able to work. The result was an income loss. Plus, the costs of replacing a broken item were significantly high. Even those drivers who did not encounter a technical issue were afraid that fixing/maintaining their EV taxi in the future would be significantly higher than fixing/ maintaining an ICE taxi. Furthermore, some drivers were aware that the subsidised public charging would come to an end shortly. This meant that they will be paying more for charging, exacerbated by the higher energy and electricity prices. To summarise, drivers were concerned that fuel savings from electric vs diesel fuel costs will eventually diminish.

Other concerns related to the availability of sufficient public charging points in the future. Several taxi drivers stated that Oxford is experiencing a rapidly increasing demand for EVs from different users, and hence, there should be enough charging points to match that demand. This is particularly true when a significant proportion of Oxfordshire’s newly-registered vehicles in 2022/2023 were EVs. It is worth noting that Oxford has one of the highest numbers of installed charging points per capita across the UK (Figure 2.3), and OCC is continuously working to deliver a charging infrastructure that can meet the EV transition’s demand.

Finally, several taxi drivers complained that their designated charging bays – especially the one in Manzil way – were sometimes occupied by non-taxi drivers, including EV and non-EV vehicles. However, parking and vehicle control patrol officers have been starting to enforce illegal use. Continuity of such a service will play an important role in the future, especially with the rapidly increasing number of EVs.

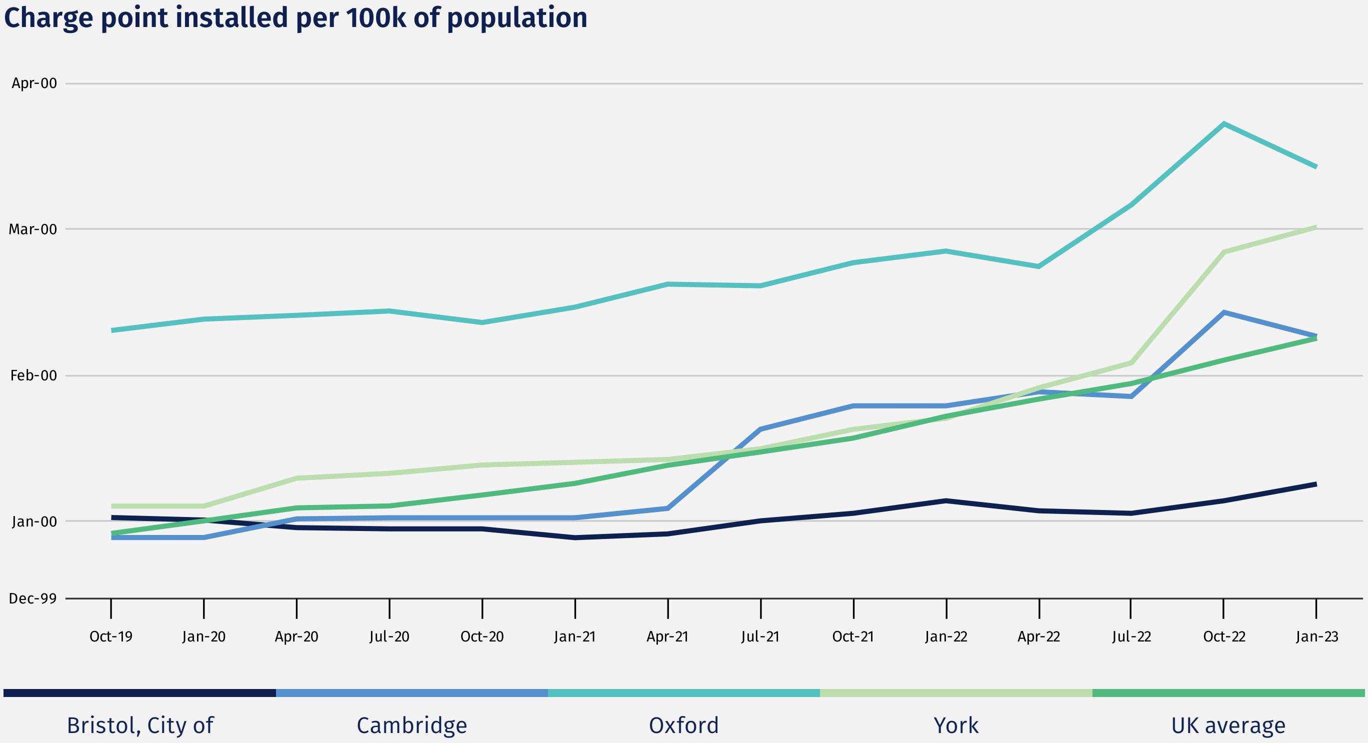


Figure 2.3: EV charge points installed per 100,000 people, 2019-2023, by location

E-Hackney Taxi Business & Superhub Potential

The Redbridge station was neither familiar nor used by most drivers. This is understandable since some of the interviews occurred during the summer of 2022, mostly before launching the station.

During the interview, the station was briefly introduced, and the interviewees were surprised by its size and the number of available rapid charging points. Further, they expressed their willingness to charge their taxis at the station in the future. However, they explained that first, they do not live in the vicinity of the Redbridge site; most of them live in Cowley and Headington. Second, they clarified that most of their trips occur in the city centre, Cowley, and Headington, whereas fewer trips take place from/towards/ the end of Abingdon Road or the vicinity of Redbridge. Drivers who were familiar with the site mentioned the lack of food/drinks services at/in the vicinity of the station, explaining that the availability of such services may attract more EV taxi drivers, particularly those who work evening and late-night shifts. One driver had safety concerns, mentioning that the old Park & Ride site was dark and quiet at night.

EV Hackney Taxis in Numbers

Based on EB charging data for 2022, it is estimated that at least 230,000 miles of EV Oxford taxi mileage were facilitated through charging at EB's network. Charging at the EB network peaked between August and November, accounting for almost 55% of 2022's usage. The taxi business activity booms in Oxford during these months since there are more students and visitors (holiday & business) and the impact of Covid-19 on the city diminished during second half of 2022.

The actual annual EV Hackney taxi mileage – and relevant emission savings – could be much higher since several drivers have reported that they either own or applied for a home charger. During normal conditions, the total annual EV Hackney taxi mileage could reach around 525,000 miles (70 miles of pure EV mode driving per day per taxi * 25 taxis * 25 working days per month per driver * 12 months). Some taxis are utilised by more than one driver, so the EV mileage could be significantly higher. Currently, there are 107 licenced Hackney carriages in Oxford, 26 of which are EVs. Plus, there are 5 vehicles for hire/accident replacement. A full transition to EVs in the Hackney taxi business would create remarkable benefits in terms of emission and noise reductions plus fuel cost savings.

Importance of Environmental Sustainability

Participants were asked whether environmental sustainability was important to them. Despite offering mixed opinions, most of the sample agreed that it is necessary to tackle pressing environmental issues, particularly those related to transport emissions. They knew that driving an EV taxi may cause less environmental damage when compared to the damage caused by ICE vehicles.

Drivers had a basic understanding of the EV taxis' environmental performance regarding emissions and energy consumption. A minority of drivers offered a rich reflection: referring to global environmental disasters; discussing that the source of electricity should be taken into consideration; and, explaining that emphasising environmental considerations should not be at the expense of compromising the social and economic aspects of sustainability.

"We need more of these electric vehicles...the police force, ambulances, and fire engines need to change their vehicles and become electric and sustainable as well. We have been damaging ourselves and the environment".

Taxis: Summary, lessons learned and suggestions

- ESO has effectively led a positive change within the Hackney taxi community and has accelerated the transition to a cleaner and greener transportation option that can reduce environmental damage.
- The Council's 2025 ULEV policy plus the purchase grant have been pivotal motivational switching factors.
- Other factors included incentives and personal factors.
- Some drivers were influenced by others' recommendations. The early adopters played a key role in promoting the EV taxi culture by communicating a positive experience.
- E-taxi drivers reported multiple benefits, including fuel savings, driving experience, customer satisfaction, and would recommend EVs to others.
- Findings suggest that over time, drivers are learning to optimise EV usage to maximise fuel savings.
- Drivers' concerns were future-oriented: insufficient public charging points to match growing demand, and high vehicle maintenance costs.
- Additional charging points are preferred near taxi ranks, these could be mobile/underground units.
- Other suggestions included flexible financing models and interest-free loans, purchasing grants and discounts, subsidised charging, and most importantly, extended battery range.
- Subsidised home charging points and relevant grants/discounts plus faster home charger applications are likely to attract more drivers to install home chargers.
- Try-out days, training, and other events may help drivers who are less accustomed to driving EVs.
- Interviews were informative. Drivers offered rich and generous insights. They expressed a willingness to engage in further future research.

Private Wire and Superhub

Summary:

Initial project targets - private wire and Superhub

1
Install 50-100 fast to ultra-rapid chargers at Redbridge site

2
Provide charging at ~50% lower than incumbents

3
Integrate Optimisation and Trading Engine (OTE) with chargers.

4
Convert 50 existing buses to ULEVs

One of the major components of ESO is the four-mile (6.9 km), 33 kV 'private wire' cable route leading from the National Grid high voltage sub-station in Cowley, to Redbridge Park & Ride, where the UK's largest and Europe's most powerful public EV charging 'Superhub' is located, with 42 fast and ultra-rapid chargers.

Progress on this ambitious construction project was delayed for a variety of reasons but construction on the cable route eventually began in August 2021 and it was completed in April 2022, with the Superhub formally opening on 5th July 2022.

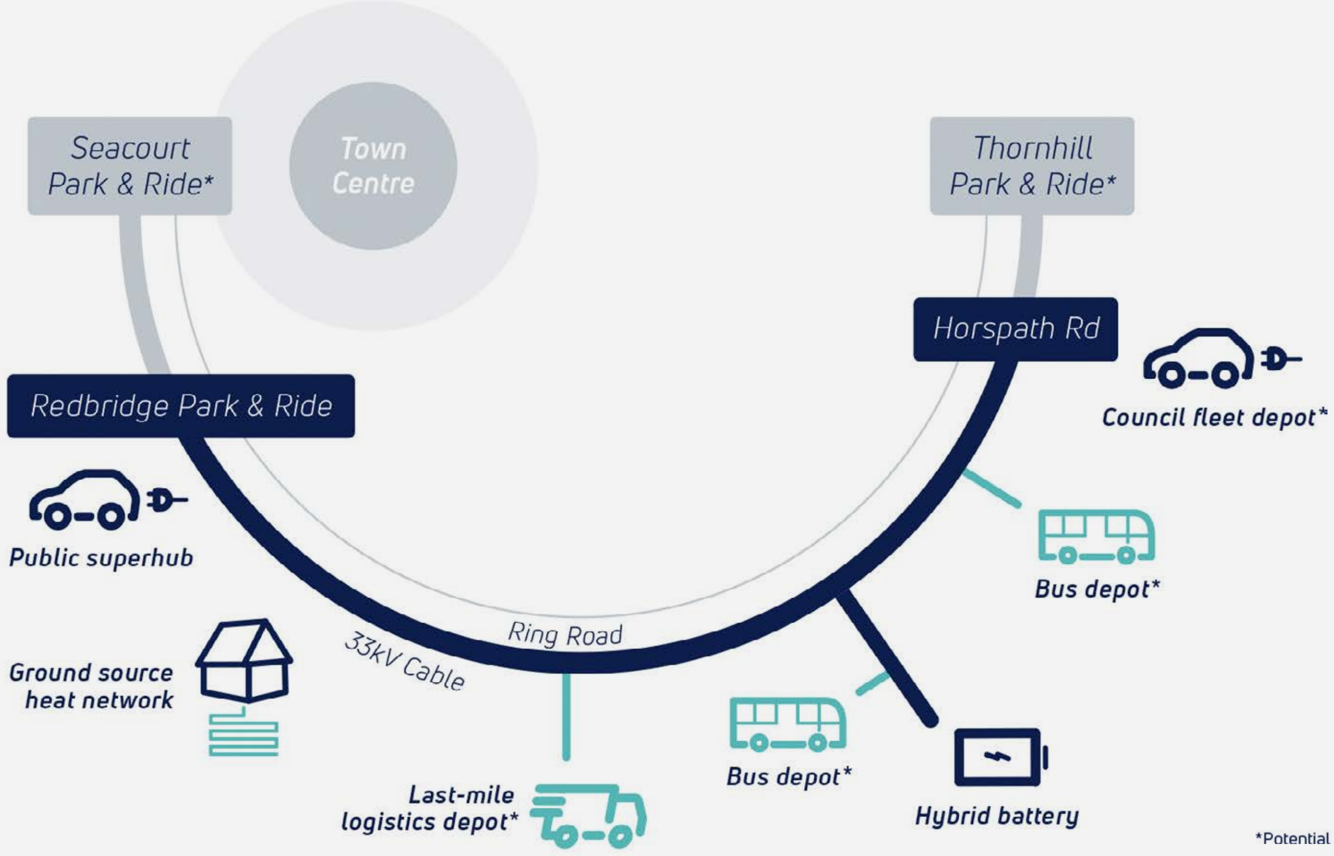


Figure 2.4: The 'Oxford Smile' - the original plan for the cable route included a substation at Horspath council fleet depot.

Overall, the team involved in implementing the private wire and Superhub have spent most of their time and effort on four interrelated tasks, discussed in turn:

1. Planning applications and procedures.

At initiation, planning permission for the private wire (and Superhub) was projected to be secured by August 2019. In reality the process was far more complex than expected. The route spans three separate planning jurisdictions (Figure 2.5), and involved a myriad of stakeholders. It became clear as the project progressed that an additional application to separately provide the detail for the Superhub at Redbridge would also be required by the local planning authority.

The team were unaware of the complexity and number of planning application studies required, including the collation of land ownership records for the entire cable route as well as the detail for the hub application, which included transport and arboricultural assessments. Communications with the local planning authorities also proceeded more slowly than expected. EDF Renewables signed 12 separate easement agreements and other authorisations for the cable construction with: National Grid, Oxford City Council, a farmer, SSEN, Thames Water, Oxford Bus Company (OBC), Network Rail, and the Highways Authority (County Council). Planning permission was eventually granted in July 2020.

Scope change: route

The original route for the private wire included Horspath depot. However, the strategic decision by OCC and ODS to consolidate its fleet at Redbridge meant that a dedicated high-powered connection was no longer needed at Horspath (Figure 2.4)

Construction

The 6.9 km cable route crosses fields, roads, cycle paths, bridges, and culverts; includes two 33 kV substations (at the Oxford Bus Company and Redbridge); and has 14 joints. 5.2 km of the cable runs through public highways and 1.5 km through private land. The route includes 10 obstacles classed as ‘Special Engineering Difficulties’, such as bridges, culverts and a roundabout.

The team had confidence in its chosen contractors, who have proven highly capable and delivered the cable route in line with expectations. However, engaging with non-consortium stakeholders, including meeting the requirements of statutory bodies such as Thames Water and the Highways Authority, led to substantially longer timeline when compared with initial expectations. COVID-19 caused delays in material supply, disrupted stakeholder engagement, and stalled contractual agreements.

It was initially hoped that construction of the cable would be completed by September 2020, but this was ultimately extended to April 2022 when the Redbridge substation was commissioned.

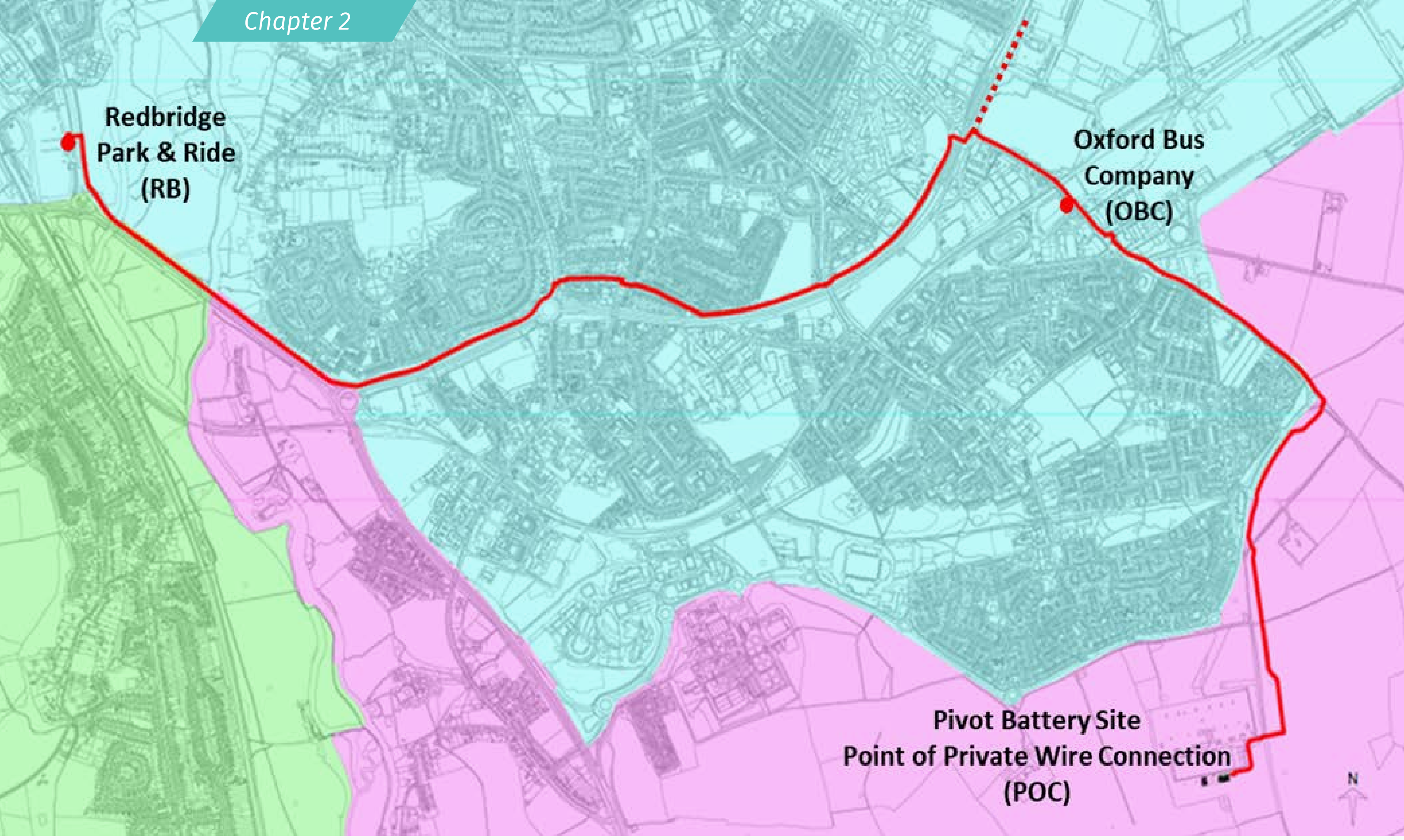


Figure 2.5: Actual cable route plus planning authority areas

Oxford City Council

South Oxfordshire County Council

Vale of White Horse

Contractual agreements

In addition to extensive stakeholder engagement on the private wire construction and securing agreements for the Superhub with non-consortium partners has demanded substantial resources and technical expertise, much of which was not anticipated or resourced at the start of the project. The original intention had been that Pivot Power would operate Superhub chargers themselves, providing power to EV drivers at market-beating rates of under 20 p/kWh.

Figure 2.6: Trench digging for the cable

Very early on, during its fundraising process, Pivot Power decided to move away from this approach and the purchase of the company by EDF Renewables in 2020 led them to consolidate their mission as a developer of grid-connected batteries and EV charging infrastructure, but not as a CPNO itself. This change in strategy meant that Oxford City Council became the lead for procuring Charge Point Network Operators (CPNOs) to operate at Redbridge. (See Concession arrangement and tender process below). The implication of the decision by EDF Renewables not to own and operate chargers means that the Superhub operates on a commercial basis. Concession contracts have been awarded to 3rd party CPNOs, who set pricing in accordance with their own standard business models. The number of stakeholders involved in delivering the cable route and Superhub was very high; Figure 2.7 gives an indication of the complexity involved and the number of agreements required.

Private wire and substation network stakeholder and agreements map

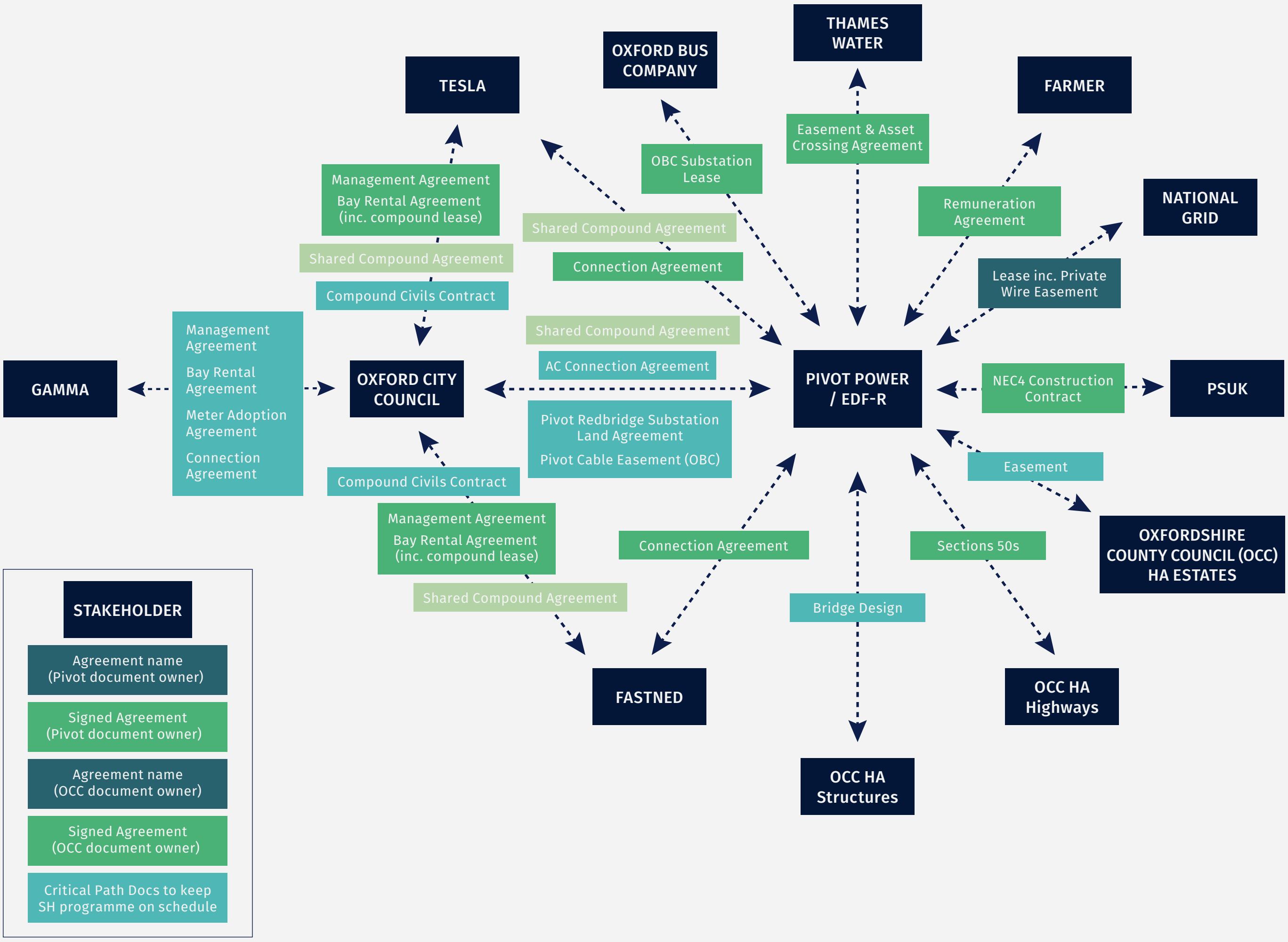


Figure 2.7: Stakeholder map for delivering the cable route and Superhub

Managing delays and disruption

The Superhub energisation date was 24 June 2022, 20 months later than originally planned.

There have been several reasons for these delays. Three have already been discussed: (1) the strategic review by ODS of its fleet depots; (2) Pivot Power's decision to not become the Redbridge CPNO; and (3) slow progress with contractual agreements.

A fourth source of delay was COVID-19, which has led to supply chain disruption and price volatility of key materials such as high-voltage cable and ducting. Fifth, both workstreams were put on hold in autumn and winter 2020-21, pending Ofgem's decision about the allocation of transmission connection charges (more on in this Chapter 6).

These disruptions and delays generated additional complexity and their own additional work, as the ESO team revised plans for cable route construction, and dates for the energisation of the Superhub. Many of these issues also led to cost increases.

Scope change: chargers

The ESO bid document estimated that 50-100 EV chargers would be installed at Redbridge, and that power flows would be optimised using Habitat's trading software. However, the decision to outsource the operation of the fast and ultra-rapid chargers meant that Habitat would no longer control the assets. A decision was also taken to allow the CPNOs to fund and own the DC chargers. In the case of the AC hardware, OCC owns the HV/LV transformer, and the AC chargers are owned by Wenea. The number of chargers installed has been guided by the minimum tender requirements and market forces. The tenders requested a minimum of 20 DC chargers and 16 AC chargers. A total of 42 charging bays have been installed, with capacity for expansion:

- **Tesla:** 12 bays, with 250 kW chargers shared by 4 bays
- **Fastned:** 10 bays, with 300 kW chargers shared by 2 bays
- **Wenea:** 20 bays, 7-22 kW chargers

Interoperability of the chargers (ability to pay on an ad hoc basis with credit/debit card via a payment terminal) was a key tender requirement. Tesla chargers at Redbridge are currently a closed network only available to Tesla vehicles, therefore these are the only type where interoperability is not a key requirement. Should Tesla open up their network to non–Tesla drivers, they will need to meet the same interoperability standards as Fastned and Wenea.

Superhub development, usage and lessons

Redbridge concession arrangement and tender process

Oxford City Council had no funding for the EV chargers at Redbridge, therefore the best contract methodology was a concession type model. This is where the landowner offers its land for a charge point company to run its business, in return for bay rental and/or income share. This can be mutually beneficial, accentuating the best of public and private sector partnerships. The landowner/local authority utilises its land for much needed EV charging and in turn generates some modest income (bay rental and or income share) to cover its costs, whilst enabling the charge point companies to deliver charging services to the public. A collaborative and proactive partnership can be created with robust long lasting charge point providers. Legal contracting should secure the right levels of service and timely interventions for dealing with loss of performance. Contract lengths need to be fair to all parties. Two procurement exercises were undertaken by OCC, firstly seeking CPNOs for DC ultra-rapid chargers and secondly AC fast chargers. Managing the tender process was challenging, requiring support from already stretched OCC teams including Legal, Property, Finance and Procurement. The need for this expert input led to several delays. The procurement process started with an open day in Feb 2020 and the decision on which companies to work with was finalised by autumn 2020. Agreeing the legal terms for all three contracts took a huge amount of OCC time and resource and required significant support from external lawyers. Fastned's contracts were completed in early 2021, Tesla by Dec 21 and Wenea in April 2022.

Figure 2.8: Fastned chargers at the Superhub

There were no standard concession style legal contracts available for use by charge point companies and local authorities, so everything had to be created from scratch, with terms replicated across the three operators. The DC procurement needed to be OJEU compliant, due to the potential value of the overall contract. This documentation has become a potentially valuable resource for other local authorities intending to pursue a similar model.

Why three Charge Point Network Operators?

The project plan was to have the largest and most powerful number of chargers in the UK. It was an aspirational target particularly for 20 x DC charge points (min 150 kWh). It was also essential to the EDF Renewables private wire business model to secure sufficient income from the DC off-take (hence 20x rapid/ultra-rapid charge points). For the prospective charge point operators tendering for the site, this required significant investment. Only two CPNOs responded to both tenders.

On the DC side, Fastned and Tesla submitted a joint bid to provide the total number of charge points needed. Both companies provided confidence in their capability and aspirations for Redbridge. Tesla's network is dedicated to Tesla drivers only. Fastned's solar canopy offered lighting and rain protection, as well as an open interoperable network for any drivers, which met all the key requirements for the Superhub.

On the AC side, Wenea, who were already working with Devon County Council, provided the right level of confidence in their capability and aspirations as a CPNO to be awarded the contract. They then went onto agree to install a further 4 charging bays. As part of the scope change and to enable the AC CPNO to have access to cost effective LV electricity, OCC needed to purchase the electrical equipment needed to step down the private wire HV to LV electricity. This included purchasing a transformer and switchgear. OCC required support from EDFR and a consultant electrical engineer to facilitate this.

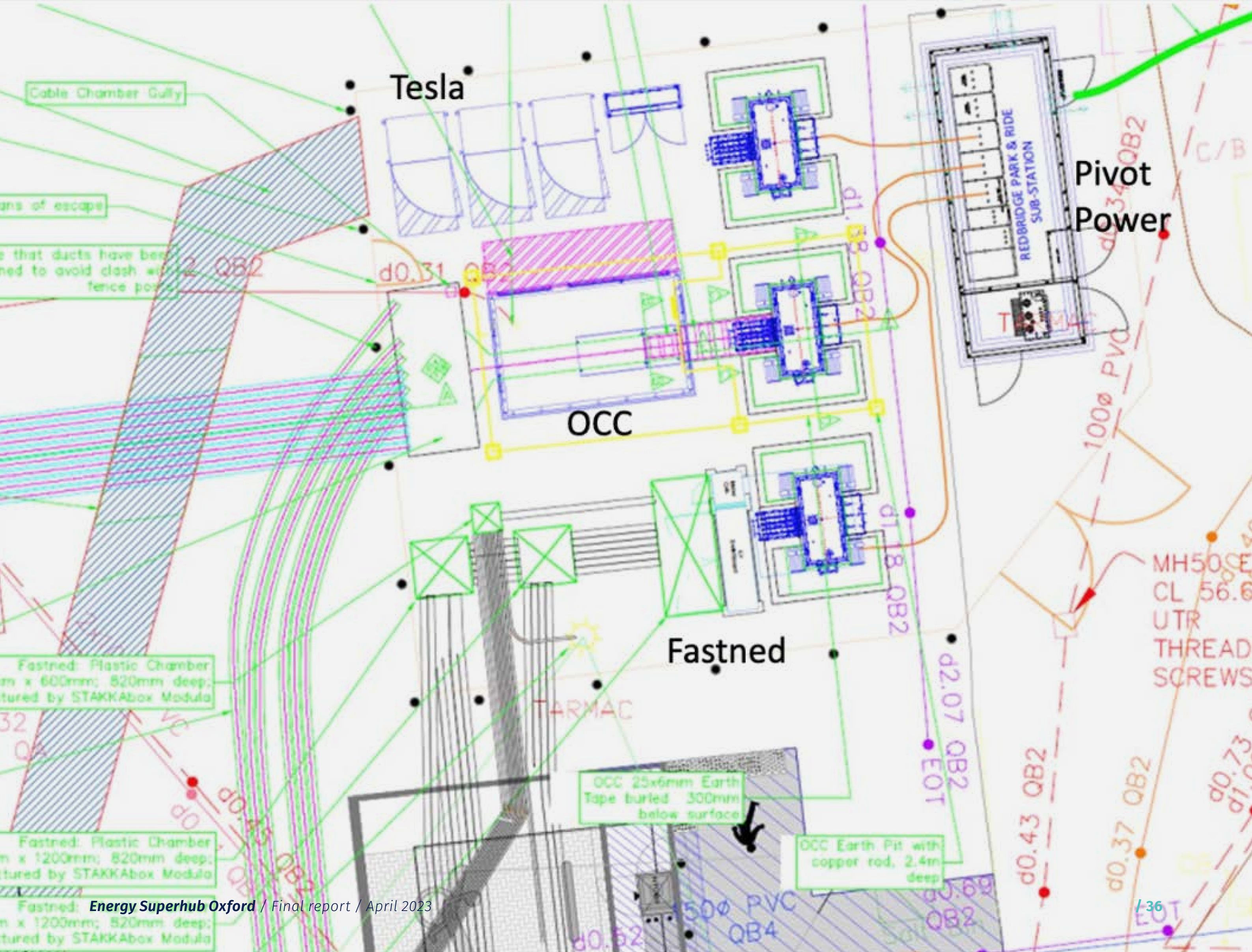
Superhub construction

The Superhub consists not only of the three CPNOs' chargers, but also the electrical equipment needed to step down HV to LV electricity. Fastned and OCC elected to install a 2.5MVA transformer at the Superhub shared compound. Tesla chose a 2 MVA transformer. OCC have installed a larger transformer to future-proof the site in preparation for expansion of the initial Wenea fast charging, but more importantly to provide headroom for other expansion at Redbridge to accommodate future potential fleet or bus charging at the site.

Early on in the project it was decided that the step-down equipment would be housed in a shared electrical compound. This approach enabled the minimum loss of car parking space. The compound contains transformers and Low Voltage equipment belonging to three different owners, plus the EDF Renewables substation (Figure 2.9).

Design and construction of the shared compound area proved to be the most complex part of the Superhub, Meeting health and safety regulations on a former landfill site required considerable work.

Figure 2.9: Plan of the shared electrical compound.



A change in leadership of compound construction and subsequent in-depth design, planning, additional contracting, alongside scheduling of works to ensure safe working, resulted in two months of additional delays to the construction of the hub and was a key learning point for the project.

Capacity Charging (EDFR business model) – comment on pricing vs DNOs

EDF Renewables model is to charge an initial connection fee for the capacity secured and then an ongoing annual capacity fee. The pricing of such a model was benchmarked against comparable DNO charges to ensure affordability for the CPNOs. Note that OCC is the holder of the AC capacity agreement, rather than Wenea, the AC CPNO. EDF Renewables ongoing charges are CPI-linked which is in contrast to the DNO charges which can vary significantly year on year.

Resourcing challenges

One of the significant challenges the council faced in developing and delivering the Superhub was the resource and skills needed to achieve the scope change to operate the hub as a concession model. Albeit this has proved to be an incredibly valuable learning tool for the council and staff involved.

Leading a project of this type to design and safely construct the shared compound required professional construction design and management support and additional programming resource.

Coffee concession

The consortium members are also aware of the need to promote usage of the Superhub chargers amongst EV drivers. Those who visit the site to use the ultra-rapid chargers are likely to stay close to their car for a relatively short (20-30 minute) charge. In competition with motorway service stations for these customers, the Superhub will benefit from a kiosk serving coffee, which is due to be installed shortly after the end of the project. Time of day usage patterns of the Superhub will be a factor in determining opening hours.

Superhub in Operation

The Superhub has been operational since July 2022 with all three CPNOs offering their own commercial charging model at the site.

Usage of the Superhub grew steadily in 2022 since launch, this is measured in both numbers of visits and in MWh used at the site. There was a spike in December 2022, aligning with colder temperatures (see below) and the holiday period. Demand dropped slightly in January and has remained at a similar level for the first two months of this year (Figure 2.10) but is expected to continue to increase throughout 2023 as EV uptake increases.

This usage is broadly in line with EDF Renewables expected volumes. Note that the majority of volume is used by the Ultra-rapid charging CPNOs, Fastned and Tesla, the OCC/Wenea demand is very much lower by comparison. This is expected as the Wenea chargers are much lower power (22 kW) and cars are plugged in over a longer period, leading to lower numbers of cars charged. From a 'visits' perspective as would be expected we see the same pattern, amounting to a total number of visits to the site of over 22,000 since launch. At the time of writing this corresponds to around 2 million miles driven by drivers charging at the Superhub. Usage patterns vary across time of day with peaks in the morning and early afternoon during working days and this pattern shifting backwards at weekends, with fairly constant usage between 10am and 6pm.

CPNO Consumption at Redbridge

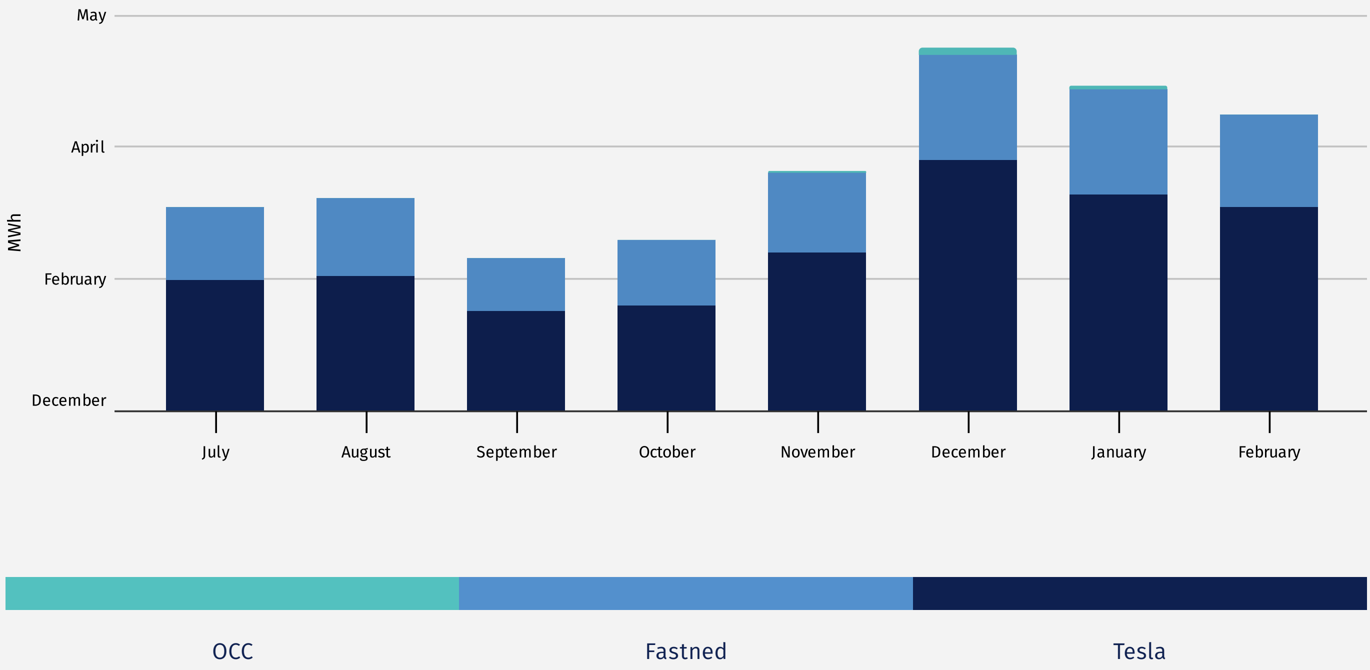


Figure 2.10: Total electricity consumption at the Superhub, July 2022 – February 2023, MWh

The section on user interviews provides interesting insights into drivers' perceptions of the Superhub as well as their **usage patterns.** We have also noticed a marked statistical correlation between maximum daily temperature and consumption at the site. This is likely to be due to varying battery performance with temperature.

In the operating time available it has not been possible to draw any conclusions about the impact of the Superhub on EV uptake in the Oxford city area. Oxford's market share of new EV registrations is high when compared to the UK's average, but most of the drivers using the Superhub are driving through from outside the county. Nevertheless, the option to use the Superhub if local on-street charging is temporarily unavailable can provide reassurance to local drivers considering a switch to electric.

Overall assessment of the Superhub Model

For the Redbridge Superhub and private wire, without the IUK grant funding a cable route of this length would not have been possible. EDF Renewables' target distance is sub-5 km in other locations.

However, EDF Renewables believes the transmission connected Private Wire model, when combined with grid scale battery storage, presents a valuable market opportunity, using a route which is currently different to all other Ultra Rapid charging models in the UK.

The objective of this model is through transmission connection, to be able to offer very large amounts of power for EV charging – something which is essential for hubs offering large numbers of ultra rapid chargers in parallel. In the case of the Redbridge Superhub the private wire can provide 10 MW or more of power for EV charging.

The opportunity for roll out of this model will be determined by geographical locations of suitable connection points to the National Grid (driven by the positions of Supergrid transformers with tertiary windings), so it will not be a solution in every part of the country, but where such connections are available the transmission model offers a route to avoid potentially very substantial upgrades of the distribution network required to offer similar amounts of power.

While we believe this is likely to be the case for the Oxford Superhub, we have not been able to source comparable figures for the costs and timescales of distribution network upgrade work to enable such a connection at Redbridge.

However, there is no doubt that for the CPNOs, both for public and private fleets, access to capacity is one of the primary challenges. The EDF Renewables private wire model provides an affordable solution within an acceptable timescale for these CPNOs.

As mentioned above, pricing of the connection capacity has been aligned with similar DNO based pricing structures to ensure that the costs of the private wire offering is comparable.

It should be noted that for the Oxford private wire, the economic model extends beyond solely the Superhub and the three public CPNOs, the addition of the buses to this model brings a significant boost to the economics of the private wire (see below). The capacity to be contracted with the Oxford Bus Company is 8 MW, which compares to the combined contracted capacity of 4.5 MW at the Redbridge Superhub site.

As this private wire model is rolled out to other locations, it is likely that future private wires will start with fleet customers (e.g., buses) as well as public charging companies such as the Redbridge CPNOs. Volumes for fleets are likely to be much higher than for public charging, due the size of the batteries and higher utilisation rates of the vehicles. Beyond buses and commercial car and van fleets, EDF Renewables is also looking forward to HGV charging facilities, which will require even higher volumes.

EDF Renewable is therefore pursuing this model at other transmission connection sites where such fleets, as well as public CPNOs can be aggregated.

Buses

Buses have always been a key target for the ESO project, although it has been known that being able to charge new electric buses would probably fall outside the timelines of the project itself.

In 2020/2021 Oxfordshire Council led a bid under the government's All Electric Bus Town competition to attempt to secure funding for electrification of Oxford's buses. This was not pursued past the first stage for timing reasons, but the County Council subsequently followed up with a proposal into the Zero Emissions Bus Regional Areas (ZEBRA) scheme, funded by the Department for Transport. This proposal required private match funding from the regional bus companies, in this case the Oxford Bus Company (part of the Go-Ahead Group) and Stagecoach.

It has been a significant benefit to the Oxfordshire ZEBRA bid to have access to the private wire cable route at the Oxford Bus Company. The Oxfordshire County Council ZEBRA bid was successful, although the bus companies raised a condition that proposals for city 'bus filters' needed to be agreed and implemented in order to ensure the new buses would not be impeded by city centre traffic which could impact bus use and the ZEBRA business case.

Agreement to these bus filters by Oxford City Council was announced in November 2022, opening the way for Go Ahead, the owner of Oxford Bus Company, to place orders for 104 electric buses. These buses are due to start to arrive in the autumn of 2023.

The Oxford Bus Company (OBC) is planning to sign an 8 MW connection agreement with EDF Renewables to use the private wire route and the substation constructed in the OBC compound under the ESO project.

This will be a major win for ESO and Oxford, even though the buses will arrive after the close of the project. It was always the intention that the private wire would expand with new customers, strengthening the economic case for the private cable route beyond Redbridge Park and Ride itself. Addition of the Oxford Bus Company is a demonstration of the viability of this model.

In addition, Stagecoach, the other bus operator in Oxford, with 55 buses, is now in discussions with EDF Renewables regarding a connection at their depot via a spur which would be run from the existing private wire, some 400 m away. If successful, it is anticipated that works to provide that connection to Stagecoach would take place in the summer of 2023.

It is not intended initially to use the Optimisation and Trading Engine as an optimisation tool for overnight charging of the OBC buses, as suggested in the ESO interim report, although this could be a future opportunity for Habitat, should the bus company and their charging installer wish to explore this.

Key Achievements: private wire and Superhub

- UK's first Transmission-connected EV charging hub.
- 7 km private cable built to provide power to the Superhub and Oxford Bus Company.
- UK's largest and Europe's most powerful charging hub with capacity for up to 10 MW of power or more.
- Currently 42 charge points at a range of charging speeds, with capacity to extend to hundreds.
- Private & public sector collaboration at its best, resulting in a successful hub with 3 CPNO's co-located on one site.
- The Superhub is a major EV charging asset in OCC's wider EV infrastructure strategy, which was also funded by the project.
- The team achieved changes to Ofgem policy on charging bands for transmission network use of system (TNUoS) residual charges for transmission-connected demand customers, without which the project would have been impossible.
- The project explored and clarified arrangements with Elexon to facilitate transmission-connected metering for other customers in future.
- Addition of charging for between 104 and 160 buses is a major win for the project.
- Private wire economics are proving viable and EDF Renewables are seeking follow up projects at other connection points, including both fleets and public charging options.

Summary of lessons learned: private wire and Superhub

- Up-front buy-in from senior stakeholders across all Local Authority functions is essential. Land and legal departments can be key bottle necks due to the complexities of stakeholder agreements in these areas.
- Local Authority Master site planning essential at the earliest possible stage to give confidence in Superhub design layout and future options for expansion.
- Consideration should be given to multiple possible procurement routes. OCC pursued concession-based contracts, still requiring the OJEU tender process. Other councils may find alternatives which reduce tender timescales.
- Confront regulatory processes that do not support innovation. Lobbying of Ofgem secured changes to the Targeted Charging Review which allowed this project to progress, and opened up the market for other transmission connected assets.
- For a public charging hub multiple CPNOs adds complexity, a single CPNO would be a simpler model if achieved in conjunction with other fleet customers to enable suitable private wire economics.
- Start Superhub design and construction discussion as early as possible and continue throughout contract negotiations. This became a city council led role without understanding of the necessary resources.
- Planning procedures were complex and time consuming.
- A wide variety of stakeholders need to be consulted for private wire construction and superhub build.
- There are no ready-made legal agreements for contracting with CPOs, nor technical specifications or performance and maintenance standards. The need for legal expertise increases costs significantly.

User experience at the Superhub

About the Study

The study aims to gather insights into users' charging experience at the Redbridge ESO Charging Hub. Informal discussions were carried out with users at the station between August and October 2022. These have influenced the design of a pilot questionnaire which was then deployed on-site in October 2022 (n=30).

The pilot questionnaire and relevant responses led to further refining research questions and adding new items to be explored. Then, the final version of the questionnaire was formally launched and a total of 151 complete responses were collected during winter 2022/2023. Data collection occurred at both weekends and weekdays and during different times of the day including mornings, afternoons, and evenings. The questionnaire comprised 30 questions reflecting on the socio-economic background, previous EV experience, charging habits, charging habits, and the expected vs the realised charging experience.

User characteristics

Users of the three providers (Fastned, Tesla, Wenea) were approached and asked to complete the questionnaire (Table 2.2). 55% and 42% of the sample were Tesla and Fastned users, respectively. Fastned users belonged to a more diverse socio-economic background when compared to Tesla users. It was hard to recruit Wenea users: they mostly left their cars unattended. 82% of the sample were private users, and another 13% were commercial fleet drivers, with a very low representation of taxi drivers (1.32%). The sample did not feature delivery/council drivers. The station attracted many first-time users during the Christmas season. Most cars were single-occupied.

AGE	
Under 30	6%
30-50	53%
Over 50	41%

INCOME	
Less than £18,600	1.32%
£18,600 to £26,000	7.95%
£26,000 to £39,300	4.64%
Above £39,300	67.55%
Prefer not to say	18.54%

GENDER	
Males	**Females**
80%	20%

Table 2.2: Characteristics of Superhub users

The EV driving experience and charging habits

66% of respondents stated that their household also owned a non-EV car. The EV driving experience – in terms of length – varied across the sample: 26.5% less than 6 months, 21.9% 6-12 months, 33.7% 1-3 years, and 17.9% over 3 years. 58% of respondents own a charging point at home, with a further 10% and 15% having applied for one or considering applying, respectively. Only 17% of users neither owned nor expressed an interest in getting a home charger.

Almost three-quarters of respondents said that they drive their EV >30 miles on one journey, at least once per week, with another 20% driving a journey of >30 miles less than once per week but several times a month. The definition and threshold of what counts as a long journey varies across locations. For reference, participants were informed about the distance between Oxford and other locations like Bicester, Swindon, Reading, and London.

Users' Journey Profile

70% of respondents stated that they were driving a long journey that day (>30 miles), and 66% said that the purpose of their journeys was business-related. Most participants said that their trips were obligatory and there was a need – rather than a desire – to fulfil these trips. Less than 20% of the trips were socially oriented (Figure 2.11). There was no association between the distance travelled and the purpose of the trip.

Purpose of the journey

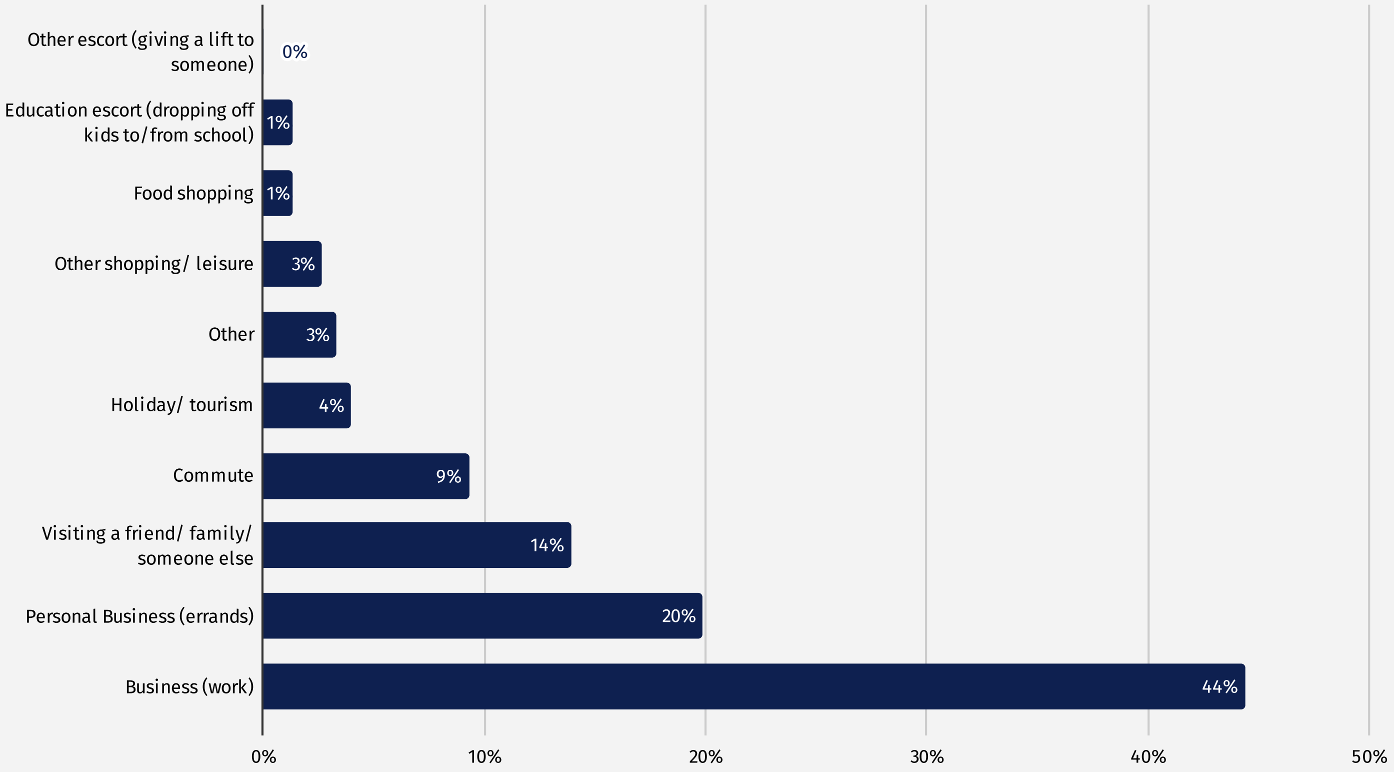


Figure 2.11: Journey purpose

Nearly 60% of respondents lived outside of Oxfordshire (Figure 2.12), and these users were much more likely to have access to a home charging point (73%) than those who lived in the city or county (34%) (Table 2.3).

	I HAVE A CHARGING POINT AT HOME	I DO NOT HAVE A CHARGING POINT AT HOME
I live in Oxford city/county	34%	66%
I live outside Oxford County	73%	27%

Table 2.3: Superhub users' access to home charging points

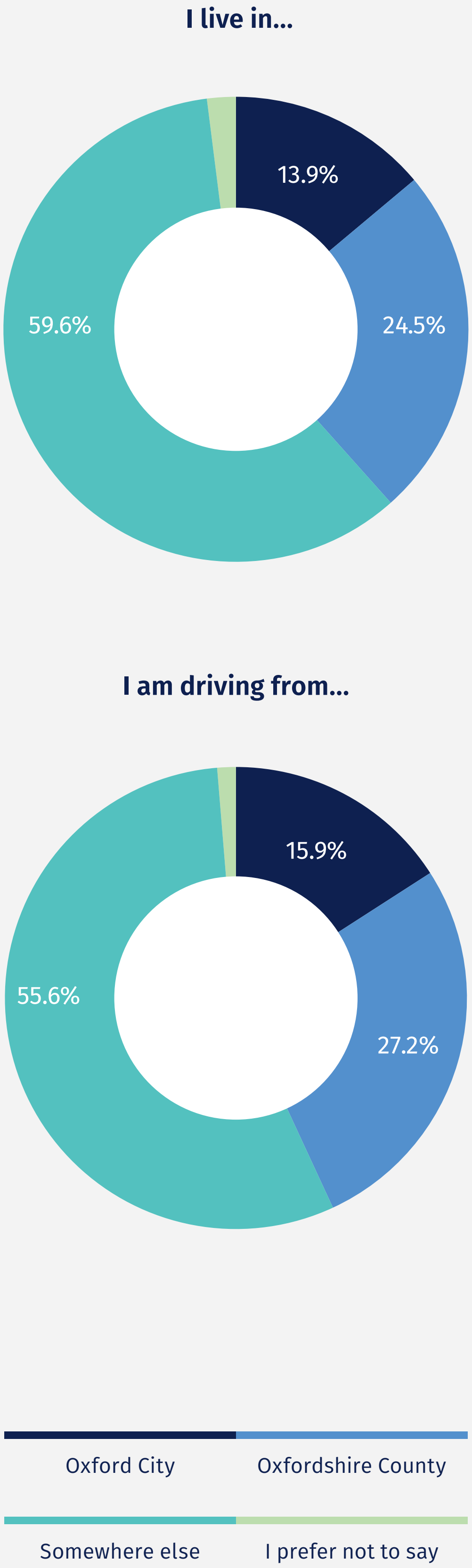


Figure 2.12: Drivers' home location and where they are driving from

Charging Preferences

Around 50% of users prefer to charge on weekdays, which reflects the high proportion of business users. When asked about the most preferred time during the day for charging, almost half the sample stated that they have no preference. Mornings, afternoons, and evenings were all popular, however, charging late at night was by far the least preferred option (1.3%).

Regarding the frequency of charging at Redbridge, findings show that almost 70% of respondents were not frequent users; 45% stated that they use the Superhub 'less than once a month'. In contrast, only 30% used the chargers more than once a week.

Participants were asked to select the reasons for charging at the Superhub (Figure 2.14). On a list of 14 items, the item 'the station's proximity to major roads allows me to access it with ease' followed by 'it features rapid charging' were the most selected reasons. Proximity to the ring road and the A34 allowed users to easily find, enter, and exit the station. It is worth mentioning that most of the sample did not pick one singular reason for choosing Redbridge. On average, each participant selected two reasons, confirming that multiple factors influenced users' choices.

Around 50% of users prefer to charge on weekdays, which reflects the high proportion of business users.

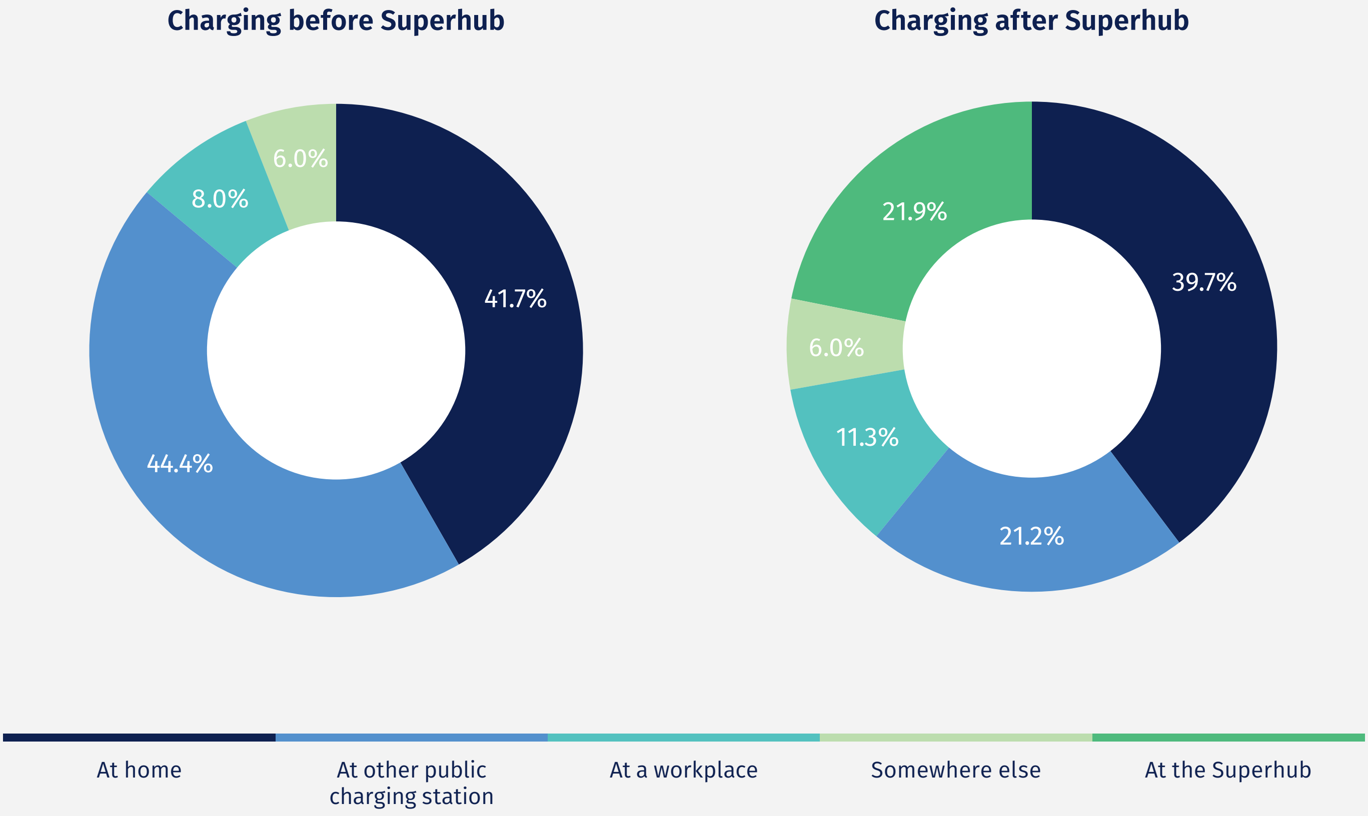


Figure 2.13: Charging preferences before and after the Redbridge Superhub was opened

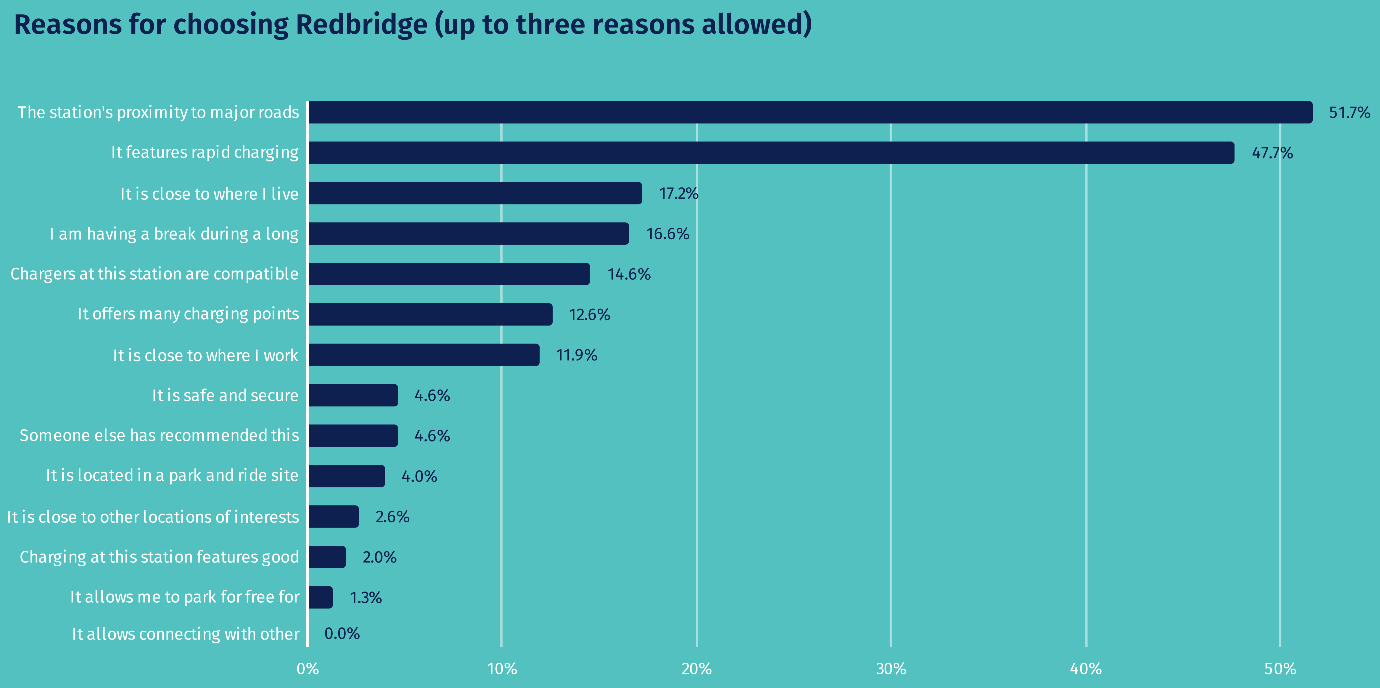


Figure 2.14: Reasons drivers chose Redbridge (up to three reasons per driver)

The station’s proximity to major roads was valued by long-distance travellers especially, where 58% of them selected this reason for choosing Redbridge, compared to 37% of short-distance drivers selecting the station for the same reason (Figure 2.15). Rapid charging was attractive to long-distance drivers, while short-distance travellers were more likely to highlight the Superhub’s proximity to where they live as a reason for charging there.

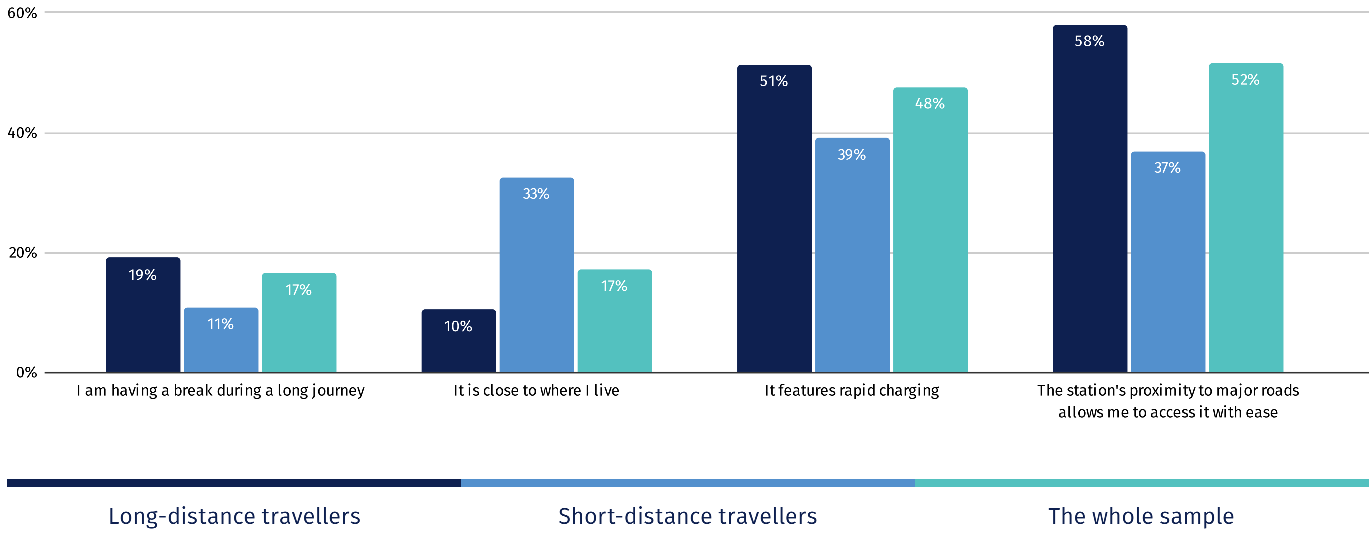


Figure 2.15: Journey distance and reasons for choosing Redbridge

Regarding activities with which respondents occupied their time while charging, 'sit and relax' was the most selected item (43%), followed by 'get something to eat/drink' (31.8%), and 'do some work on my laptop/ mobile phone' (31.1%) (Figure 2.16). Most participants stayed near/inside their cars during charging, and 95% of them stayed on the charging bay for less than an hour. The item 'it allows connecting with other transport modes' was not selected by any participants. Even the four Wenea users – who stayed longer on the charging bay – did not express an interest in using other transport modes at Redbridge to visit the city centre/other locations.

Activites while charging (multiple choices allowed)

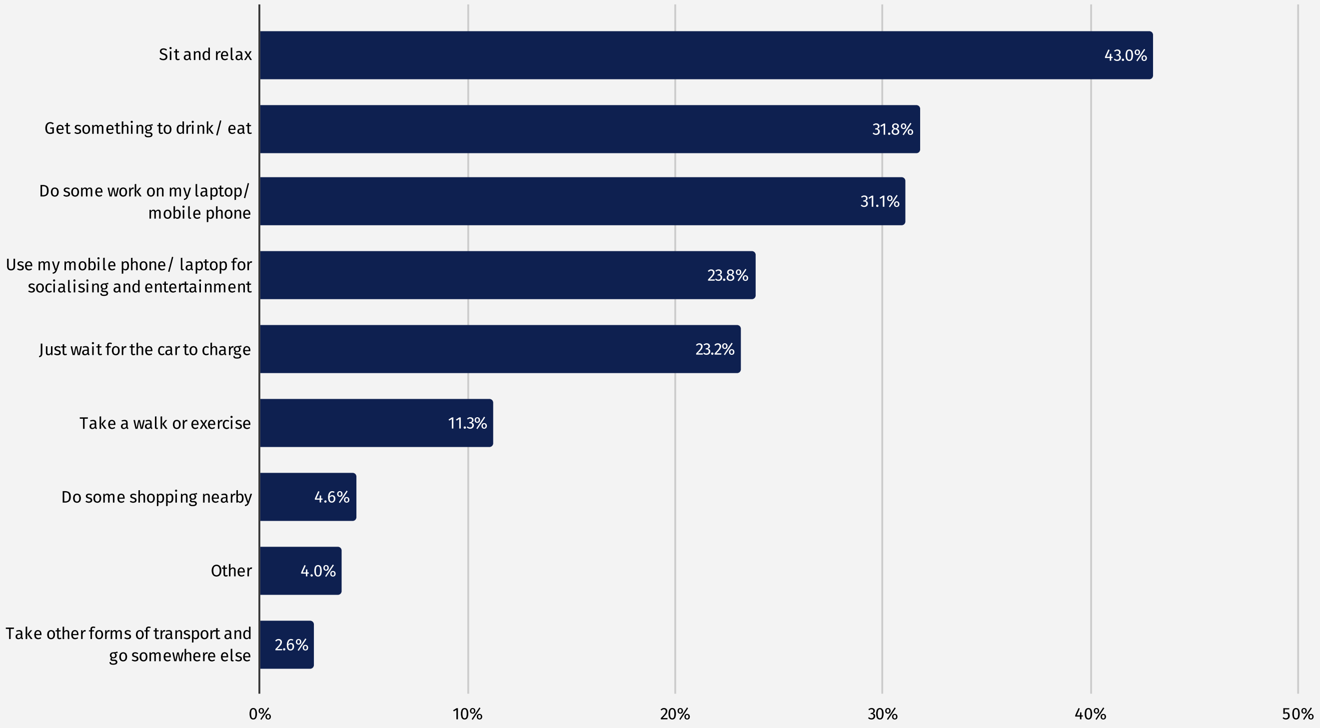


Figure 2.16: Activities while charging

The Superhub influences how participants plan their journeys, but not their decision to buy/drive an EV (Figure 2.17).

However, this may change in the future given that many prospective EV drivers cite insufficient charging infrastructure as a barrier to take up. Some of those who expressed their willingness to visit the city centre while waiting for their car to be charged perceived the price of the bus ticket to be a barrier. Some older users indicated that they visited the city by bus, benefiting from free rides. Wenea users tended to live more locally and use the chargers more regularly. They often brought their charging cables and while charging, they would take the bus from the station to other parts of the city.

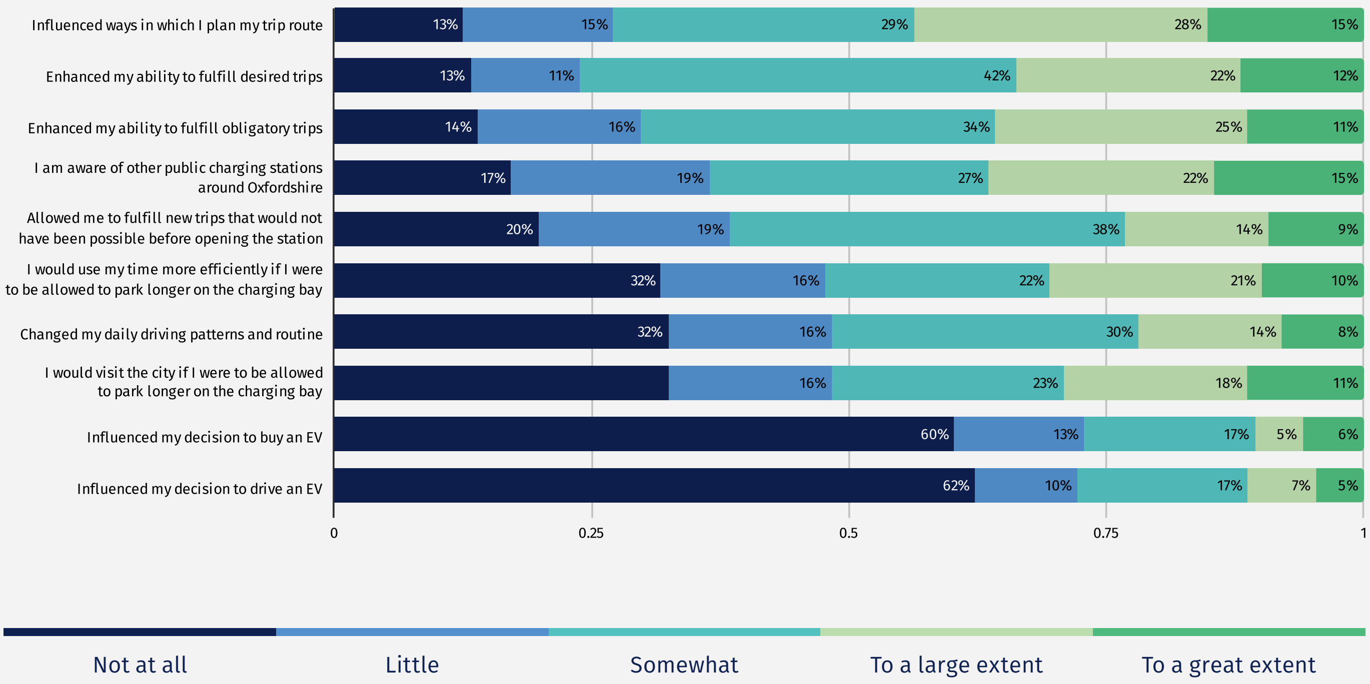


Figure 2.17: User views on Redbridge and its influence on their decisions

Cross-tabulation analysis shows that participants who travelled for business/commuting purposes charged their EVs at the Redbridge station more frequently when compared to those who travelled for social/other purposes. Similarly, frequent long-distance travellers tended to use the station more frequently when compared to those who conducted fewer long-distance trips. Also, the station was significantly used more frequently by those who did not own a charging point at their home. Finally, there was no significant difference between those who drove an EV for more than a year and others with a shorter driving experience in terms of charging frequency.

> *The station was significantly used more frequently by those who did not own a charging point at their home.*

TRIP PURPOSE VS FREQUENCY OF CHARGING AT REDBRIDGE

The purpose of my trip is	**I use the Redbridge station**		
	Several times a week	**Once a week**	**Less than once a week**
Commute + Business	17.1%	20.7%	62.2%
Social + other	12.5%	2.5%	85%
Total	15.9%	15.9%	68.2%

LONG-DISTANCE TRIPS FREQUENCY VS FREQUENCY OF CHARGING AT REDBRIDGE

I drive EV over long distance	**I use the Redbridge station**		
	Several times a week	**Once a week**	**Less than once a week**
At least once a week	18.2%	16.4%	65.5%
Less than once a week	9.6%	14.6%	75.6%
Total	15.9%	15.9%	68.2%

EV DRIVING EXPERIENCE VS FREQUENCY OF CHARGING AT REDBRIDGE

My EV driving experience	**I use the Redbridge station**		
	Several times a week	**Once a week**	**Less than once a week**
More than one year	15.4%	14.1%	70.5%
Less than one year	16.4%	17.8%	65.8%
Total	15.9%	15.9%	68.2%

HOME CHARGING OWNERSHIP VS FREQUENCY OF CHARGING AT REDBRIDGE

Home charging point owner	**I use the Redbridge station**		
	Several times a week	**Once a week**	**Less than once a week**
Yes	4.6%	14.9%	80.5%
No	31.3%	17.2%	51.6%
Total	15.9%	15.9%	68.2%

Table 2.4: Cross-tabulations of trip purpose, distance of trip, length of EV driving experience and home charger ownership

The expected vs the actual charging experience at the Redbridge station

A total of 30 items were presented to participants who then scored each based on the extent to which they would expect this item in a public charging station, on a 5-point Likert scale ranging from not expected at all (score 1) to very expected (Score 5). Participants were then asked to score the same 30 items based on their actual – realised – experience at the Redbridge station, on a scale ranging from strongly disagree (1) to strongly agree (5). The score difference between expected and realised experience was calculated (Figure 2.18).

Regarding the expected experience, the aggregate scores indicated that the five most expected items – items are: charging points are easy to use (4.3), the location of the station is easily accessible (4.21), finding the station is easy (4.2), chargers offer rapid charging (4.17), I can pay with ease (4.17). Moreover, 8 out of 30 items got a score of (4) or above, belonging to the expected/very expected category. Concerning the realised charging experience, the Superhub got its highest scores on the following five items: chargers offer rapid charging (4.51), there is a vacant, fully-working charger (4.42), the location of the station is conveniently accessible (4.36), charging points are easy to use (4.29), I can pay with ease (4.27). Furthermore, 11 out of 30 items scored (4) or higher, belonging to the agree/strongly agree category.

Interestingly, the realised experience scores for 21 out of 30 items were higher than the expected experience scores of the same items, indicating that the realised (actual) experience at the Redbridge station is exceeding the expected experience. The high realised scores of some key items like the ease of payment, the ease of using the charging point, the ease of finding and accessing the station, the availability of rapid chargers, and the availability of a vacant fully-working charger suggest that the station is delivering a pleasant and seamless charging experience.

The highest disgruntlement scores relative to expected experience are: 'there are food and drink services' (0.42), 'there is reliable remote assistance for fast issue resolving' (0.36), and 'ways in which my charging data are used are clear to me' (0.34). The disgruntlement factor of these items is relatively low; 0.42 out of a possible score of 5 can be viewed as a service dissatisfaction level of 8%. Still, these three items offer an area of potential improvement. Several users expressed that the station should offer a 'proper' café and often compared the Superhub with other stations that contain food/drink amenities. A food and drink service would serve existing users and will encourage others like taxi drivers and commercial fleets to use the station during their break time. Charging providers may improve the ways in which they offer remote assistance. Finally, some drivers were confused about the specificities of parking rules, and when and how to pay. They didn't know whether they need to pay for parking or get a ticket. Others struggled to find the ticket machine as it was not clearly visible and so they asked their fellow drivers for directions.

Several users expressed that the station should offer a 'proper' café and often compared the Superhub with other stations that contain food/drink amenities.

Conclusion

The Redbridge Superhub is well-positioned to serve the transition to EVs in the short, medium, and long term. Its location attracts a range of users from within and outside Oxfordshire. The station is delivering a charging experience that is exceeding users' expectations and is fulfilling duties that are at the core of any public charging process. Still, there is space for further improvements.

The Superhub's influence on accelerating EV uptake locally and regionally may be more evident in coming years, especially if appropriate policies, incentives, and measures are put in place. It is important to regularly monitor the station's performance in terms of delivering the desired service and meeting users' expectations.

Lessons learned

- Charging experiences at the Redbridge Superhub are exceeding user expectations.
- Its location and proximity to major roads make it easy to find and access.
- The availability of rapid chargers is attractive to users.
- The station attracts long-distance travellers from outside Oxfordshire.
- The Superhub attracts users of other public charging stations, and most users are business travellers.
- Offers, discounts, and subsidised charging may attract a wider range of users like taxi drivers.
- Users' most important charging needs like ease of payment, being able to find a rapid, vacant, and working charger, and being able to easily access and find the station are being fulfilled.
- Providing food and drink services would elevate users' experience.
- Integrated and discounted ticketing could facilitate a seamless park/charge/ride experience.
- Parking duration/ payment rules and regulations could be simplified.

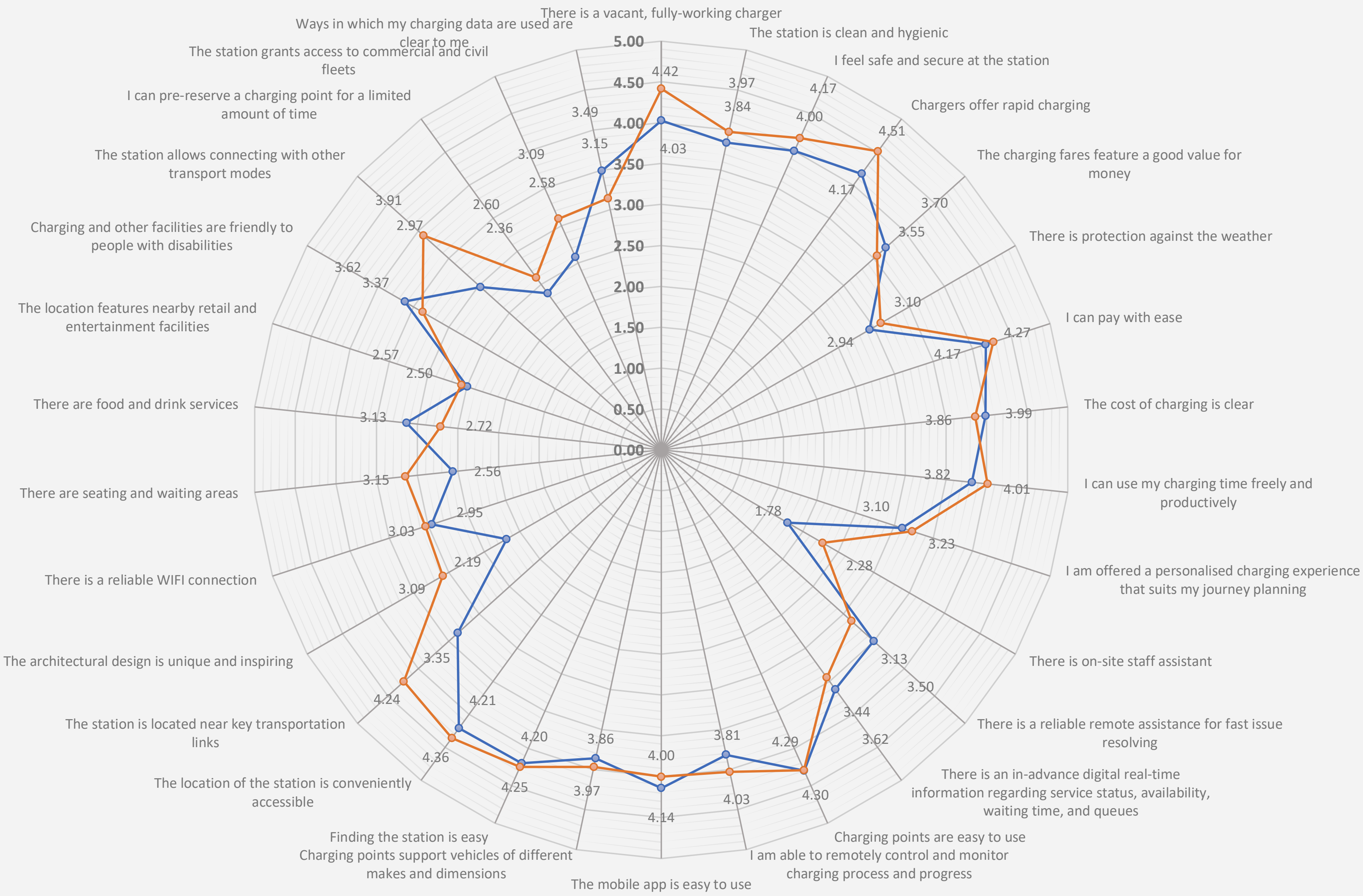


Figure 2.18: Actual and expected experience of Redbridge Superhub

Oxford Direct Services Fleet Electrification

Summary

1

Install 50 chargers across council depots, integrated with Habitat's Optimisation and Trading Engine (OTE)

2

Acquire two refuse collection vehicles (RCV), nine tippers, 14 vans.

Oxford Direct Services (ODS) is a social enterprise wholly owned by Oxford City Council. It operates over 325 vehicles, and ESO has contributed £1,137,000 towards the electrification of its fleet.

Prior to the project, ODS had 11 EVs on fleet, all of which were cars. The council was starting to make plans for the first UK zero emission zone (ZEZ), which meant a considerable expansion would be needed of its electric fleet.

ESO funding enabled the council to procure 40 additional EVs, across a full range of vehicle and council work types. These are owned by OCC and leased to ODS. Whilst the majority of EVs purchased were cars (e.g. Nissan Leaf, Renault Zoe) and vans (e.g. Renault Kangoo), funding also enabled the purchase of larger vans (Kangoo Maxi; Peugeot e-Expert), and several specialist vehicles including one street sweeper, one digger, two 3.95 t tippers, and a Refuse Collection Vehicle (RCV).

Scope change: hardware

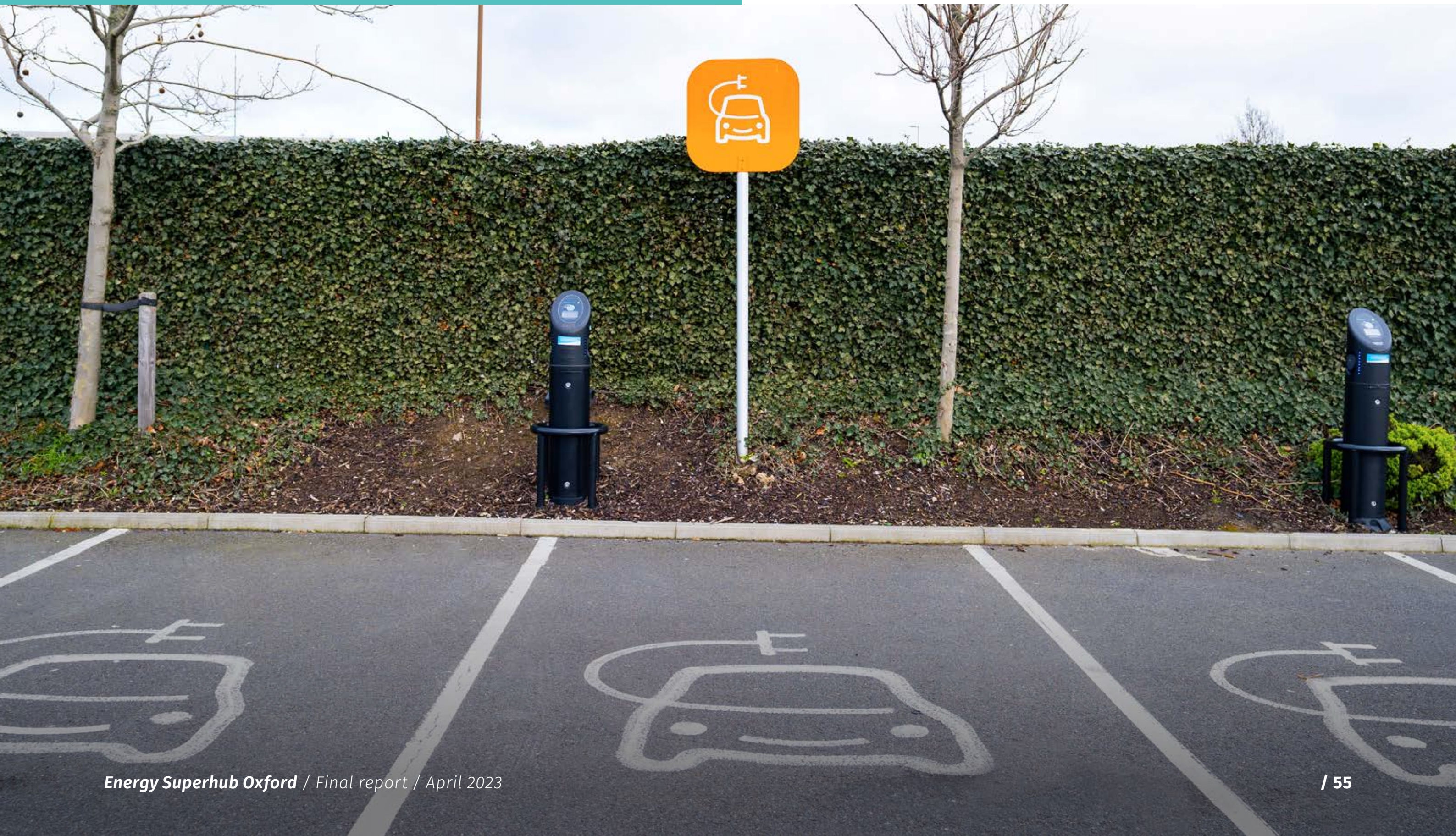
The original bid for funding included plans to connect the ESO Private Wire to ODS sites at Horspath and Cowley, to provide 50 fast and rapid electric vehicle chargers.

However, shortly after the start of the project, ODS announced plans to change their business model, with the majority of smaller fleet to be taken home and also an aspiration to gradually consolidate their fleet at Redbridge, in the south of Oxford. Conveniently, this is where the public Super Hub will be located, so it seemed perfect for ODS to make use of the 10 MW connection for their fleet.

The move to Redbridge was put on hold, so there was an immediate need for more chargepoints at existing depots. The chargepoints installed at the Cowley and Horspath depots have therefore been connected to the distribution network, with a view to relocating these in future. While many are capable of 22 kW, these are limited to 7 kW due to DNO constraints.

In the project proposal document, it was hoped that these vehicles (including more tippers and another RCV) would be purchased by March 2020. Unfortunately, the availability of electric versions of large commercial vehicle-types has been limited, and supply chains were heavily impacted by COVID-19. The pandemic impacted some car manufacturers more than others, and in some cases led the ODS team to choose alternative vehicles that could be obtained with less delay. This included switching from Nissan to Renault for smaller cars, and from Mercedes to Peugeot for larger vans. Despite the delays, Oxford is one of the first cities in the UK to have such a wide range of commercial EVs, and ODS' total fleet of full EVs is now 61, with an additional 22 Partial Hybrid Electric (PHE) vehicles.

> *Oxford is one of the first cities in the UK to have such a wide range of commercial EVs.*



Insights into Emissions

Since the purchase of the ESO fleet, Oxford has saved a minimum of 122.6 tonnes of CO_2 and a significant amount of NO_x emission. The ESO fleet acceleration is continuing, a further 40 EVs have been procured (but not yet delivered), enabling the council to easily meet its initial target to electrify 25% of its fleet by 23/24. It will in fact have over 100 EV's out of a fleet of @340 vehicles in this timescale.

The city council declared a Climate Emergency in 2019 and set a council net zero target of 2030, alongside the wider Oxford net zero target of 2040. This requires the council to decarbonise all of its remaining fleet (a further 200-250 vehicles) by 2030. Based on emissions from the fleet and respective mileage in 2022, this would save up to 1,093 tonnes of CO_2 and 387 tonnes of NO_x.

Further, over almost two years (2021 and 2022), the available data show that the mileage of operating 379 vehicles – 44 EVs and 355 non-EVs – surpassed 2.1 million miles, of which, 12% were EV mileage. On average, each vehicle – both EVs and non-EVs – had an annual mileage of 3000 miles. Three out of the five vehicles with the highest mileage were domestic refuse trucks, each having almost 16,000 miles a year. A conservative estimate indicates that a mileage of 2.1 million miles may create up to 760 tonnes of CO_2 emissions.

In 2022, EV trips counted for almost 24% of the total fleet trips. These reduced direct CO_2 and NO_x emissions by around 90 tonnes and 39 kg, respectively (Figure 2.19).

In 2022, operating EVs reduced the ODS fleet's emisssions by at least

56 tonnes

Emissions vs EV trips in 2022

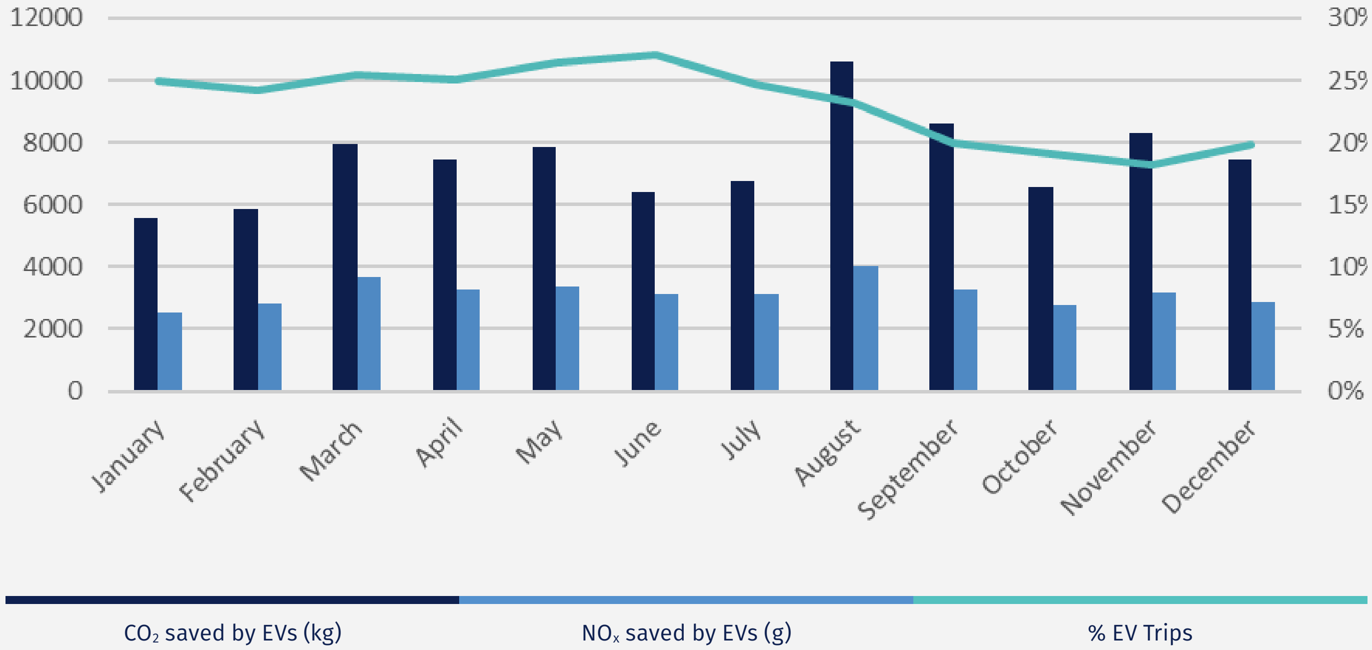


Figure 2.19: Carbon dioxide and NO_x savings by ODS EV fleet in 2020

Deploying more EVs in the fleet will increase the share of EVs (trips and mileage) and the result will be further emission reductions.

It is worth noting that the realised and future CO_2 emissions plus potential savings will depend on multiple factors including:

- **Vehicle types:** heavy vehicles like domestic refuse trucks emit significantly more per-distance emissions than other vehicles, plus they already have some of the highest mileage. Despite accounting for less than 10% of the total ODS fleet mileage, domestic refuse vehicles generate almost 35% of the total CO_2 emissions.
- **The energy mix:** a cleaner energy mix that maximise the use of renewables for generating electricity will magnify CO_2 savings.
- **Drivers' working patterns, skills, and competency:** for instance, harsh braking and excessive speeding contribute to higher emissions. However, the Opti Drive indicators show that the vast majority of ODS drivers maintain low driving speeds of 20 miles per hour or less.
- **Transport activity:** the ODS fleet mileage of 2022 was remarkably higher than 2021's mileage. This is mainly because the ODS fleet's operations were directly impacted by the COVID-19 pandemic. Also, more data was collected in 2022.

Scope change: Charging optimisation and fleet simulation

At the start of the project, it was hoped that ODS fleet charging would be provided by the private wire connection and managed by Habitat Energy's Optimisation and Trading Engine (OTE), potentially using wholesale energy prices and resulting in optimal charging costs.

With the ODS fleet now using the distribution network for charging, this was not possible and Habitat have instead, using data gathered from the fleet, simulated the potential benefits of charging the fleet at a consolidated depot where overnight charging could be optimised for minimum cost.

The main findings of these simulations are that the fleet's EVs are charging for less that 13% of the time they are plugged in to the chargers. This means there are sufficient chargers to continue to charge a significant increase in the EV fleet if charger use can be optimised. However, this will either require intelligent charging equipment to enable the necessary scheduling, or changes to staffing to enable the resulting benefits to be captured.

At ODS depots the highest charging load is currently between 17:00 and 22:00 and then between 12:00 and 16:00, with a further smaller peak between 06:00 and 09:00 in the morning. Interestingly, home usage highest load is between 22:00 and 01:00, indicating that home users may be using time of use tariffs to reduce energy costs.

The simulations found that ODS and the Council could improve efficiency and cut costs by plugging in only when they need to charge (not necessarily every night). This would require smart software for next day work planning and/or a change in shift patterns.

Savings could be made by shifting charging for many vehicles to the midnight to 07:00 period, when the Council's tariff is lowest, however due to current energy price conditions and the limited charging volume this would result in only limited savings (approximately £3k on the current EV fleet). ODS and OCC will continue to monitor these savings, as by the end of 2023 there will be over 100 EVs in the fleet.

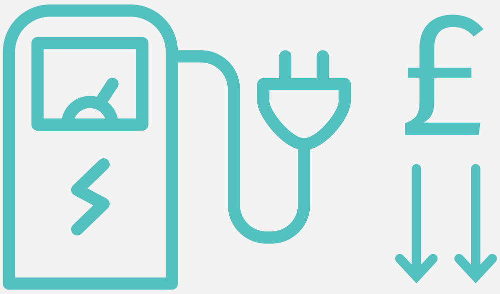
OCC will continue to review its electricity tariff, however as EV charging is a proportionally low part of their overall energy costs, night vs day tariffs must be balanced to achieve the optimal goal for all council activities, not only EV charging.

Insights into Costs

In 2020 it was cost-neutral to replace cars and small vans with electric equivalents but the larger vans, HGVs and less mainstream vehicles (sweepers, tippers etc) were cost-prohibitive. These account for around 50% of the fleet. Unfortunately, smaller EVs are no longer as economically viable as they previously were. The energy crisis, due to the Ukraine war, has doubled the cost of electricity for the City Council, impacting EV fuel savings. In comparison, the cost of diesel and petrol has remained broadly similar.

ODS fleet operates within a relatively small location boundary (less than 40 miles/ day) and its average fleet vehicle mileage is less than 5,000 miles pa. This and the still considerable difference in initial costs of electric vs diesel vehicles in the small to medium EV bracket of £5,000-£25,000 mean that the reduced fuel savings from electric no longer offset this. The reduction in maintenance costs have so far been minimal.

In 2022, the per-mile cost of charging the EV fleet was around £0.10, and this could be significantly lower when electricity is priced at the pre-2021/2022 rates. In contrast, the realised per-mile fuel cost of the non-EV fleet was around £0.29. From a pure direct operational cost perspective, the cost of charging the EV fleet was not only cheaper than using fuel but also close to the average national/international charging fees of around £0.05-0.08 per mile, considering the high electricity costs during 2022.



*From a fuel cost perspective, operating the EV fleet could be up to **82% cheaper** than operating ICE fleet in the long term*

Example of the unique challenges of fleet electrification

Electric Vehicles are generally much heavier than their fossil fuelled equivalents, due to the weight of lithium-ion batteries. For some vehicles this has regulatory implications. Tippers with 3.5T+ payloads are required to follow HGV standards for servicing and testing, and drivers are required to attend a dedicated five-hour training course. ODS are fortunate to have ample trained staff, but one staff member said it was difficult to find training providers to deliver this specialist training, and that other local authorities may struggle to get their drivers qualified.

Additionally, the government is removing subsidies for the purchase and operation of electric vehicles i.e. removing the OLEV grant or the introduction of RFLs to EVs in 2025, closing the savings gap even further. So, despite being cleaner for the environment, many EVs are no longer a cheaper option.

Due to global economic challenges, the prices of vehicles are still fluctuating and the market has still not stabilised. It is also a seller's market as demand outstrips supply and there is not a developed second-hand market. It is hoped that this settles down, as the EV market moves to the mainstream. The council has also considered leasing options, using reduced-emission fuels and/or hydrogen. Hydrogen is still an unknown quantity with a very limited vehicle pool and extremely high infrastructure cost. Hydrogenated Vegetable Oil (HVO) could reduce fleet emissions by up to 90% and it is already utilised by many other respected council and business fleets, however the council have concerns over the sustainability credentials of sourcing HVO and are currently rejecting this as a potential strategy.

The current fleet capital programme budget is around £14-17 million. To fully convert the remaining fleet to EV would cost an estimated £12m, based on purchasing figures. Currently, the council does not have the funding to support this additional funding gap and is therefore continuing to work intensively on the options to reduce emissions as cost-effectively as possible.

ESO has also funded the installation of charge points at ODS depots in Cowley, Horspath, Oxpens and Cutteslowe. Five chargers have also been installed in the homes of ODS drivers so that they can finish and start their shifts without commuting to depots. Such arrangements had been incorporated into employment contracts when using petrol and diesel vehicles, and ODS determined that electrification should have minimal impact on existing operations, not least causing additional travel. While simple and appropriate, this solution is not straightforward from an administrative perspective, as chargers are linked to employees' electricity meters, and remain ODS assets.

The five early adopters have been enthusiastic, but ODS anticipates that this solution may not be appealing for all drivers, for instance where off-street parking is not available.

So far, ODS report that electrification has not required any changes to operations including shift patterns or alternative route planning. This is a result of extensive planning and analysis of existing vehicle usage, including a detailed assessment of the whole ODS fleet by consultant Peter Stevens in 2019. His report found that the oldest and dirtiest vehicles in the fleet averaged less than 30 miles per day, so were ideal candidates for electrification.

While concerns had been expressed over the viability (and availability) of electrifying larger vans, it also concluded that many vans were carrying excess stock (e.g. tools and equipment), and identified a potential to downsize and electrify this fleet. This analysis illustrates the importance of having high-resolution information available – both qualitative and quantitative - to support the smooth transition to EVs. The speed of change in the EV market also highlights the need for frequent updates to organisational data and EV market intelligence. This is illustrated by the conclusion in Stevens' report, drawing on Electric Blue's analysis, that ESO funding would not be recommended for RCV replacement, due to lack of availability. Just two years later, the eRCV is in operation.

Obtaining operational data for the new ODS vehicles and chargers procured through ESO has proven challenging. This is primarily due to the difficulty of extracting and coordinating outputs from the large number of stakeholders involved in the transition. Chargers installed before ESO are operated by Hubeleon, while Innogy has been selected as the Charge Point Operator (CPO) for 38 new installations, at Cowley Marsh (24), Horspath (2), Oxpens (6) Cutteslowe (4), Home (5). Kempower are the supplier of the mobile e-RCV charger. ODS has three separate providers of telematics information: Webfleet, CMS, and VT. Finally, data on specifications, maintenance and emissions come from several sources, including vehicle manufacturers and ODS' workshop. Work has been ongoing to design a reporting protocol and software platform for accessing and analysing these data, which is now completed and working well.

Insights into Charging Habits

The fleet data platform provides insights into charging inefficiencies and behaviour. Some vehicles were overcharged almost daily, indicating a need for optimising charging behaviour. This will maximise the use of charging points and is particularly necessary when more EVs are expected to join the fleet in the future. Moreover, optimised charging will prolong the life of the EV batteries. The Opti Drive indicator refers to the number of speeding events and excess speed; this will help drivers to optimise their speeds. An optimised driving speed will decelerate the drainage of the battery and prolong the life.

Insights for Local Authorities

The experience of electrifying the ODS fleet has produced a myriad of insights which are likely to be valuable to other local authorities. The OCC/ODS team have, for instance, highlighted the importance of focusing migration strategy on the characteristics of the existing fleet and gathering detailed information on use and utilisation, as well as vehicle specifications, efficiency and parking locations. A good understanding of the nascent and emerging EV market is essential, as to date, relatively few options have been available for larger or specialist vehicles, and prices and lead times can vary widely. The ESO trial revealed the dependence on the DNO for assessing and approving applications for new charging connections, which led to an unexpected delay of six months due to the need for grid upgrades (SSEN's capacity was also impacted during this time by COVID-19).

Besides the direct involvement of the OCC/ODS team working on the ESO trial, the fleet migration has also placed new demands on other teams within the council, including procurement, finance, HR, legal, planning, and teams responsible for council lands such as parks and car parks. Liaising with these teams is essential, as their expertise can help overcome a variety of detailed and technical challenges around acquiring and operating new vehicles and chargers, and changes to operational arrangements. These include decisions about whether to own and operate physical charging infrastructure, or to outsource these and pay for charging; how to fund ongoing maintenance; and which specific data will be required relating to the chargers and vehicles, in which format, by whom, and how often.

Before COVID-19, local authorities were already struggling in the face of incremental budget cuts and competing priorities. In 2021, OCC's income was £500,000 below normal from the council's leisure centres, £850,000 lower from town hall room hire, £1.5 million down from car parks and £3.74 million less in rents from commercial premises. OCC forecast the total financial impact of COVID-19 between 2020-2026 to be a loss of £23m. These financial constraints help to explain the challenges of securing interdepartmental support for ESO. Given the central role played by local authorities in achieving smart local energy systems, future innovation projects will need to include adequate resourcing to cover the true costs of implementation.

The principal upshot of these insights is that to ensure a smooth transition, the staffing resource required should not be underestimated. One OCC officer said local authorities should expect to treble their estimates of resources needed in coordinating roles. Equally important is the need for buy-in from senior leadership at an early stage, to secure priority support from internal teams. Linking fleet electrification to climate commitments may be an effective way to build consensus and capacity for driving change.

These insights are based on findings from ESO's first two and a half years, and less than one year's operation of the ODS/OCC fleet. Further insights for local authorities resulting from the PFER programme are being developed by the Energy System Catapult's Energy Revolution Integration Service (ERIS), who have developed a **toolkit for local authorities.**

Lessons learned:

ODS fleet electrification

- Data analysis and strategic planning is essential for electrification, but the EV market is changing rapidly, so information can become out of date quickly.
- Availability of larger vehicle-types remains limited, and the price discrepancy between electric and conventional vehicles increases with size.
- Electrification has so far not required operational changes.
- New charging and vehicle technologies may further reduce the cost of the transition.
- Gathering and collating data on usage of chargers and EVs has been difficult due to the number of actors involved and concerns over data rights and access.
- However, what is well measured is well managed. Regular data collection & analysis will help to optimise the ODS fleet performance.

The Oxford EV Strategy and transitioning to a sustainable future

Summary

One of the key objectives of ESO was to support OCC to meet their net zero ambitions, by facilitating the transition to EVs for those who live, visit and work in the city.

In 2019 the council was involved in grant-funded EV delivery, including the ESO project as well as the Go Ultra Low On-street and Taxi projects. However, to assess the types and level of EV charging infrastructure needed to meet the 2040 targets of 100% transition to EVs, and give us the mandate to deliver it, OCC needed an EV Infrastructure strategy and data to evidence the trajectory. OCC also has responsibility for air quality in the city and transport emits 75% of NO_x in Oxford. The migration to EVs is one of the key methodologies for achieving a carbon-neutral sustainable transport model and reducing NO_x transport-related emissions by 88%.

The ESO hub infrastructure addition of 22 x ultra-rapid and 20 x 22 kW fast chargers as part of ESO has significantly augmented the current EV infrastructure across the city, but just as importantly it has played a huge role in raising the profile around the need for EV charging within the council and beyond, for our city public and private sector partners.

The Oxford EV Infrastructure strategy OxEVIS was funded by the ESO programme and was ratified by Cabinet in July 2022. It sets out the low, medium and Zero Carbon Oxford Partnership (ZCOP, a city partnership of key public sector, education and businesses, committed to work together to achieve the 2040 net zero target) targets for transition to EV at three key points; 2026, 2030 and 2040 (Table 2.5).

% EVS IN OXFORD AS PROPORTION OF ALL CARS AND VANS			
Trajectory	2026	2030	2040
Medium uptake	24%	50%	100%
High uptake	29%	61%	100%
ZCOP target	36%	80%	100%

Table 2.5: Projections of EV uptake in Oxford under different scenarios, 2026-2040

The trajectory for transition to EVs is steep, even using the Medium Uptake trajectory (Figure 2.2, Figure 2.20).

Based on 2022 data, Oxford currently has just under 53,000 car and light van car registrations, of which approximately 1400 are EVs. By 2026, using the Medium Uptake it is estimated some 12,500 will be EVs (Table 2.5). 54% of residents in Oxford will have access to off-street charging and the ability to privately fund home chargers, but a significant number will not. Data for Oxford shows that 46% of residents cannot charge a vehicle from their homes and therefore will rely on publicly available charging infrastructure.

Expected no. of plug-in vehicles to 2040

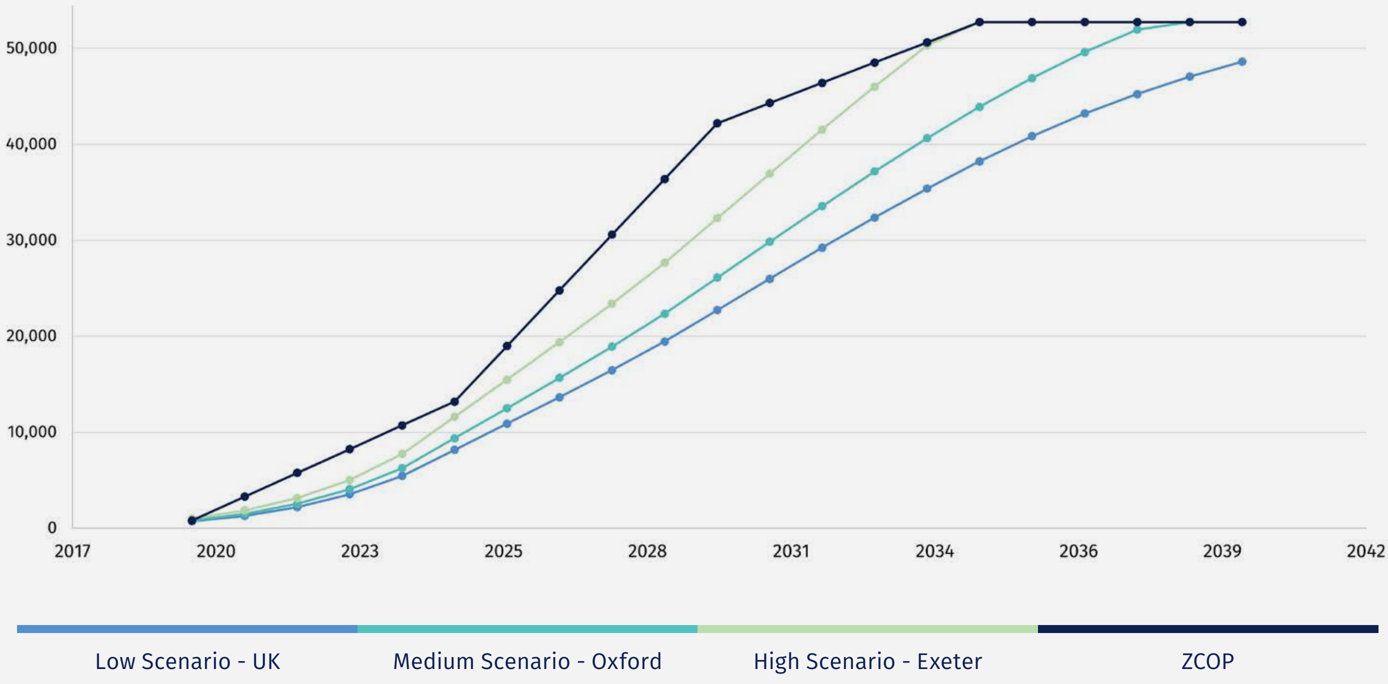


Figure 2.20: Projections of EV numbers, various scenarios, to 2040

Based on 2022 data, Oxford currently has just under 53,000 car and light van car registrations, of which approximately 1400 are EVs.

Chapter 3

Heat

This section focuses on ESO's work on decarbonising heat in Oxford through the deployment of smart ground source heat pumps (GSHPs), dynamic control systems and heat batteries.

Activities:

- GSHPs were installed in 57 Stonewater properties in Blackbird Leys, an Oxford suburb.
- Heat pumps were part-funded by ESO, and partly by the Non-Domestic Renewable Heat Incentive. The cost per property was around £13,100, including drilling boreholes, full plumbing and installation, and some fabric insulation upgrades.
- Market turmoil and technological barriers prevented real-world testing of flexibility through the retail market. Trials were implemented using simulated costs.
- Two flexibility trials were conducted to demonstrate the technical capabilities of dynamic heating. Lessons were used to improve the tenant experience.
- Innovative heat pumps coupled with heat-batteries were trialled in six properties in Sonning Common, South Oxfordshire.

Findings

- The business case for investing in ground-source heat pumps remains dependent on subsidy, and public funding became less reliable during the project.
- It proved difficult to convince Oxford social housing providers and non-domestic customers to install GSHPs in the timescale of the project. However, there are signs of more positive social landlord attitudes developing; the success of our installations are likely to have helped create a better environment for future HP installations in Oxford.
- Tenants expressed high levels of satisfaction with their heating and hot water systems, the installation process, and customer support. Tenants saved up to 50% on their energy bills, compared with electric storage heaters.
- Load shifting on GSHPs is a socio-technical challenge. Technical capabilities were demonstrated successfully and improved over time.
- The energy price crisis of 2022-23 has not affected satisfaction with GSHP systems.
- In flexibility Trial 1, tenants in Blackbird Leys complained of overheating and lack of control. Thermal comfort was improved in Trial 2.
- GSHPs with heat-batteries were effectively optimised using price signals, and delivered reliable, responsive heating and hot water to tenants in Sonning Common.
- Control and communication systems enabling dynamic use of HPs in response to variable prices are still in the development phase, and not yet fully reliable. Further RD&D investment is needed.

Initial project targets: heat

1

Install 320 ground-source heat pumps

2

Demonstrate smart load control for cost optimisation

3

Integrate GSHPs with Habitat OTE

4

Explore potential of phase change heat batteries

Background

The original ESO proposal document included an ambition to install 320 GSHPs in domestic (300) and commercial (20) buildings across Oxford.

Kensa Contracting is the sister company of Kensa Heat Pumps, which manufacturers GSHPs in Cornwall. Kensa Contracting (hereafter 'Kensa') works with social housing providers around the UK to install shared ground-loop systems for multiple properties in close proximity (Figure 3.1). The cost of drilling deep bore holes makes GSHPs currently uncompetitive for single households. However, where landlords own multiple properties, they can benefit from economies of scale.

Figure 3.1: A shared ground loop array for a shocial housing block

This proposition is well established, and Kensa have worked with several social housing providers across the UK to install GSHPs in new-builds, and retrofit existing properties. The innovation being demonstrated by ESO is to install smart controls alongside the GSHPs and connect these to real-time fluctuating electricity prices, so that heating and hot water systems can be run at times when electricity is cheap. In doing so, it was hoped that the smart use of GSHPs could become competitive with the running costs of gas central heating.

The original intention was for Habitat Energy to tailor its software to optimise heat pump schedules. However, in the relatively early stages of the project, it became clear that the use of real-time trading for heat pumps would require residents to take on excessive market risk. While Habitat has focused its efforts on trading larger assets, Kensa chose instead to work with Homely, a software developer specialising in heat controls. They would develop a protocol for using price signals from time-of-use (TOU) electricity tariffs to optimise heat pump usage. This approach still requires residents to take on a degree of risk, but far less than the original proposal.

At the start of the project there was only one energy supplier offering a TOU tariff, with settlement periods of 30 minutes: Octopus Energy's Agile. Kensa made initial plans to couple their smart controls with Agile, to allow users to benefit from flexible pricing.

Unfortunately, dramatic increases in wholesale electricity prices meant that from summer 2021, Agile was no longer an attractive proposition for social housing tenants (see below for further discussion).

By the end of the project, 57 GSHP with smart controls were installed in Oxford. The next section provides a detailed evaluation of these installations, and explains the reasons for the shortfall against original project targets. Towards the end of the project, some of the underspend was used by Kensa to develop and trial GSHPs coupled with heat batteries using a phase-change material (PCM). The following section evaluates the installation of prototype units in six dwellings. The chapter then provides an overview of challenges faced and lessons learned, and concludes with a discussion of implications for policy and research.

Environmental benefits

Domestic heating accounts for around 14% of UK carbon emissions. Heat pumps are a critical technology for meeting net-zero, as they are typically 3-4 x more efficient than gas, or electric resistive heating. The Climate Change Committee estimates that by 2050, the majority of homes in the UK will need to use heat pumps if climate targets are to be met (CCC, 2020).

This will require an increased electricity supply, which will come largely from renewable sources and nuclear. To keep this system expansion affordable, and to enable increasing use of intermittent renewables, heat pumps need to be operated flexibly. Flexible operation means heat pumps use more of their energy when the renewable electricity supply is plentiful (and cheaper), reducing reliance on fossil fuels in the electricity mix.

Government funding for Renewable Heat

During the course of the ESO project, policy support for renewable heating has been substantially reformed.

Prior to the start of the project, social housing landlords seeking to install Kensa GSHP systems were eligible to apply for funding from both the Energy Company Obligation version 2t (ECO), and the Non-Domestic Renewable Heat (ND-RHI) incentive. However, from Autumn 2018, ECO3 removed the eligibility of heat pump installations in properties with an Energy Performance Certificate rating of C or above. As most social housing providers have adopted a 'fabric first' approach to energy retrofit in recent years, this effectively closed the door on ECO funding for GSHP systems. Additionally, the ND-RHI was reduced in 2020, and then closed in March 2021. The onus for funding GSHP systems increasingly fell to Kensa's customers during the ESO project timeline (Figure 3.2).

The Social Housing Decarbonisation Fund was launched in 2021 and went some way towards filling the funding gaps left by ECO and ND-RHI. However, funding is issued on a competitive basis, and there is no guarantee of success.

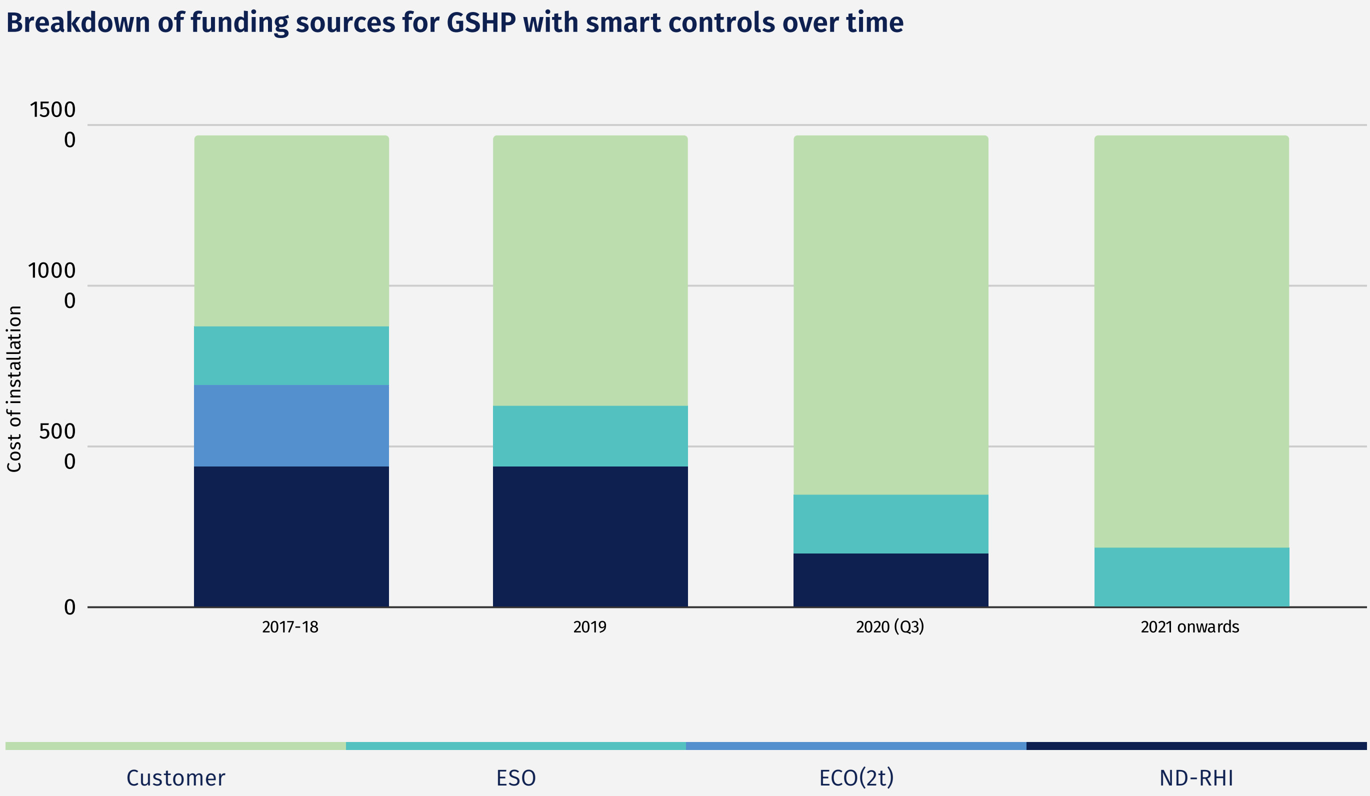


Figure 3.2: Funding sources for renewable heat

Research findings: Blackbird Leys

In early 2020, Stonewater Housing commissioned Kensa to install GSHPs equipped with smart controls in 60 of their properties in Blackbird Leys, Oxford. A social housing provider with 32,000 homes across the UK, they had already completed a handful of successful projects with Kensa before committing to be part of ESO.

Drilling commenced in August 2020, and the first fully operational systems were commissioned in October 2020. By March 2021, 57 homes had received GSHP heating and hot water systems. Three homes were deemed unsafe or inappropriate for installations. In 20 properties, Stonewater also upgraded cavity wall insulation. 55 of the installations replaced electric storage heaters, and in two properties, gas boilers. A Tenant Liaison Officer (TLO) was appointed by Kensa to consult with residents about the works, and in this case, the TLO also acted as Site Manager.

The total cost per property was £13,100. ESO provided funding for around £1,700 each (~13%), covering design, internal plumbing works and smart thermostats.
The project qualified for the Non-Domestic Renewable Heat Incentive (ND-RHI), which is paid over 20-years.

Oxford's challenging geology

When drilling bore holes for ground source heat pumps, depths of up to 300 metres can be achieved in some parts of the UK.

Unfortunately, an artesian aquifer sits underneath the city of Oxford at a depth of around 90-100m, limiting the extent of drilling. The depth of bore hole is crucial for extracting heat from the subsurface, as the thermal response depends on the surface area between the refrigerant and the surrounding earth.

In Blackbird Leys, additional bore holes were required to provide adequate heat supply for the Stonewater properties, leading to increased cost and a small time delay.

Stonewater tenant research participant characteristics

Residents from 32 of the 60 original homes agreed to take part in our research study. Of these, 20 (63%) are male, and 12 (38%) are retired. 14 (44%) are employed either part- or full-time. 28 (88%) of these respondents live alone, and the average age of the cohort is 58. 83% of those responding to our question on annual income (n=30) reported earnings of less than £15,000/yr.

22 (69%) respondents pay for their electricity on a pay-as-you-go basis, using a pre-payment meter. Of the 25 tenants who answered the question 'how long have you been with your current supplier', 60% said at least 5 years, with most of these never having switched provider at their current property. Only four tenants had supplier relationships lasting less than 2 years, and in two such cases, this was because they had recently moved in.

Unfortunately tenants from neither of the two properties previously heated with gas were recruited to the research study. One property was vacant at the time of recruitment, and another family was due to move house shortly after installation.

69%

of all surveyed tenants use pre-payment metres

Installation

During the drilling stage of installation, Kensa faced some resistance from tenants, and when our researchers conducted door-step surveys, several (roughly 30%) tenants said they did not want the new system, and would refuse entrance to the contractors.

Reasons given included concerns over COVID-19, the disruption of installation, and general frustration with Stonewater as a landlord. However, it is testament to the effectiveness of Kensa's approach to tenant liaison that all of those householders eventually received new heating and hot water systems.

COVID-19 restrictions were lifted in summer 2021, and interviews lasting 45-60 minutes were conducted with 22 of the 32 residents who initially signed up to take part in our research study and completed surveys before HP installation. Our team managed to secure funding for participant incentives from a parallel research project, as these payments are ineligible for Innovate UK funding. Interviewees are given a £20 supermarket voucher for their time. This incentive proved essential for motivating participation. We recommend IUK reviews its policy on such expenditure, which is standard practice for qualitative research.

Despite several tenants raising concerns in advance of installation, all tenants interviewed gave positive feedback on the process once completed. This is a remarkable finding, considering the noise produced by drilling outside their homes, and the disruption caused by internal plumbing works. Several interviewees commented on the politeness and diligence of the installers, and three tenants remembered the names of the workmen, even 9-12 months later.

Despite this positive feedback, Kensa have noted that combining the role of Tenant Liaison and Site Manager was not ideal in this case. They said the roles require ‘different skill sets’ and represent too much work for one person. They also reflected that future similar projects would benefit from more visits from Kensa permanent staff.

> *“I can only recommend them 100%...They were absolutely fantastic. They were polite, courteous, hard-working and safety conscious. And they let me make them coffee, which made me feel good, because it made me feel like I was doing something.”*
>
> Stonewater Tenant

Heating system feedback

The original case for support for ESO’s heat work stream was that domestic users would: ‘benefit from increased comfort and reduced heating related electricity bills, thereby helping reduce fuel poverty, potential for shared revenues from participation.’

Tenant feedback indicates high levels of satisfaction with their heat pumps (Figure 3.4). We asked these tenants to respond to the statement: ‘I am satisfied with my current heating system’, before (when they had direct electric storage heaters installed), and after the heat pump installation. 59% said that they strongly disagreed with the statement in our pre-installation surveys, 63% strongly agreed once they had started using the heat pump.

“I am satisfied with my current heating system”

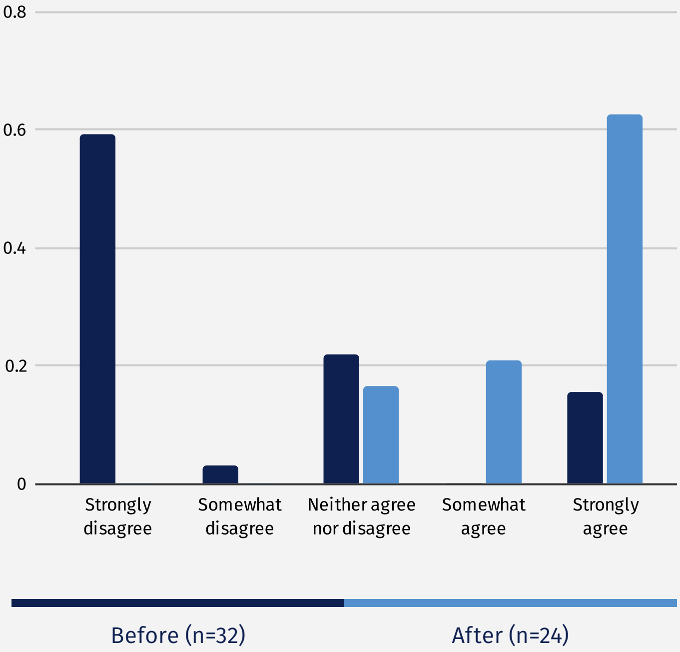


Figure 3.4: Tenant satisfaction with heating system

There is also evidence that the aim of increasing comfort for tenants has been realised. Colleagues at Oxford Brookes University installed temperature and humidity sensors in nine dwellings prior to heat pump installations. Sensor readings taken from 1st-8th October 2020 (before installation), and 26th-15th December (after installation) across five bungalows found an increase in mean indoor temperature from 20.4°C to 23.4°C, while average readings from four flats saw a slight decrease from 22.6°C to 22.1°C. This may be partly due to the replacement of cavity wall insulation in the bungalows: a hypothesis strengthened by the observation that the mid-terrace properties saw slightly higher mean temperatures. This finding indicates that tenants may have previously been under-heating their homes.

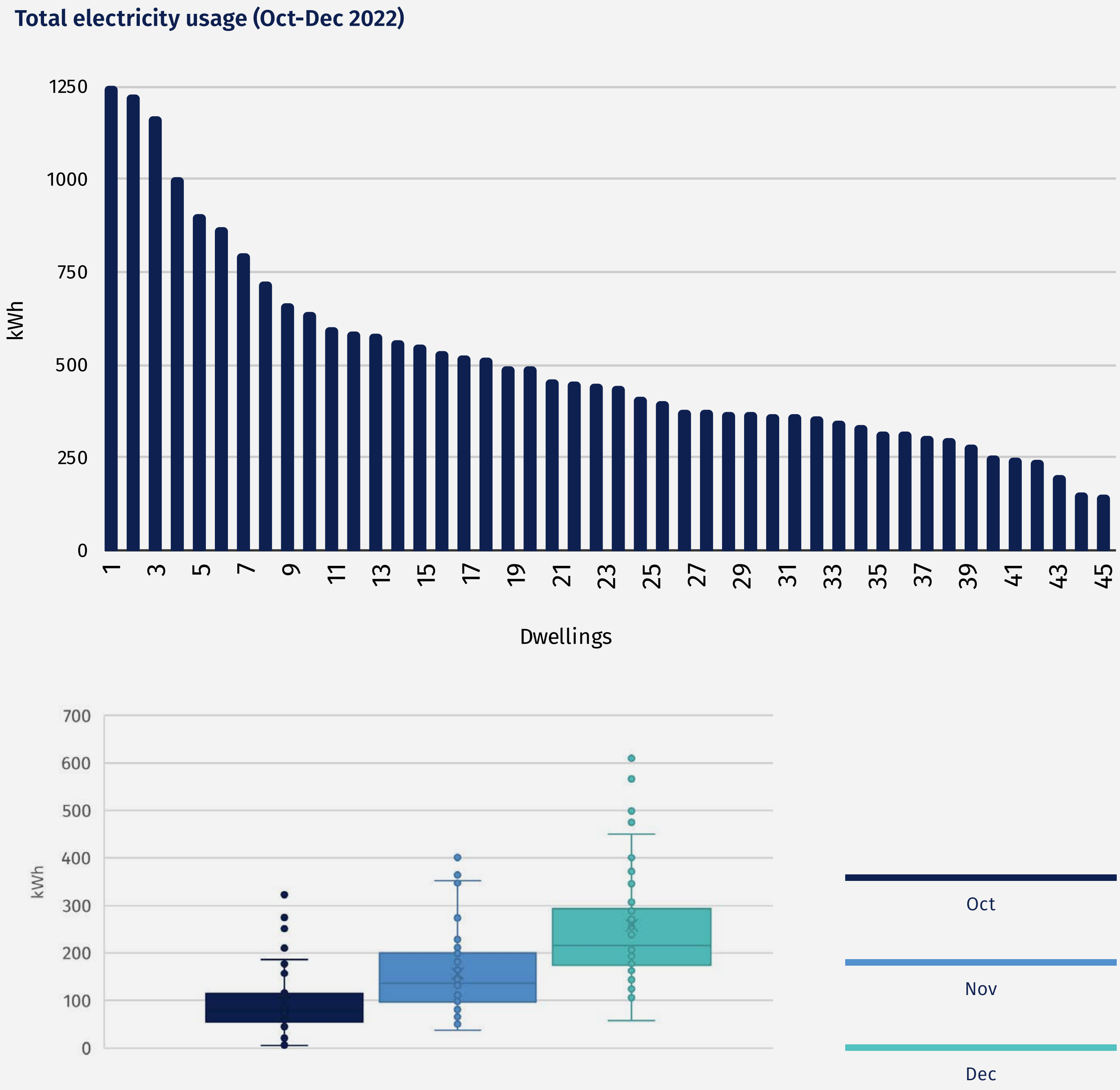


Figure 3.5: Variability of electricity usage between households

Running costs

Obtaining data on electricity usage and cost proved challenging throughout the project. Most tenants pay for their electricity using pre-payment meters, topping up either from the local Post Office or online, and only a minority receive bills detailing usage.

In an effort to gather quantitative data, we sought to install 'clamp meters' to monitor electricity usage for individual properties prior to heat pump installation. Unfortunately, most meters were found to be incompatible with clamp meters, and only two were installed. In these two properties electricity consumption was found to be lower following GSHP installation, when normalised for outdoor air temperature using heating degree days (HDD)1. In one dwelling, usage reduced from 2.2 kWh/HDD to 1.34 kWh/HDD (-39%), and in the other, from 1.70 kWh/HDD to 0.86 kWh/HDD (-49%) (note these figures are for all household electricity use, not just that used for space and water heating).

This is corroborated by survey and interview findings. For instance, before installation, 72% tenants strongly agreed with the statement 'my heating system is expensive to run'. When referring to their heat pumps however, only one tenant (4%) gave the same answer (Figure 3.6).

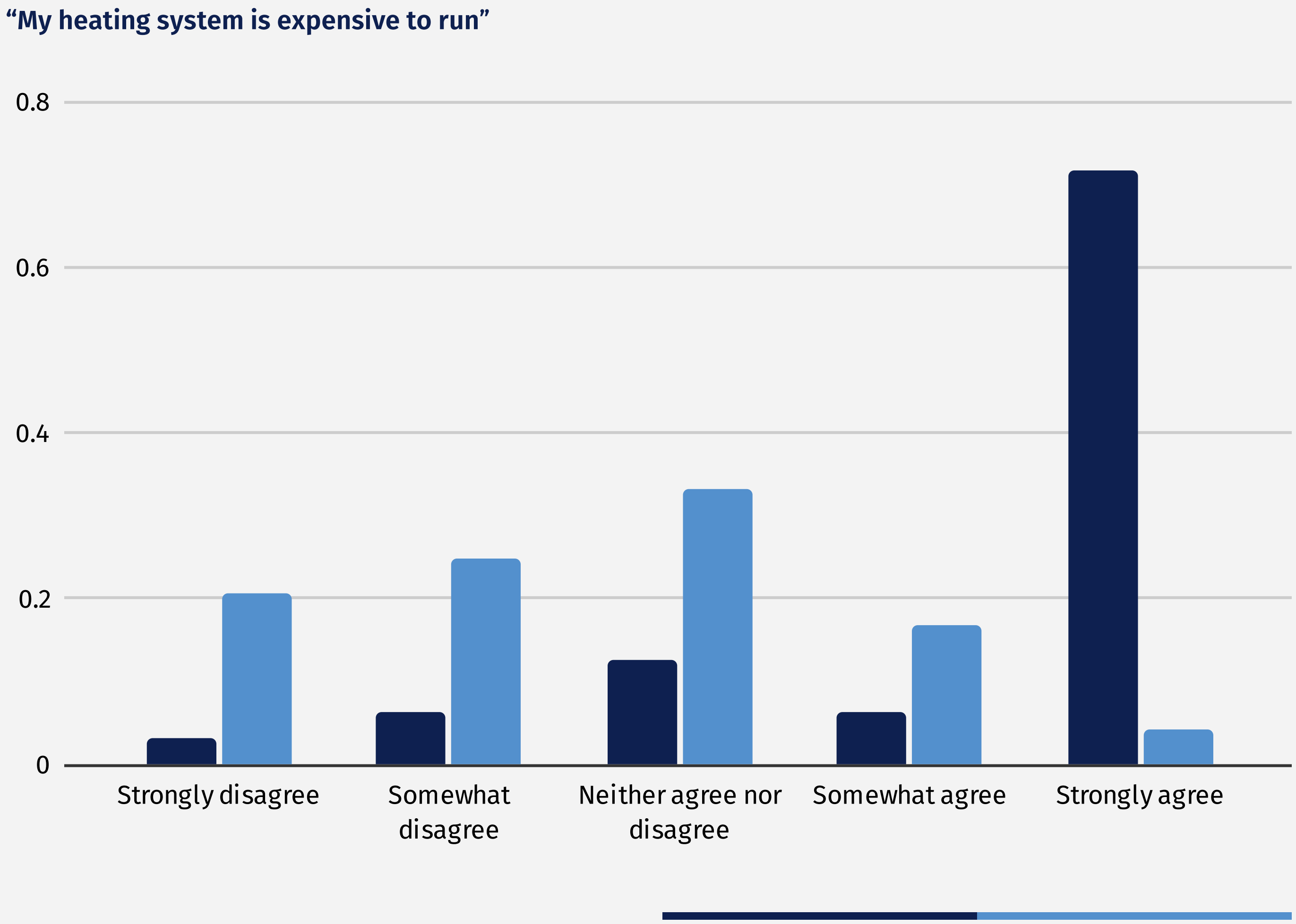


Figure 3.6: Tenant perceptions of cost

Surveys conducted before GSHP installations revealed the average spend on electricity by tenants was £73/month (n=27). In interviews, several tenants explained that they had simply not used their storage heaters due to the high running costs. Relatedly, 38% of tenants strongly agreed with the statement ‘I often sacrifice my comfort to save money’ (Figure 3.7). After GSHP installation, this fell to 8%.

“I often sacrifice my comfort to save money”

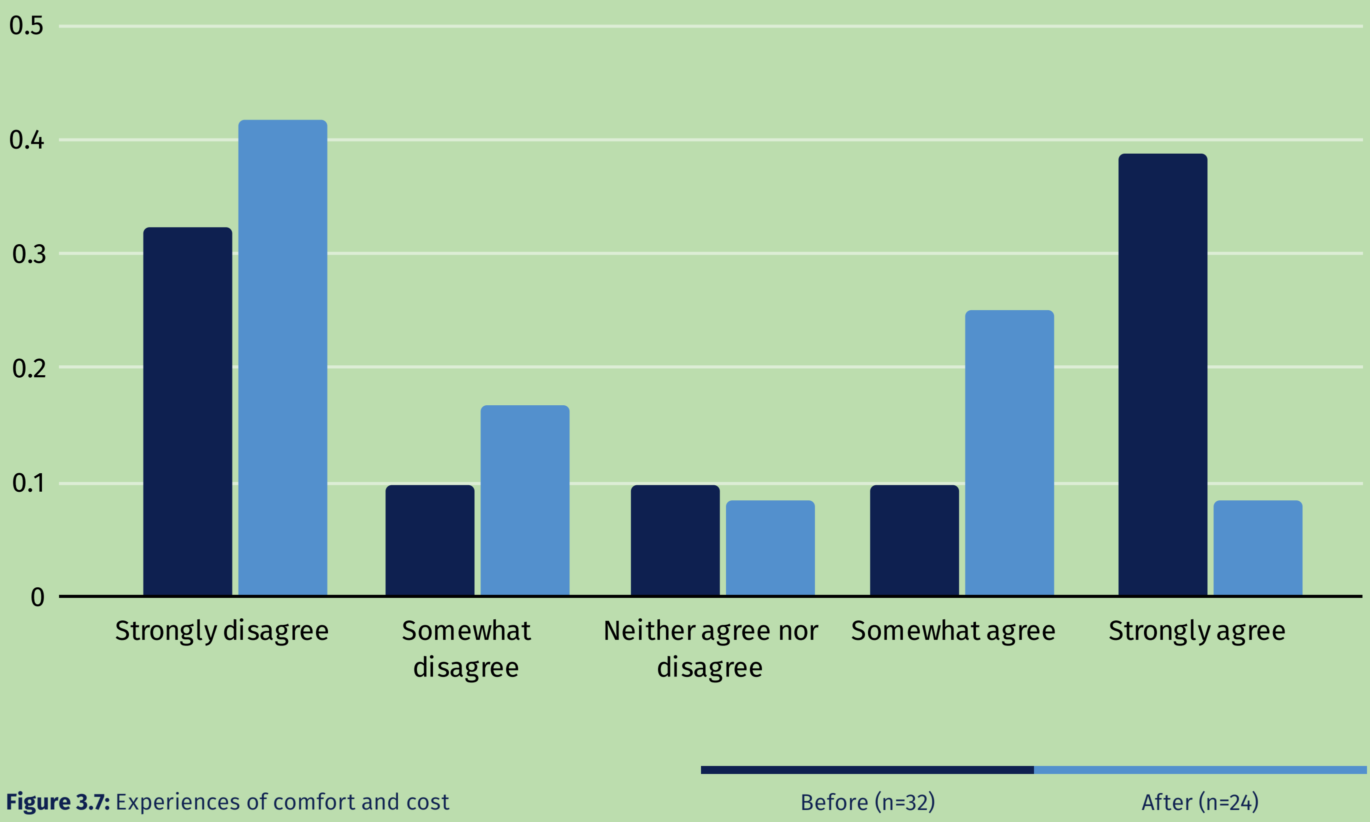


Figure 3.7: Experiences of comfort and cost

Prior to receiving GSHPs, a majority of tenants relied on plug-in heaters (57%) and heavy clothes and blankets (73%) to keep warm. After installation, these figures reduced to 8% and 25% respectively. These findings show that the GSHPs have been effective at improving comfort levels for Stonewater tenants.

Despite evidence that mean internal temperature had increased in several properties following GSHP installation, in interviews, most tenants reported having seen savings on their electricity expenditure, and several reported savings of around 50%.

> *“Where I was putting on five pounds a day, now I'm putting on 10 pound for a week."*

> *“I estimate that it's costing me probably between a third and a half as much in electricity.”*

Over the course of the project, these savings were eroded by gradually increasing electricity prices. These particularly impacted those on pre-payment meters who typically pay slightly higher rates per unit, and who do not benefit from fixed term contracts which acted to protect many UK customers from the rising wholesale price of electricity from late 2021.

In winter 22/23, the running costs of the GSHP system for many tenants had reached the levels they were paying when using storage heaters. However, the benefits of increased comfort and the ability to control internal temperature meant that overall satisfaction levels remained high (Figure 3.8).

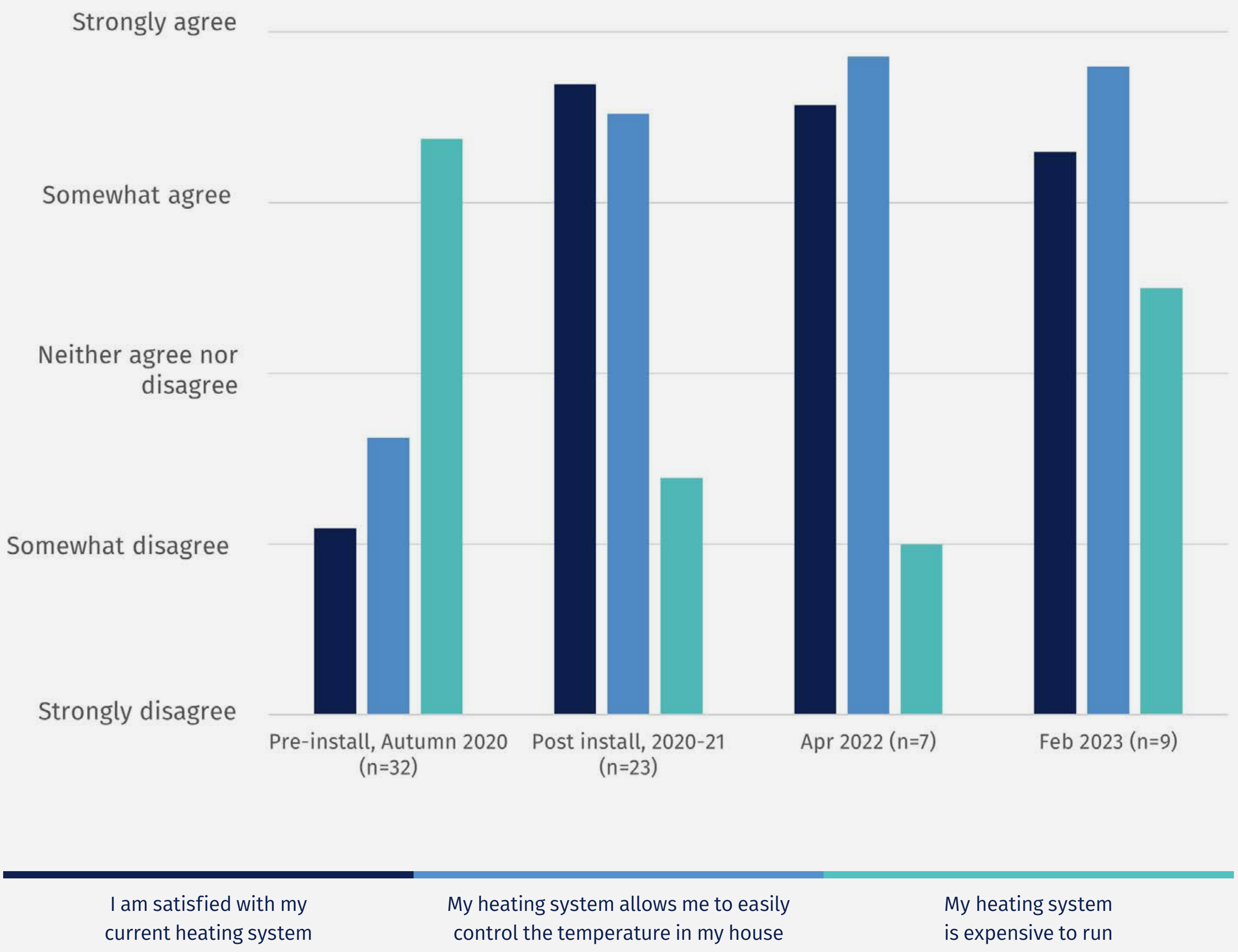


Figure 3.8: Tenant perceptions over time

Introducing flexibility

A key objective for the ESO heat work package was to demonstrate the cost saving potential of demand flexibility. The original intention was for tenants to switch to a time-of-use tariff, so that the GSHPs, equipped with smart controls, could be run using a smart schedule which was optimised for minimal running costs. Only one time-of-use tariff was available during the trial, Octopus Agile.

Unfortunately, the project encountered a number of barriers to implementation (Table 3.1).

Table 3.1: Barriers to real time-of-use pricing

BARRIER TYPE	DETAIL
Heating system	It took longer than anticipated to develop the technical capabilities of the smart heat pumps. This included linking GSHPs with thermostats manufactured by Switchee, as well as the development of optimisation software, by Homely. Several Switchee units were found to be faulty and needed replacing.
Metering	Most tenants use pre-payment meters (69%), which are not compatible with the Octopus Agile tariff. Many did not have smart meters installed, even at the end of the project. In some cases, this was due to tenant preference. However, several tenants requested smart meters from suppliers so that they could eventually sign up to Octopus Agile, and were given lead times of nine months or more.
Electricity market	The proposition of switching to Octopus Agile looked highly attractive throughout much of 2020. Average unit prices were consistently lower than those available on fixed rate or standard variable tariffs, and if coupled with flexible usage of electricity, substantial savings could be made by tenants. Unfortunately, Agile prices in 2021 rose drastically, because of rising wholesale costs (Figure 3.9). All energy suppliers were affected, and price increases were gradually being passed on to consumers across all tariffs. However, as Agile rates are pegged to wholesale rates in real-time, its customers faced increases more quickly than others who were on fixed-contracts, or protected by the Ofgem regulated price cap.
Users	Kensa and our research team encountered significant resistance to change with regards electricity supply. Most tenants do not switch electricity supplier on a regular basis (60%). Many tenants are content with their existing pay-as-you-go method, despite the higher costs per kWh associated with prepayment tariffs. The advantages are that tenants feel in full control of their expenditure: they will not be surprised by a large bill arriving at the end of the month as might happen with standard metering.

Kensa stopped promoting the Agile tariff to Stonewater tenants in autumn 2021, following other consumer interest groups in advising customers not to switch for the first time since the retail market was liberalised in the UK in the 1990s (see Figure 3.9).

Octopus agile prices

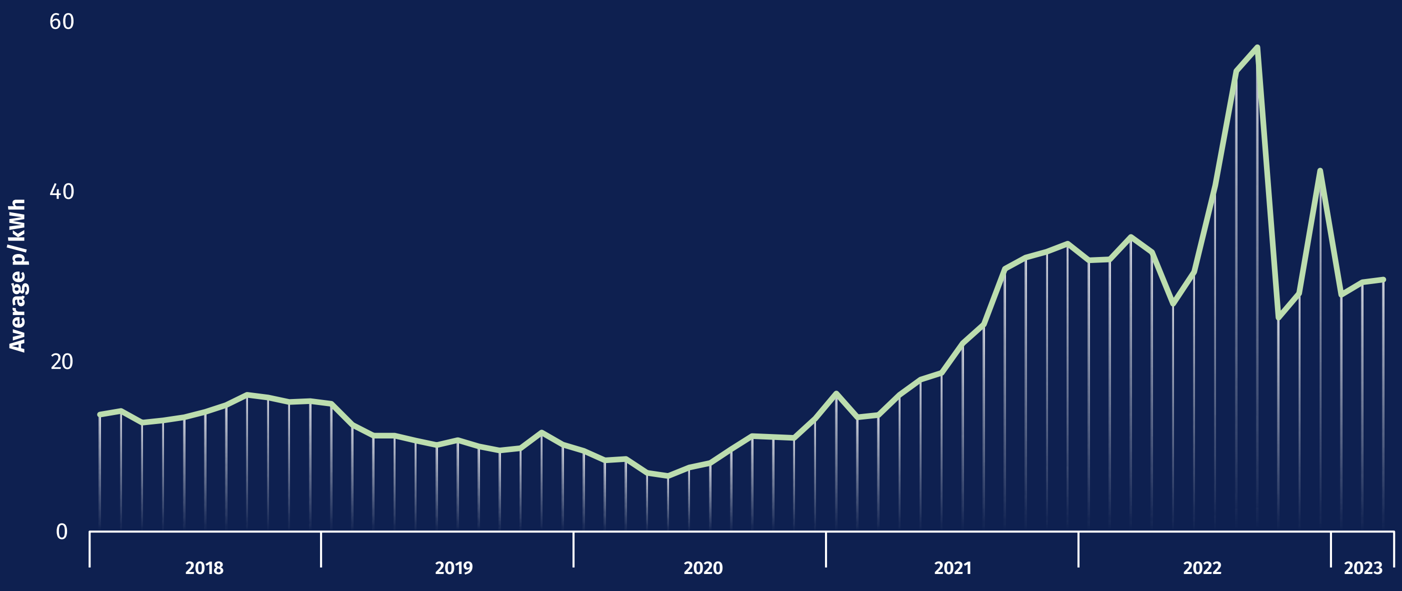


Figure 3.9: Octopus Agile electricity price per kWh, 2018-2023. Source: energy-stats.uk

Flexibility trials

Prevented from implementing the original trial design, an alternative approach was adopted to test the use of dynamic heating schedules. Two time-limited trials were undertaken in April-May 2022, and January-February 2023 (Table 3.2).

Trial design

Of the original 22 tenants taking part in interviews, seven chose to take part in the first trial, and ten in the second. All households were occupied by one adult, and six of those in trial 1 also took part in trial 2. Tenants remained on their existing electricity tariffs, and were reimbursed with supermarket vouchers.

Table 3.2: Summary of flexibility trial characteristics

	TRIAL 1	TRIAL 2
Dates	22nd Apr to 5th May, 2022	26th Jan to 27th Feb, 2023
Duration	14 days	32 days
Number of dwellings included	7 (6 men, 1 woman)	10 (6 men, 4 women)
Financial incentive offered	£50 voucher	£100 voucher
Tariff used to train algorithm	Octopus Agile Export	Octopus Agile Export

During the trials, GSHPs were remotely controlled using an algorithm which was trained using electricity prices from Octopus Energy's Agile tariff, where unit prices change every half hour, and are highest from 4-7pm. The algorithm retrieves dynamic price signals from the Agile Export tariff, which is only available to customers who generate electricity e.g. with rooftop solar. The export tariff was chosen because during the period of the trial, the import tariff was set at the Ofgem-capped rate for large periods of the day (35 p/kWh), with minimal fluctuations. The export tariff is not subject to a cap, so allows the algorithm to use real-time dynamic price signals.

Before the first trial, tenants were asked to specify their temperature preferences for morning, daytime, evening and overnight. These were incorporated into the algorithm as minimum temperatures. To ensure that these minimums were exceeded while optimising heat pump operation for price, the algorithm pre-heated dwellings prior to peak pricing periods. Heating would then be turned off from 4-7pm, with temperatures falling gradually during this time. This meant that set-point temperatures between 2pm and 4pm might typically be 1-3CO higher than at 7pm. For the second trial, tenants' recent set-point temperatures were used as inputs to the model rather than stated preferences (see explanation in the results section).

Tenants could use their wall-mounted thermostats to override the algorithm and change the set point temperature. However, new target temperatures were downloaded by the thermostats every 30 minutes, overriding the tenants' settings.

(Not so) smart meters

Time of use tariffs require smart meters in order to implement flexible pricing. The smart meter roll-out has been slower than expected across the country, and in some cases, Stonewater residents requested smart meters but were let down by suppliers after waiting for over nine months.

Most Stonewater properties in the ESO trial have now got smart meters, but a large proportion are smart prepayment meters. Unfortunately, the Octopus Agile tariff cannot be implemented through a smart prepayment meter. If tenants were willing to switch to Octopus' Agile tariff, these newly installed meters would need to be replaced.

Research Data

Data are available on energy usage and set-point temperature for each property from the date of installation until the end of February 2023, at 10-minute intervals. However, intermittent connections between the thermostat and heat pump controls means that there are gaps in data for some properties for extended periods.

Interviews and surveys were conducted with tenants before and during both trials, and tenants also completed comfort diaries. Survey questions included overall satisfaction with the heating system, control, and running costs. External temperature records were downloaded from darksky.net.

Results

On the first day of both trials, one participant chose to withdraw, each citing dissatisfaction with pre-heating and inability to control the temperature sufficiently (Table 3. 3). Although the trial team took care to explain the scope and purpose of the trial, dynamic heating is complex and unfamiliar in the domestic setting. User withdrawal has been reported by several similar trials (Calver et al., 2022; Higginson et al., 2018), and may be unavoidable.

In trial 1, a communications failure meant that the heating system could not be remotely controlled in one dwelling. In trial 2, insufficient set-point temperature data could be retrieved from two dwellings, meaning that the model could not be adequately trained.

Table 3.3: Dwelling numbers involved at different stages of the flexibility trials

	TRIAL 1	TRIAL 2
Dwellings recruited to take part	7	10
Tenants withdrawing from trial	1	1
Dwellings excluded from trial due to data and communications failures	1	2
Number of dwellings completing trial, with high resolution energy and temperature data available	5	7

Tenant experiences

From the tenants' perspective, Trial 2 was much more successful than Trial 1 (Figure 3.11).

In Trial 1, the main complaints related to the indoor temperature being too high during (but not limited to) the early-afternoon pre-heating period (Figure 3.12). One explanation for this is that when asked to specify their preferred set-point temperatures to be used during the trial, some tenants overestimated the temperature at which they were thermally comfortable. In response, for Trial 2 Kensa chose to use recent set-point data for each dwelling. Tenants expressed greater overall satisfaction with Trial 2, including comfort. That said, data collected from comfort diaries indicates that during the middle of the day, internal temperatures dropped below comfortable levels. This may be partly explained by the comparatively high cost of electricity during the second trial: pre-trial diary entries also scored lower on average before Trial 2 than Trial 1, indicating that in winter 22-23, tenants were tolerating colder internal temperatures to save money.

"I am satisfied with my current heating system"

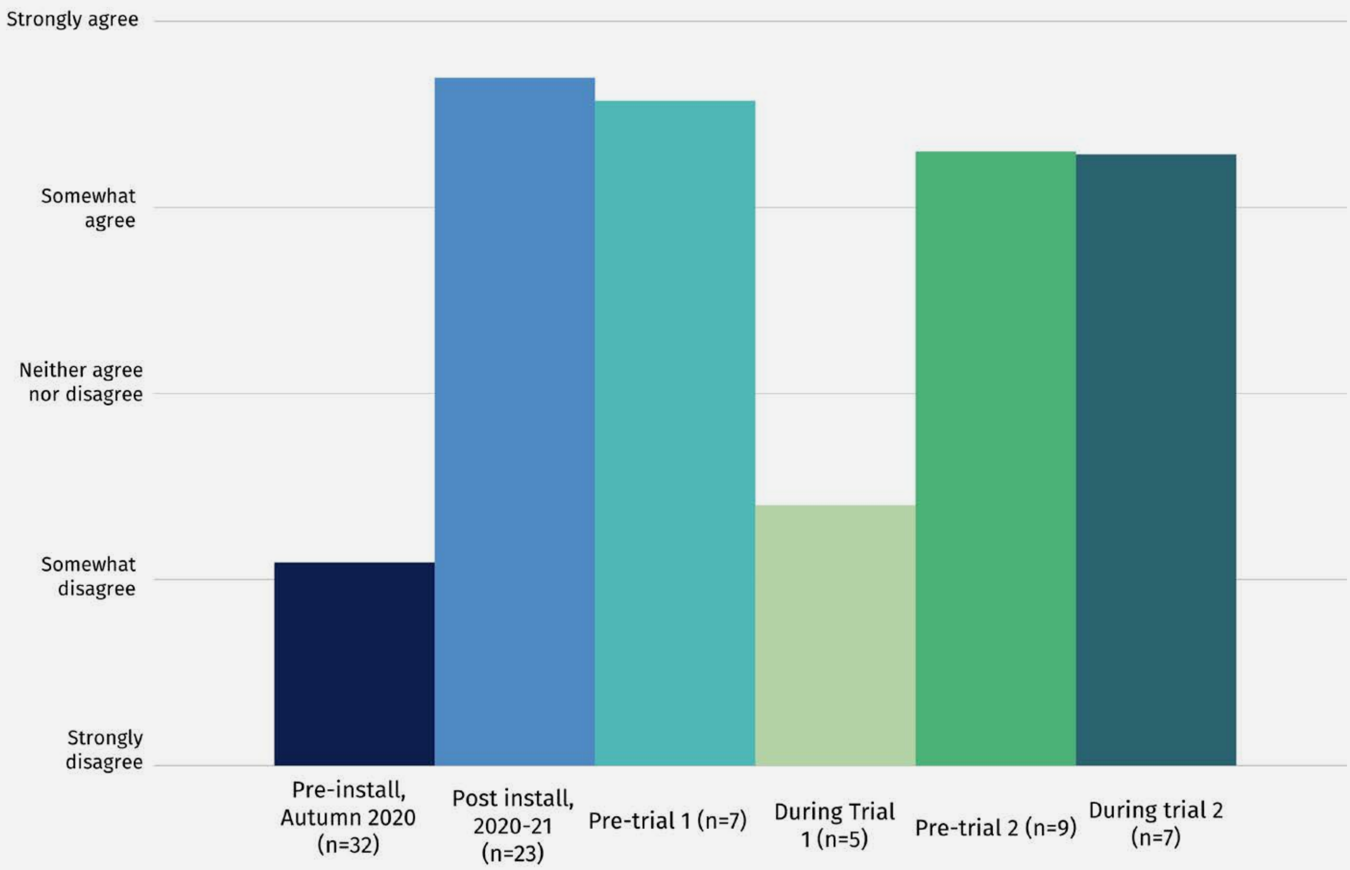


Figure 3.11: Tenant satisfaction over time

Comfort diaries

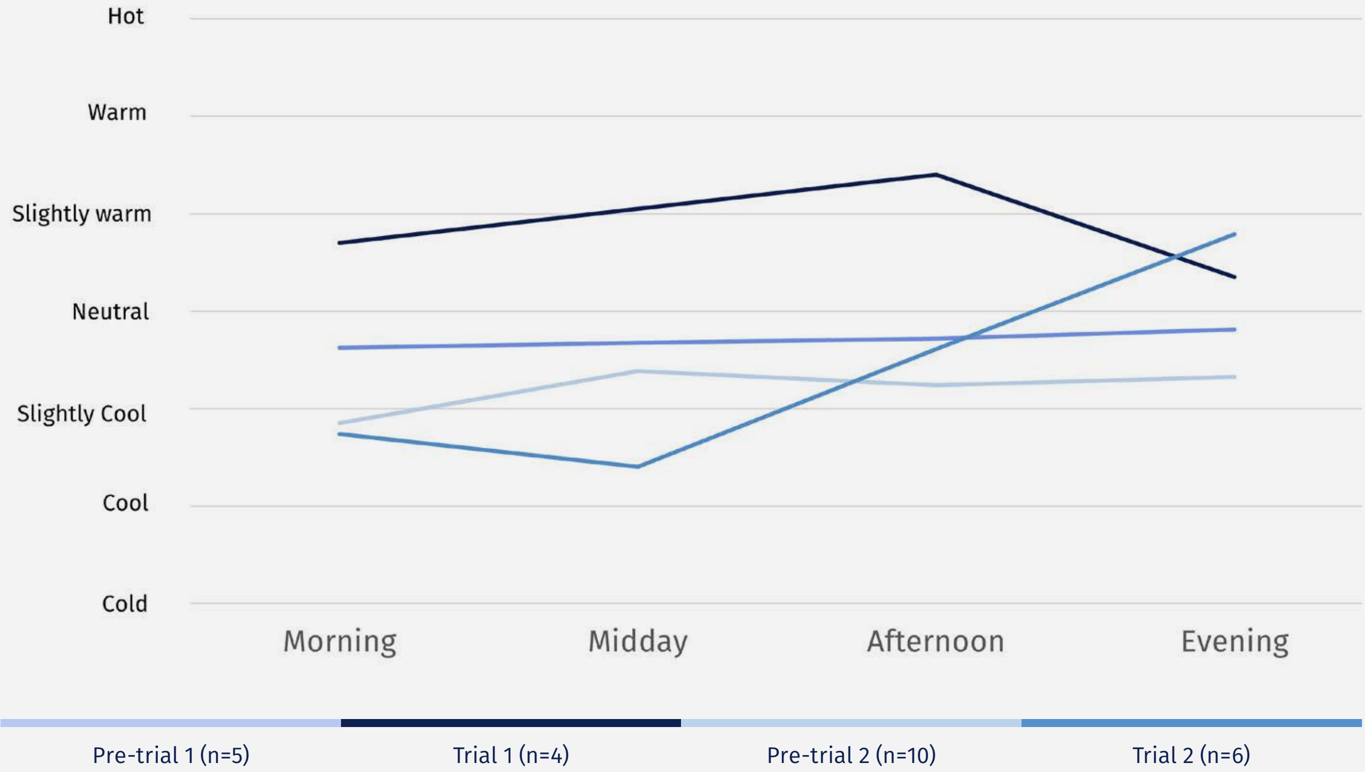


Figure 3.12: Average tenant thermal comfort before and during Trial 1 and Trial 2, by time of day

Another complaint in Trial 1 was related to control. All five tenants said that they had used the manual override function, but found it frustrating that their settings would only last for up to 30 minutes.

Several were also confused about how (or whether) this worked, and messages displayed on the thermostat did not help. For instance, a frequent message read: ‘Hot water schedule suspended until Monday’. This message did not, as it might appear, mean that tenants would have no hot water until the following week, but was simply an automatic response from the thermostat to being remotely controlled. A common response to perceived lack of control was to open and shut windows to moderate temperature, and several tenants expressed concern about wasted energy (and associated cost) as a result.

Finally, the load-control algorithm prioritised the use of the heat pump for heating, rather than hot water (HW). In Trial 1, two tenants reported lower water temperatures than usual. In one case, the heat pump was in heating mode for large periods of the day, not switching to water-heating mode for a sufficient period to provide HW. This was a result of the set-point temperatures exceeding the tenant’s actual comfort preference: frustrated with being too hot, they were opening windows to reduce indoor temperatures. The heat pump continued to run, trying to meet the target set-point. Midway through the trial, set-points were lowered in this property and the heat pump was able to switch to HW mode. Another householder preferred to set his HW timer manually, every other day, to conserve energy. He expressed concerned that during the trial, the water was heated more than necessary.

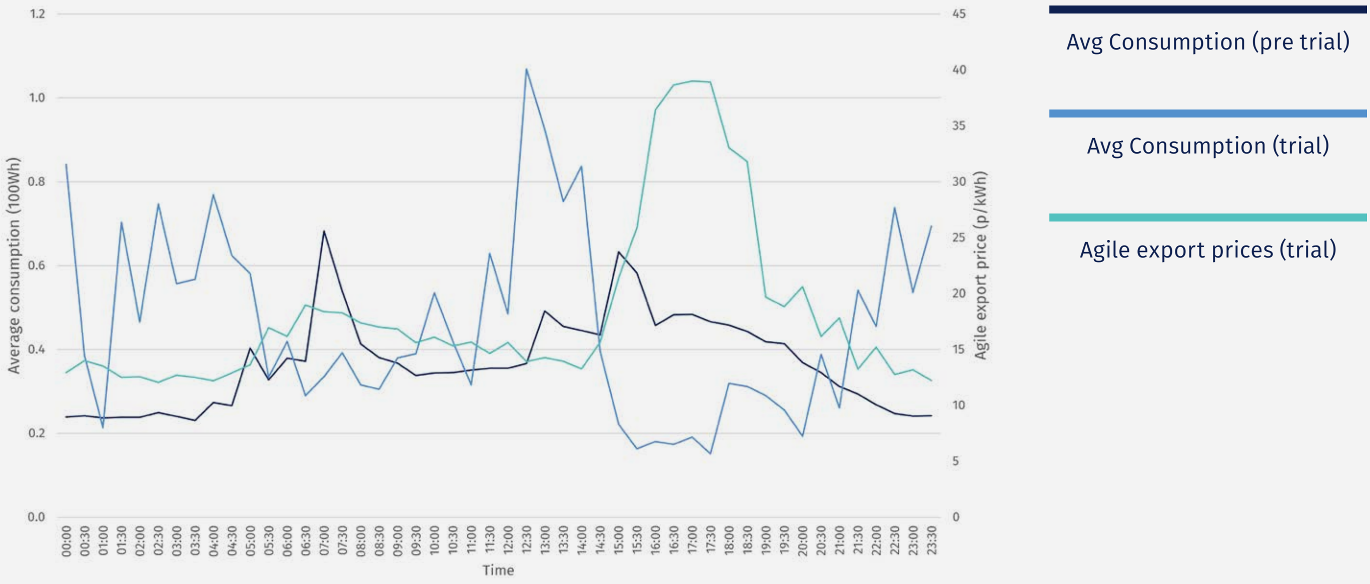
Energy usage

Figure 3.13 plots diurnal electricity consumption before and during both trials.

Data are derived from a pulse meter internal to the heat pump, so exclude other household electricity consumption. Agile Export price signals are also plotted on a secondary y-axis.

These are lower in Trial 2, because wholesale prices of electricity in the UK were beginning to fall from historic highs. Pre-trial consumption data is taken from November 1st (2021 and 2022 respectively), until the start of the trials.

Trial 1: Aggregated demand profile



Trial 2: Aggregated demand profile

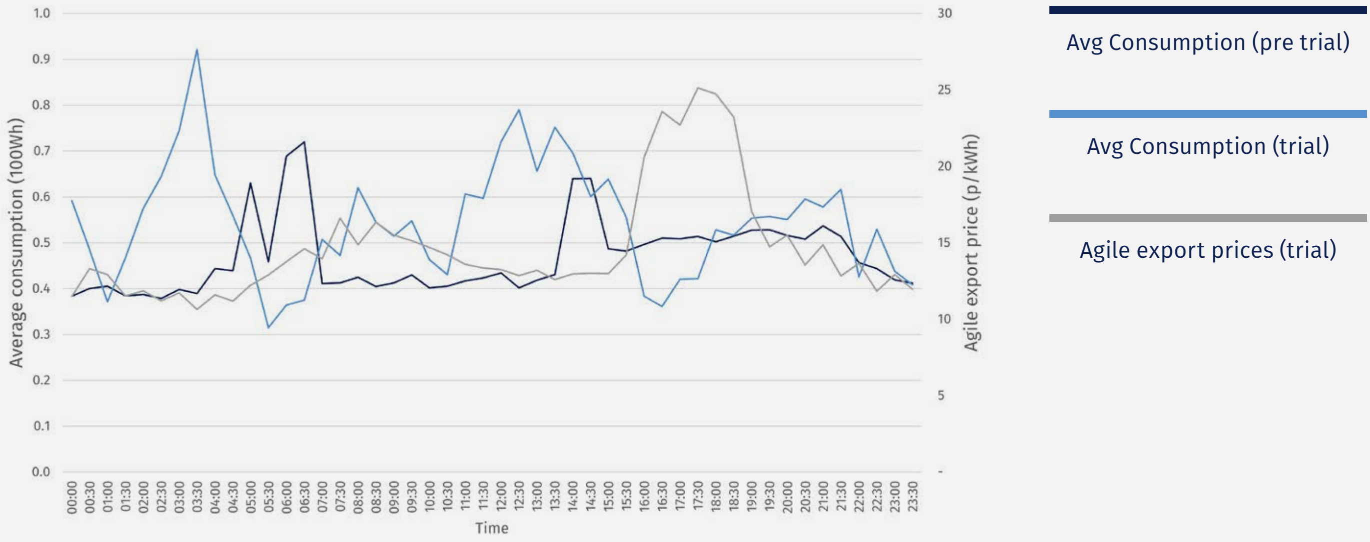


Figure 3.13: Electricity demand profiles averaged for trial participants

These charts demonstrate that Kensa and Homely were successfully able to operate heat pumps remotely, optimising for price signals and tenant set-point preferences. Both charts show evidence of pre-heating before periods of higher prices in the morning and early evening, although the consumption profiles at household level fluctuate over the course of the day. This is a result of using 15 minute time-intervals, over a relatively short period of time (the lines depicting average usage during trials fluctuate more than the pre-trial data, which represent an average over a greater number of days in the heating season). Further, Trial 1 took place at the end of the heating season, and for some periods outdoor temperatures exceeded 15°C. This led to lower-than-expected energy usage by heat pumps during some afternoons. A lesson for future trials is to avoid the 'swing season'.

Figure 3.14 shows the effects of Trial 2 on simulated running costs. Heat pump energy consumption data at 10-minute intervals is multiplied by real-time prices for the Agile Export tariff. Pre-trial figures run from 1/11/2022 to the start of the trial. This assumes that tenants were paying these rates without their heat pumps being optimised. Although this bears little relation to reality, it allows us to evaluate whether the algorithm was successful in reducing overall running costs when optimising for price. As expected for this simulation, most tenants (5/7) would have made savings. The two dwellings with the largest savings (labelled 2 and 3) were occupied by tenants preferring high, constant temperature settings. By contrast, the tenant in number 5 worked irregular hours and travelled often. Their GSHP did not follow a regular schedule, and they manually controlled heating and HW when home. This is an example of a household where the approach to dynamic heating adopted in this trial is unlikely to deliver savings.

Running costs, Trial 2

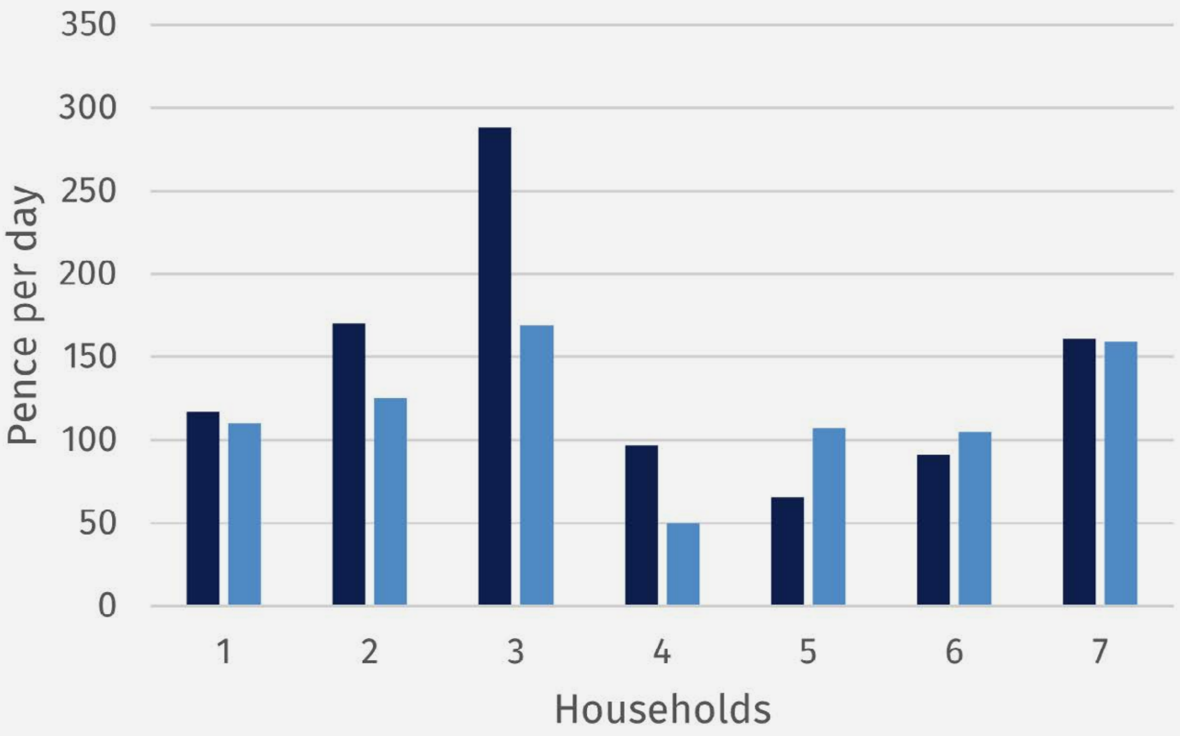


Figure 3.14: Running costs by household during Trial 2

Research Findings: Sonning Common

Six Stonewater properties in Sonning Common, South Oxfordshire, were identified for the installation of prototype heat pumps coupled with a phase-change material (hereafter GSHP-PCM).

The intention of this trial was to test a new technology which would allow for greater electricity demand flexibility, with minimal impact on internal temperature and tenant comfort. GSHP-PCMs also avoid the need for hot water storage tanks, which is considered a barrier to the widespread deployment of heat pumps (Figure 3.15). The majority of English dwellings do not have hot water tanks (59% in 2019 (MHCLG, 2020)), so developing a GSHP-PCM system removes an important barrier to uptake.

Starting in May 2022, five prototypes were successfully installed, while one property received a standard 'shoebox' heat pump with hot water tank, due to the needs of a vulnerable tenant. All six homes had been previously heated by gas boilers, and both tenants and Stonewater expressed concern about the potential for increased bills, especially given the looming energy price crisis. Kensa committed to paying the cost of electricity used by the heat pumps for all tenants during the trial (July 2022 to February 2023). They also funded the purchase and installation of electric hobs for tenants so that the gas supply to the dwelling could be cut off, avoiding standing charges.

Tenants were able to adjust their heating schedules and temperature preferences using a smart-phone app. In one case, an analogue, manually adjustable thermostat was installed for an elderly tenant. Given the early-stage nature of the technology, Kensa provided substantial customer support to the six tenants, and a dedicated project administrator made weekly calls to residents to provide information on the system, troubleshoot issues and collect feedback.

The trial finished in mid-February 2023 and prototype units were replaced with shoebox heat pumps, alongside hot water tanks. The trial ended two weeks earlier than planned due to difficulties finding qualified installers.

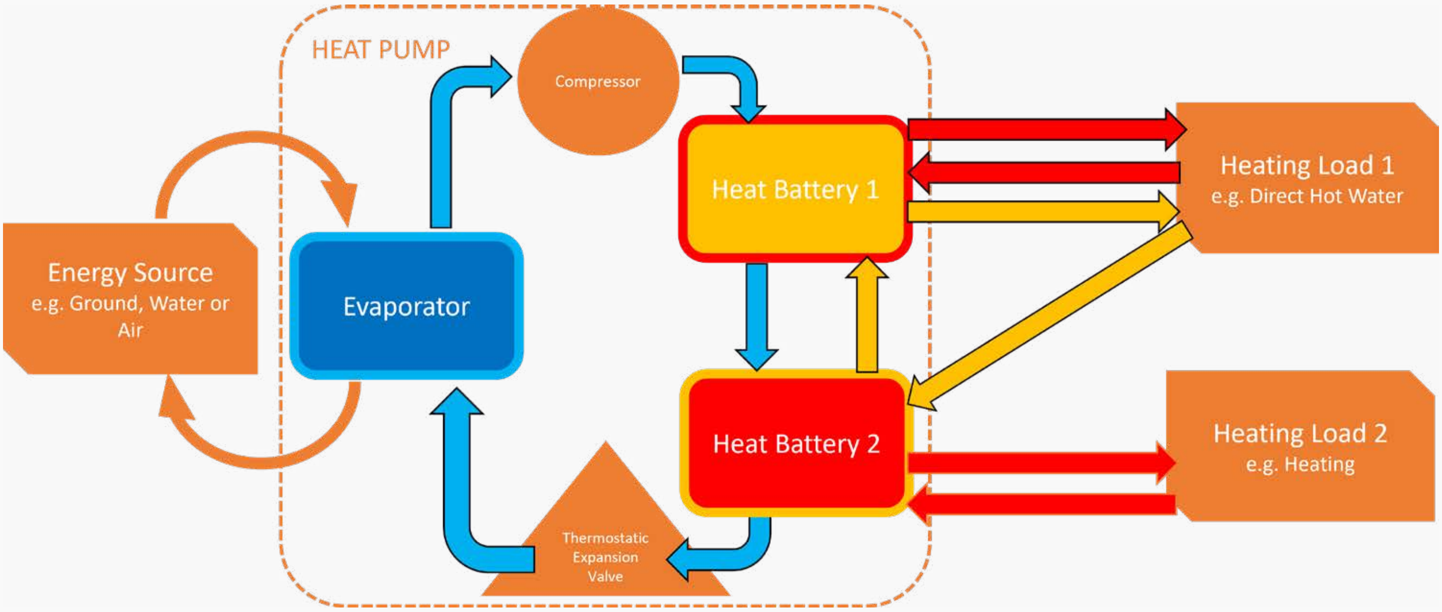


Figure 3.15: Schematic diagram showing the design of the heat pump with phase-change material (PCM) heat battery

Oxford University researchers visited the six dwellings in Sonning Common shortly after bore-hole drilling had started. Three households agreed to provide survey responses and partake in three interviews: before, during, and after the trial. Each dwelling was occupied by one adult (two women, one man), and each were retired with an income of less than £15,000/yr.

Installation

Tenants explained that they had been given little notice of the planned trial and replacement of their gas boilers. Drilling in Smith Close began only four days after notice had been given and several tenants expressed dissatisfaction. Unlike in Blackbird Leys where tenants generally disliked the electric storage heaters which were removed, Sonning Common tenants were satisfied with their existing heating systems. Tenants in one of the six dwellings declined to have the GSHP-PCM prototype installed. Here, a shoebox unit was installed instead.

Tenants reported the overall installation took eight weeks, overrunning by two weeks. All interviewees said that the installers were polite and tidy. However, Kensa also received several complaints relating to the installation. This included workers smoking outside properties and leaving cigarette butts, noise associated with drilling, and damage to driveways.

Kensa responded promptly and effectively to issues raised. One tenant was reimbursed for damage to their car from the uneven driveway surface, while technical faults associated with the prototype were rapidly fixed by engineers. Residents expressed overall satisfaction with Kensa's responsiveness.

During the installation, cupboard doors had to be removed to fit the units. While there were no doors, tenants complained about a low humming noise, particularly at night. This was investigated and seemed to only be an issue while the compressor was running. A software update disabled the compressor from running during a set time period agreed with tenants. However, this resulted in a drop in performance of the units and in some cases, colder internal temperatures in the mornings.

Figure 3.16: The HP-PCM model is substantially larger than Kensa's shoebox model, but does not require a hot water tank

Heating system feedback and usage

The three research participants provided detailed feedback on their experiences of using gas boilers, the prototype GSHP-PCM system, and the shoebox heat pump installed post-trial. The prototype systems in each dwelling suffered several technical breakdowns during the trial, requiring regular visits from engineers. Kensa also provided plug-in electric heaters to tenants.

Two tenants felt confident using the smart-phone app to control their heating schedules. Nonetheless they found it to be a frustrating way to adjust the temperature. Although they appreciated the ability to adjust their heating away from their home, this was considered only a minor benefit. However, one participant, a 94 year-old man, was unable to use the app. In this dwelling, the heating was set to a constant temperature throughout the trial period, and temperature data collected from a sensor in his living room indicated an average of 22.7CO in this property. His daughter raised some concern over the unsuitability of the smart controls for her elderly father, and questioned why somebody in their 90s was considered a suitable participant for a trial of cutting-edge technology.

All tenants explained that they much preferred the wall-mounted thermostats which had been installed alongside the shoebox systems, after the GSHP-PCMs were removed. They valued the accessible design and visual feedback.

Survey responses from before, during and after the trial corroborate interview findings (Figure 3.17).

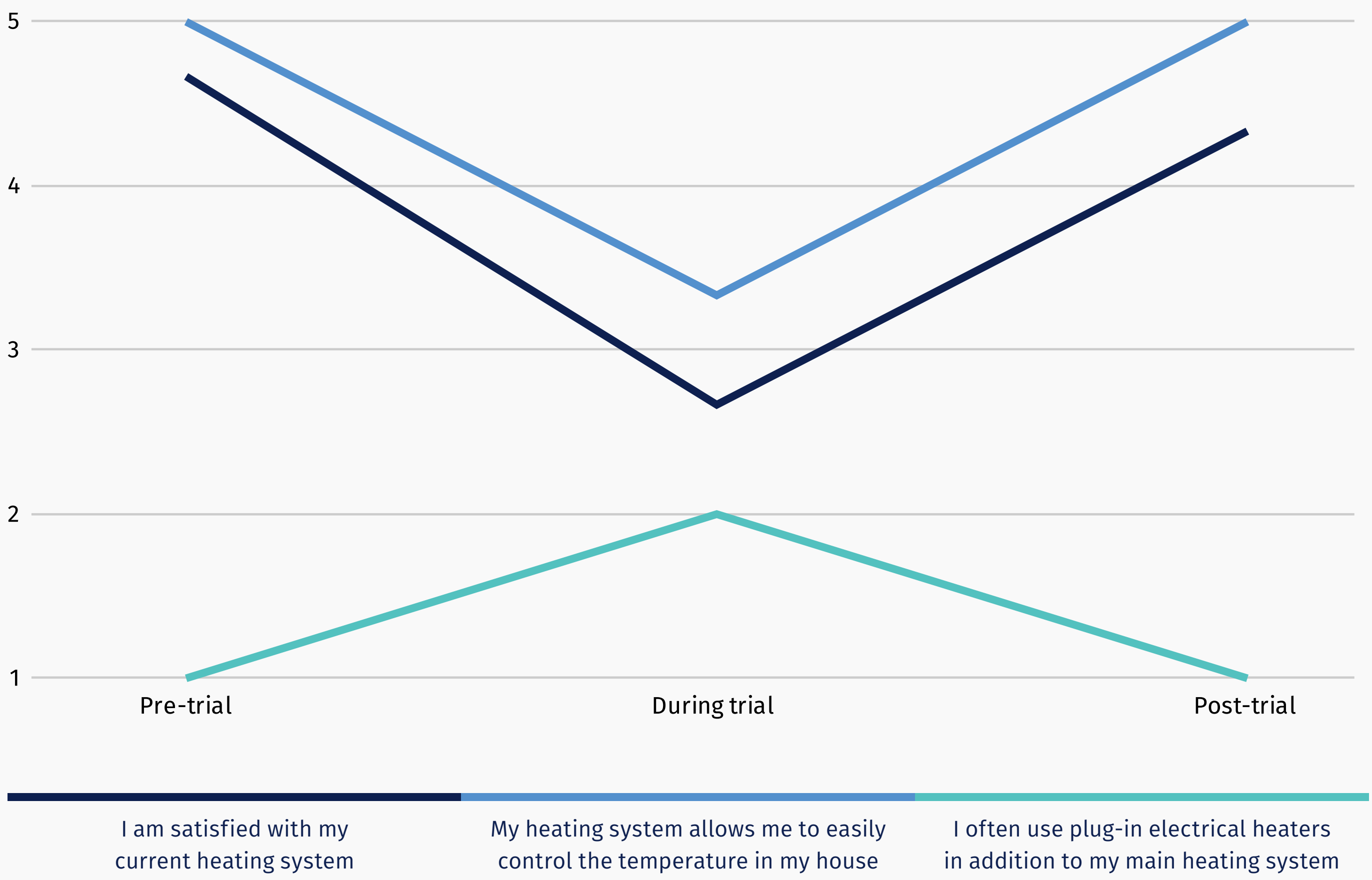


Figure 3.17: Sonning Common tenant satisfaction

Figure 3.18 shows internal temperature data (using sensors in living rooms) for each of the five Sonning Common properties from 1st November 2022 to 31st January 2023, alongside average external temperature for the period. Average temperatures were relatively high, which may be partly explained by the fact that tenants would be reimbursed in full for their heating usage during the trial period. Analysis of variance for temperature data revealed that these temperatures were relatively stable, indicating that the systems effectively maintained temperatures. The chart also reveals significant variation between properties, reflecting tenants' different thermal comfort preferences.

Finally, while the temperature profiles for four dwellings are similar, 3_SC (whose heating system was set at a constant temperature) is a notable exception.

In Sonning Common properties, the smart thermostat (Homely) required tenants to use a smart phone app. Some residents said that they did not own or like using their smart phone, and adjusted temperatures less frequently compared with using more conventional wall-mounted thermostats. The learning is that any smart thermostat should have user interfaces that are simple to use and ideally wall/surface mounted.

Average temperature readings (Winter 22-23)

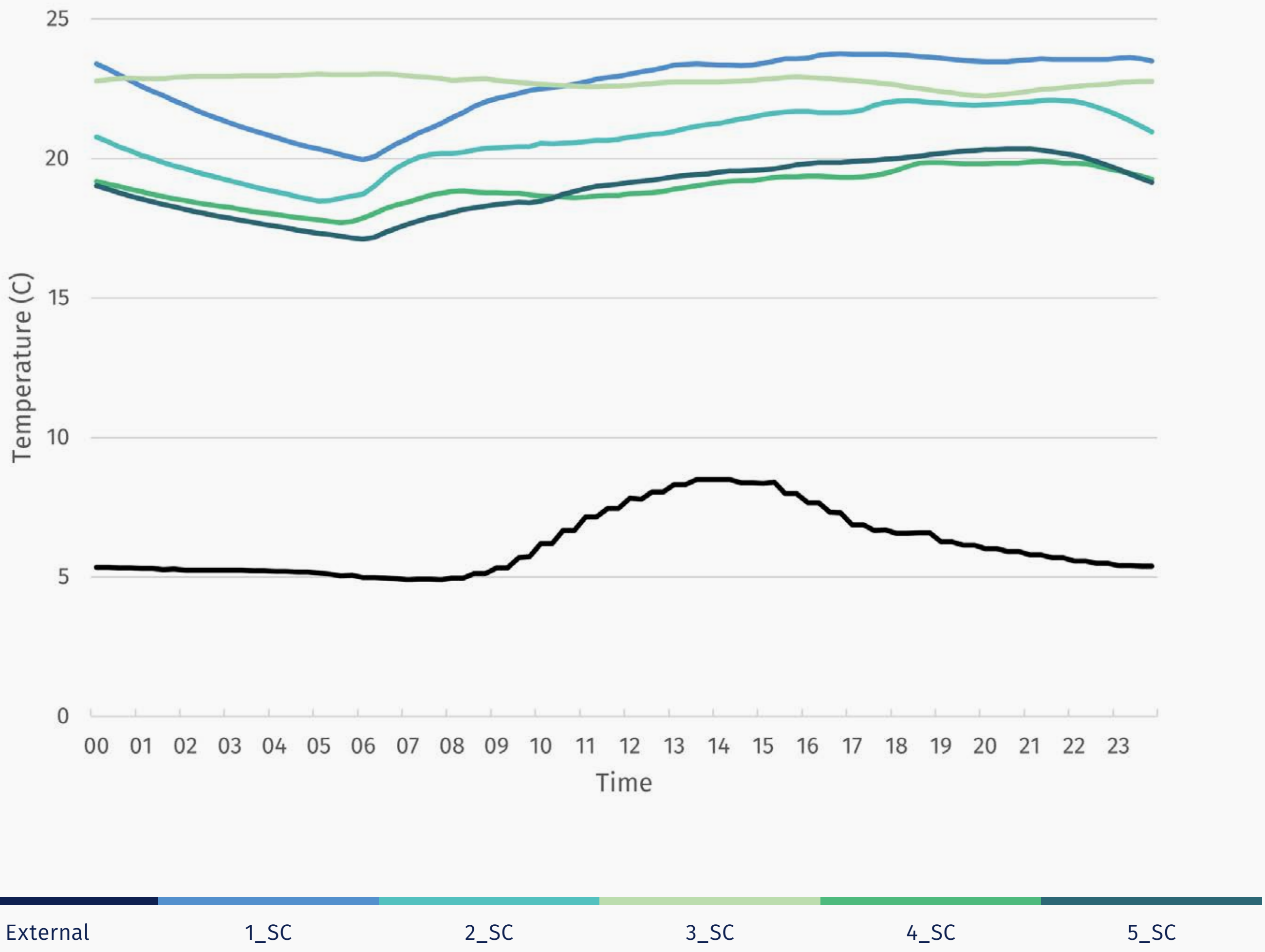


Figure 3.18: Average internal and external temperature over 24 hours by property

Flexibility using heat batteries

Notwithstanding occasional technical faults, the prototype GSHP-PCM units performed well during the trial. The Coefficient of Performance (COP) ranged from 2.6 to 2.9 for each of the units, which is lower than Kensa would expect for a commercial heat pump, but reasonable for a prototype. Performance dropped by up to 25% in winter compared with summer months. In terms of flexibility, the GSHP-PCM units responded effectively to price signals from the Octopus Agile export tariff, powering down during the peak pricing period of 4-7pm (Figure 3.19).

> *Evidence from tenant interviews indicates that during early evenings thermal comfort was not affected, and analysis of temperature data found low variability around mean temperatures.*

Demand profiles, Sonning Common (winter 22-23)

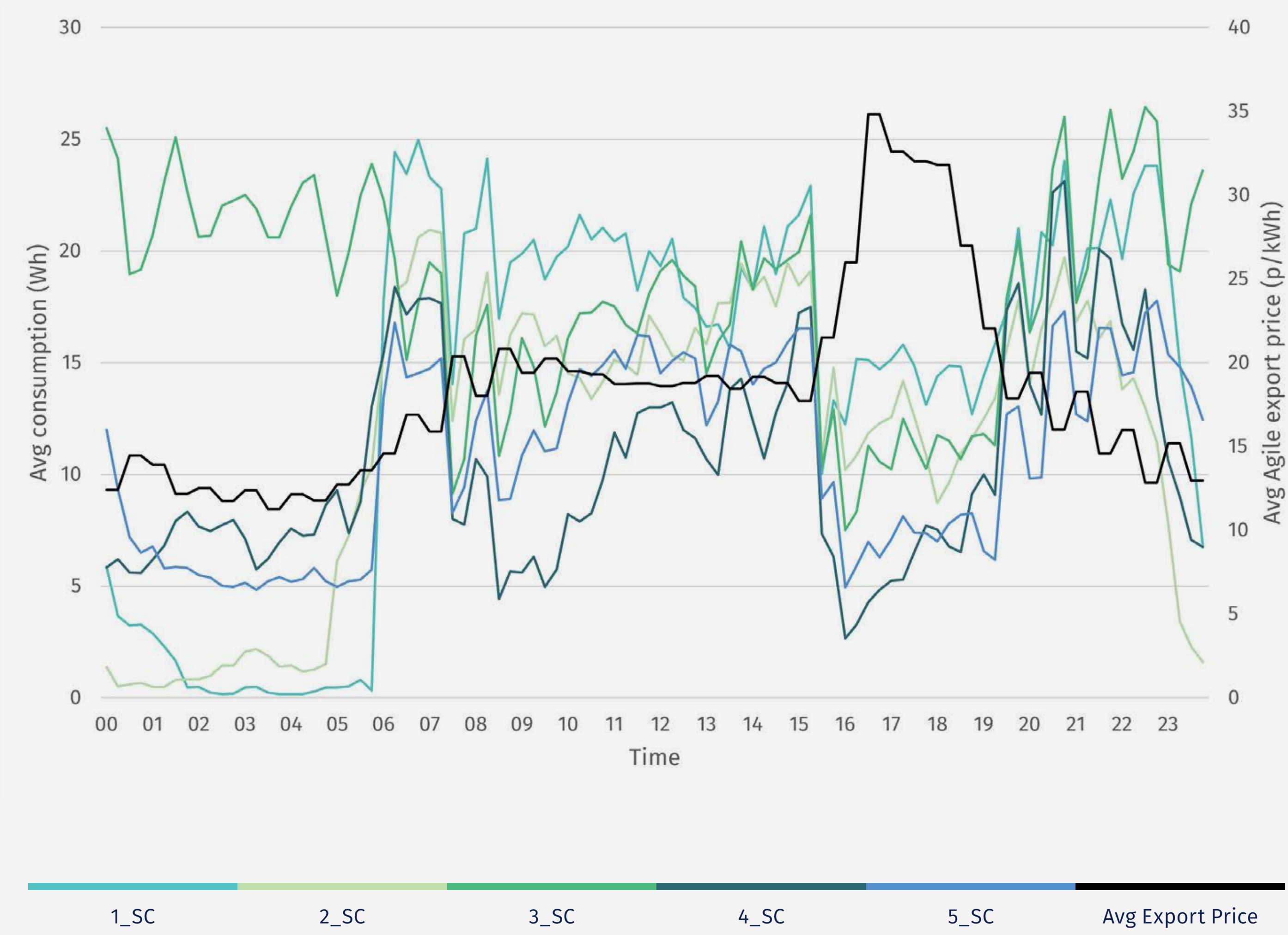


Figure 3.19: Electricity demand profiles by household, Sonning Common

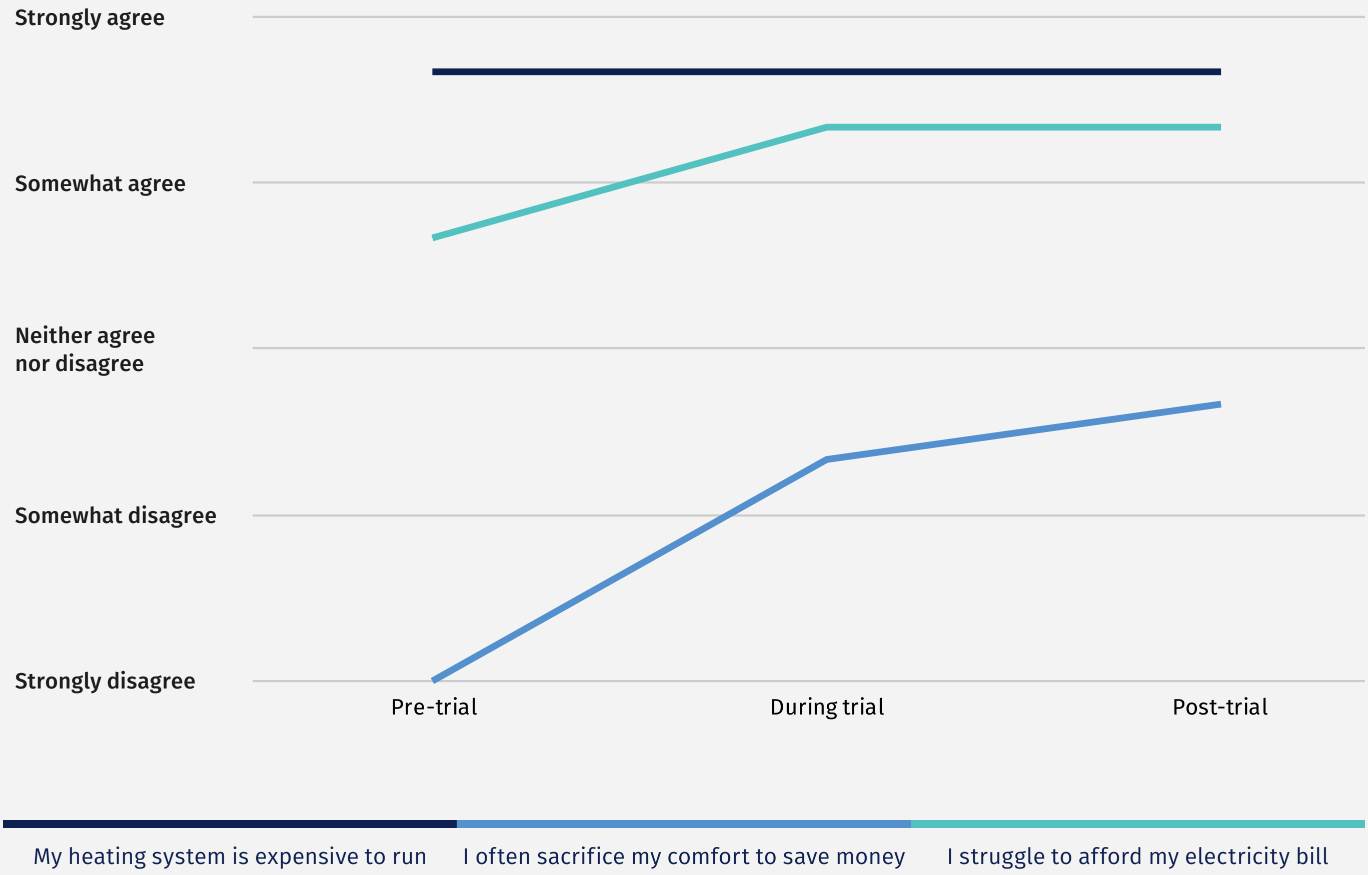


Figure 3.20: Tenant perceptions of running costs

Running costs and reimbursement

Sonning Common tenants' experiences of three separate heating systems has coincided with the energy price and cost of living crises in the UK. Each interviewee said that this made it difficult to compare the running costs of each system. One tenant said that in the space of a year, their monthly payment had increased from £112 (for gas and electricity) to £358: an increase of over 300%. Another had seen a 250% rise.

Tenants perceived that all three systems were expensive to run, and they were increasingly struggling to afford their bills (Figure 3.20). While they disagreed that they often sacrificed their comfort to save money, this question saw a slight increase over time.

Interviewees expressed some dissatisfaction with the communications around financial reimbursement. Each explained that they had been told to expect a fixed monthly payment, which would be issued regardless of energy usage. However, Kensa clarified that payment would be made according to usage, tracked using heat pump electricity meters.

> *While tenants welcomed the financial incentive, communications around payments could have been clearer.*

Challenges and lessons learned

Onboarding

Only 63 of the 300 planned domestic installations of GSHPs have gone ahead on ESO, and none of the 20 non-domestic sites targeted went ahead. Kensa attribute this shortfall to four main factors.

Firstly, Oxford is a relatively small city which is extensively served by natural gas **(83% of properties)**. There are just under 12,000 social housing dwellings, of which Oxford City Council (OCC) owns 7,502 (63%). In recent years, the housing team have gradually replaced electric storage heaters with gas boilers across their portfolio. They were sceptical about installing GSHPs through ESO due to concerns over running costs compared with gas, and negative experiences of installing air-source heat pumps in the past. OCC were also concerned about tenants' ability to understand and use heat pumps, and their effectiveness in properties with low levels of air tightness. Citing improved technology, OCC are now experimenting with HP technologies in new-builds, and through a project in Rose Hill called **Clean Heat Streets**. Kensa reflected that trust in ground source heat pumps can take time and effort to build with prospective landlords. ESO and other demonstration projects are gradually helping convince social housing providers of their benefits.

Secondly, as highlighted in the 'government funding' box at the start of this chapter, public funding for renewable heat became less reliable during the project. This is a concerning development, considering that during the same period, the government has set targets for **radically scaling up heat pump installations** in the UK.

The 'spark' gap

The difference in the unit costs of gas and electricity is known as the 'spark gap'. The comparatively high cost of electricity is considered a deterrent to consumers switching from gas boilers to electrical heating. In the last two decades, this has been exacerbated by successive governments' decision to raise climate policy costs on electricity bills, rather than spread across energy vectors, or absorbed into general taxation (Barnes and Bhagavathy, 2019).

The UK Government is aware of the issue, and as part of the Energy Price Guarantee during Winter 2022-23, the caps placed on the unit costs of electricity (34 p/kWh) and gas (10.3 p/kWh) reduced the effective spark gap to a ratio of 3.3:1. Reducing this ratio further will be crucial to boost the uptake of heat pumps.

A third factor explaining the shortfall of GSHP installations is that initial estimates were simply too ambitious. Despite strong growth and significant interest in GSHPs in recent years, the market for shared ground loop systems remains small. Roughly 2,500 installations were made in the UK in 2020. Even accounting for soaring natural gas prices in late 2021, gas remains roughly 3-4x the price of electricity. Although GSHPs can be more than 300% efficient, running costs are currently equivalent to gas boilers, while installation costs are substantially greater. The stated aim in the funding bid to 'reduce greenhouse gases and air pollutants from 300 gas-fired boilers in the heart of the city' appears now to have been over-optimistic.

A fourth factor relating to new-build homes became clear during the project. While Kensa have successfully sold GSHP systems to developers in recent years, there are few incentives for these clients to invest in smart controls alongside heat pumps. The attractiveness of a low carbon heating system appears to be a sufficient selling point for prospective buyers, without the need to add smart thermostats and flexible capabilities.

> *The attractiveness of a low carbon heating system appears to be a sufficient selling point for prospective buyers, without the need to add smart thermostats and flexible capabilities.*

Installation

Drilling and heat pump installation took longer than anticipated in both Blackbird Leys and Sonning Common. Kensa provided the reflections on the challenges and lessons learned (Table 3.4).

Table 3.4: Installation learnings

ISSUE/CHALLENGE	LEARNINGS FOR FUTURE
Combining the role of Tenant Liaison Officer (TLO) and Site Manager proved not ideal. These roles require different skill sets and too much work for one person.	Hire separate TLO & Site Managers. Better communications expected with Tenants through having dedicated TLO. Plan more regular visits from permanent Kensa staff, particularly on more novel and challenging sites.
Switchee thermostats proved unreliable, with many units needing replacement.	Experiment with different providers, including Homely (as in Sonning Common).

Flexibility

The trials in Blackbird Leys and Sonning Common raised several challenges and highlighted a series of valuable learnings (Table 3.5)

Table 3.5: Flexibility trial learnings

	ISSUE/CHALLENGE	LEARNINGS FOR FUTURE
Promoting flexibility to tenants	Social housing tenants generally distrustful of energy market and not likely 'early adopters', so found lack of enthusiasm for switching to TOU	• ESO demonstrated the need for effective, simple communications relating the benefits and drawbacks of flexibility, using different channels (letters, face to face, phone-calls, SMS) • Participant incentives are crucial. • Demand flexibility is attracting increasing media attention, e.g. driven by National Grid ESO's Demand Flexibility Service (DFS) during winter 2022-23 This could boost public acceptance
Market barriers	• Only one TOU tariff available in UK • Agile prices pegged to wholesale prices, so shot up faster than other retail tariffs Became unethical to promote to tenants	• There is a need for market stabilisation and greater competition in the retail market • NG ESO's DFS rewarded consumers generously for demand shifting (at £3/kWh), demonstrating significant potential for consumer savings
Technology: hardware	Many tenants (~70%) on pre-payment meters, which are incompatible with Agile at present	NG ESO's DFS was designed to include customers on smart pre-payment meters, demonstrating that flexibility is technically compatible
Technology: software	Tenants desired the ability to override controls for longer than 30 minutes	Incorporate longer override into algorithm
	Lack of ability to control hot water schedule	Include hot water preferences in pre-trial survey
User experiences	Some tenants over-estimated their heating preferences	The second flexibility trial used tenant data to train the heating algorithm, which improved outcomes for most. However, there is a need to improve control and user override, especially for occupants with irregular daily schedules.
	Lack of awareness of purpose of trial nor environmental benefits	Improved communications about the benefits (to householder, and system), including feedback on cost savings. Potential for trial participants to advocate benefits of flexibility amongst social networks.
	Limited insights from trial 1 due to external temperature (Apr – May)	Avoid scheduling trials during swing season: colder months will lead to clearer signals for evaluation

Conclusions

Implementing dynamic heating in the domestic setting is a major challenge with strategic importance for the UK's climate goals. Doing so in social housing presents an additional set of challenges and opportunities.

On the one hand, social landlords can benefit from economies of scale using shared ground-loop arrays and boosting the energy performance of their housing stock. Dwellings using electric storage heaters represent the greatest opportunity, as ESO has demonstrated that GSHPs can deliver cost savings, greater control, and improved thermal comfort for tenants. On the other hand, social housing tenants tend to be older, poorer, and less engaged with the energy market than other populations: not the usual suspects for the early adoption of innovative technologies.

This project has highlighted practical barriers to trialling the responses of participants to flexible tariffs – most did not have the metering infrastructure to allow them to sign up to Octopus Agile. There were also barriers in terms of preferences for their current supplier, and for the peace of mind given by using a pre-payment tariff. Those who would most benefit from the lower costs that TOU tariffs and dynamic heating could bring, are not best placed to accept associated risk (lower, fixed incomes, limited market engagement). Despite this, ESO has demonstrated that well-designed dynamic control of heat pumps can be acceptable to users.

The energy price crisis has led to huge changes in the UK energy retail market, multiple energy business failures, reliance on Ofgem price caps and government subsidies. It also raised the financial risk to trial participants of signing-up to flexible time-of-use tariffs to unacceptable levels. Unfortunately, these market conditions have prevented the project from making conclusions about the potential for smart-controlled heat pumps to be competitive with gas central heating in terms of running costs. However, findings from Blackbird Leys Trial 2 show that the price-optimising algorithm produced savings for 5/7 households when compared to regular use of heat pumps, on a hypothetical variable tariff. There is a need for more flexible tariffs in the retail market to enable further empirical experimentation without relying on simulations. In recent years, many suppliers have launched tariffs specifically for electric vehicle charging, and there is an opportunity to do the same for heat pump users.

The findings from our research contributes to a growing evidence base which is testing and demonstrating flexibility in domestic heating. There is a need for further research, development of the technical solutions, and deployment in real-world settings in order to give investors such as social landlords and housing developers the confidence to choose smart heat pumps.

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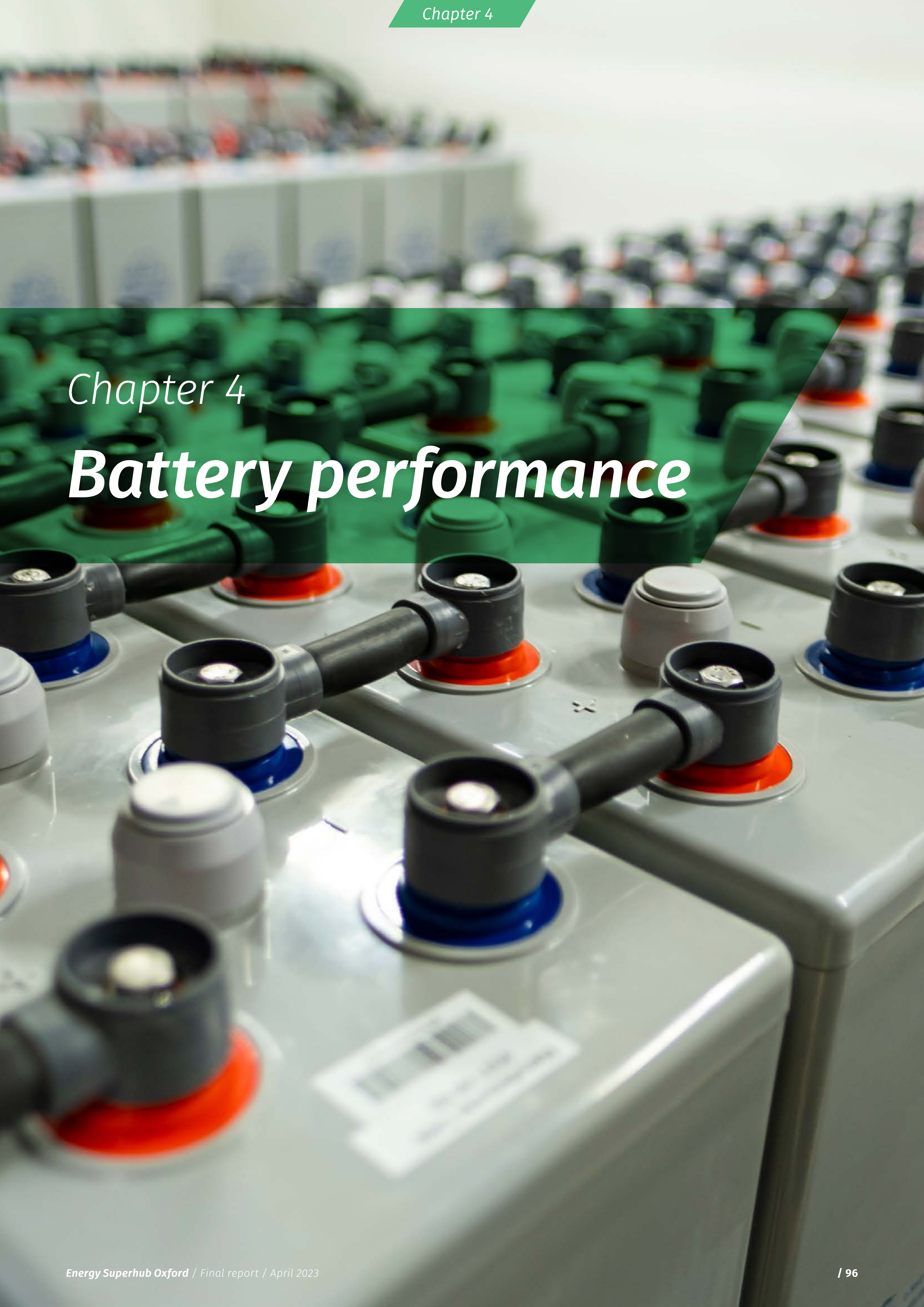


Chapter 4

Battery performance

Initial project targets: battery

1

50 MW / 50 MWh
Lithium-ion battery

2

2 MW / 5 MWh
Flow battery with 'Pulse' function

3

OTE development - to control both batteries and maximise trading/services revenuess

Figure 4.1: The hybrid battery

A central component of the ESO project is the hybrid battery, located at National Grid's Cowley substation to the Southeast of the city. Batteries are a key enabling technology for achieving the UK's ambitious net zero emissions targets by supporting integration of renewable energy sources and providing grid services.

The hybrid battery consists of two core assets, a 50 MW (peak power) / 50 MWh (energy) lithium-ion battery and a 2 MW (power) / 5 MWh (energy) vanadium redox flow battery.

The battery is a unique asset in several ways: it is the first battery in the UK to be connected to the National Grid transmission network, it is the first hybrid battery of its type anywhere in the world, and it is also the first type of connection to a tertiary transformer winding, a specific connection type suitable for this scale of asset.

The battery is owned by EDF Renewables, with the lithium-ion battery supplied by Wärtsilä of Finland as systems integrator and the vanadium flow battery by Invinity Energy Systems, a partner in the project.

The installation is controlled and monitored by the Wärtsilä GEMS Energy Management System, which communicates with Habitat Energy's Optimisation and Trading Engine (OTE), enabling operation of the battery in several electricity markets as well as the provision of ancillary services to the National Grid. The aim of combining the lithium-ion and flow batteries was to benefit from the different characteristics of each technology (vanadium flow batteries do not experience capacity degradation but have lower round-trip efficiency compared to Li-ion), and hence have the potential to improve the overall system economics.

The flow battery includes a new 'overdrive' function that was developed with the funding support of IUK under the ESO project. The overdrive function allows the flow battery to be operated at higher power levels for limited periods of time, increasing power from its nominal 1.2 MW to 2 MW.

The development of the vanadium flow battery, the National Grid connection works, and the construction of the 'Balance of Plant' (the civil and supporting electrical works), as well as the development of the OTE have all received IUK funding under the ESO project. The Li-ion battery and its installation are outside of the IUK funded scope and form part of the industry match-funding for the project. The procurement and operation of the flow battery have been funded for the duration of the project on a depreciation basis.

The development of the vanadium flow battery, the National Grid connection works, and the construction of the 'Balance of Plant' (the civil and supporting electrical works), as well as the development of the OTE have all received IUK funding under the ESO project.

Battery Construction

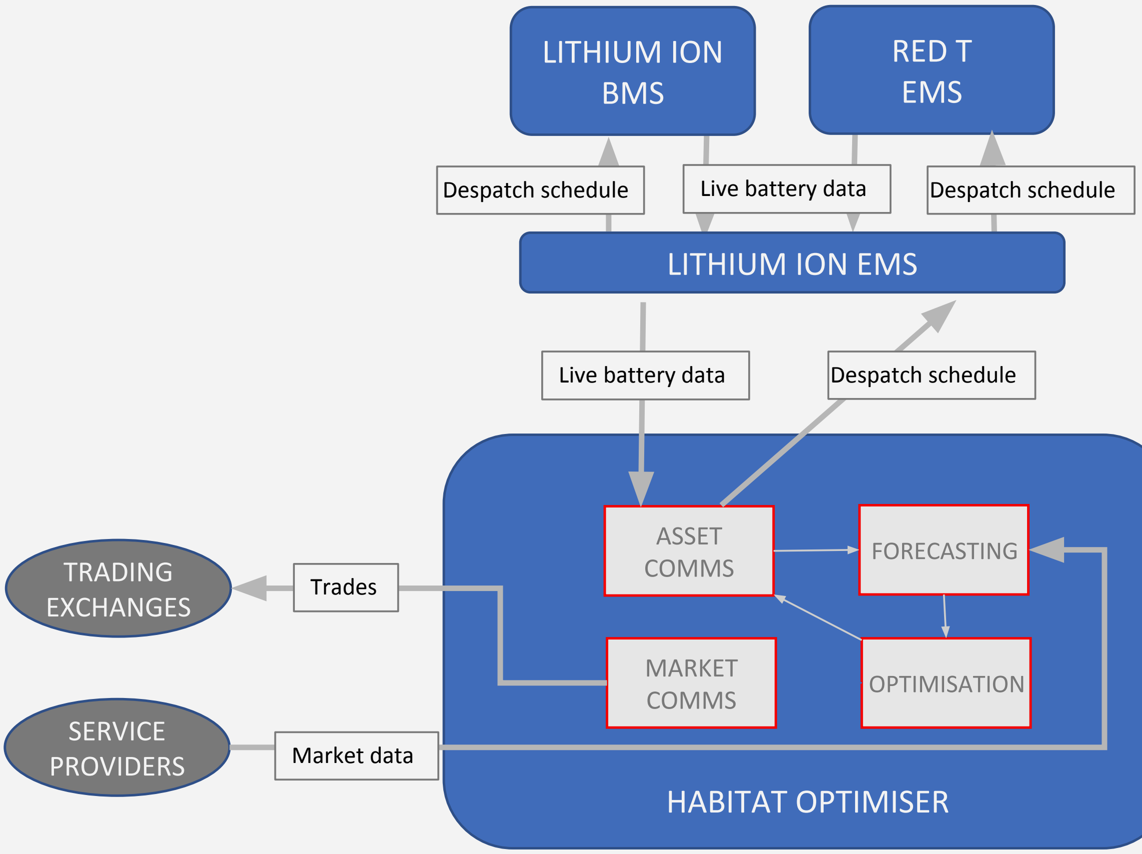
The construction of the battery was delayed for several reasons. Originally, the connection with National Grid was scheduled for April 2020, but due to Pivot Power's process for securing funding for the battery taking longer than expected, this date was postponed first to August, then to November 2020.

The planning process for the battery at Cowley also took longer than anticipated and delays were caused by various factors, including the possible ancient woodland status of Sandford Copse, where the substation is sited. Ultimately permission was received in July 2019.

The ESO battery is the first transmission-connected storage asset in the UK.

Figure 4.2: The battery under construction

Figure 4.3: Battery and optimisation trading engine system architecture



Pivot Power, Habitat and Invinity all entered the project with unclear funding routes, and it is a significant achievement that all of these were resolved to allow the continuation and delivery of the project to this point. Pivot Power's acquisition by EDF Renewables was achieved in November 2019, with formal approval for the construction achieved shortly afterwards.

However, construction was unable to commence until the battery procurement contracts had been agreed with the lithium-ion provider Wärtsilä, which took until spring 2020. Work commenced on site in summer 2020.

Further delays were caused by the National Grid connection date being moved from November 2020 into 2021, COVID-19 working practices, and supply-chain issues which hampered the final delivery of transformers and substations. The National Grid connection was finally made in March 2021 and the Li-ion battery was completed in April 2021. Commissioning and testing of the GEMS control system and its interface with the Habitat OTE (Figure 4.3) led to a 'go live' date in June 2021.

Flow Battery delays

The vanadium flow battery also experienced significant delays, initially as a result of redT energy completing a merger with Avalon Battery Corporation to form Invinity Energy Systems in spring 2020. This resulted in a redesign of the product in the first half of 2020, combining elements of the redT solution with Avalon's existing product.

The flow battery programme suffered from several other significant challenges. These included supply-chain issues relating to components of the battery 'stack', which houses the electrodes, as well as significant COVID-19-related supply constraints for a range of internal components. A carbon electrode filter required re-sourcing in early 2021, and electrolyte availability and DC/DC converter issues, all caused significant delays—resulting in a delay to the delivery and construction of the three flow battery 'clusters' (each containing 9 battery containers) until the second half of 2021.

All equipment was installed during the autumn of 2021 and live performance testing commenced. Further challenges were seen in several areas, including hardware and software issues associated with some of the 162 modules, issues with the DC/DC converters and the PCS control system. All of this led to an initial handover of the flow battery in April 2022, with an ongoing programme of work to resolve remaining issues.

At this point, commissioning of the flow battery commenced with Habitat, but integration issues were experienced which delayed this process. The final commercial 'go live' date of the battery was in November 2022 for trading. By this time, it had been demonstrated that the flow battery could achieve the response times required by National Grid to operate in the various new frequency response markets (dynamic containment, dynamic regulation and dynamic moderation), however, the combined lithium-ion/flow hybrid system needed to be re-certified for operation in those markets.

Two rounds of testing were unsuccessful due to ongoing communications issues between the GEMS system and the flow battery, and at the time of writing it is intended to carry out a third round of testing in March 2023 to achieve formal 'go live' of the flow battery in these frequency response services.

Battery Operation

The lithium-ion battery has been in operation since the end of June 2021, providing services to National Grid and trading in multiple energy markets.

At the outset of the project, it was expected that the battery would spend most of its time trading in the energy markets, and this would deliver most of the revenues, with a smaller contribution from ancillary services (mainly Firm Frequency Response, FFR). In reality, however, frequency response services have provided the majority of revenues, with 70-80% of the battery operational time being in these markets in the second half of 2021 and most of 2022. This was primarily due to the introduction of new services, particularly dynamic containment (DC), that resulted in a new market for a limited number of batteries allowing initially strong clearing prices. Other factors that influenced the market were the energy crisis at that resulted in very high prices for provision of non-battery assets, and generally high price volatility.

In addition to frequency response services, the battery has also earned revenue in the capacity market, providing back up in case of significant grid stress events, and also by providing reactive power. All of these have contributed to the revenues of the Li-ion battery since July 2021.

The changing UK frequency response markets

Energy storage can provide services at many different timescales, Figure 4.4. At the beginning of the ESO project, the primary ancillary service considered was firm frequency response (Figure. 4.5), which is a monthly 24/7 contract, bid-for in advance.

Figure 4.4: Markets for storage to provide services over different durations

With National Grid's enhanced frequency response strategy, the frequency response service has since been broken down into three new services—dynamic containment, dynamic regulation and dynamic moderation. These each have different response curves, specifying the amount of power required to be provided at departures from the nominal 50 Hz grid frequency (see example curve below). These are now contracted in six 4-hour "EFA-blocks", making for a far more variable and granular market.

In additional to these, the original FFR service still exists. Habitat had to adapt their OTE software for each of these new services, providing the appropriate levels of interface with National Grid-ESO for each, and optimising across all four of these markets rather than only one of them. This has been a significant amount of work for the Habitat team, and it reflects a high level of flexibility and agility over a short period in adapting to this new market environment.

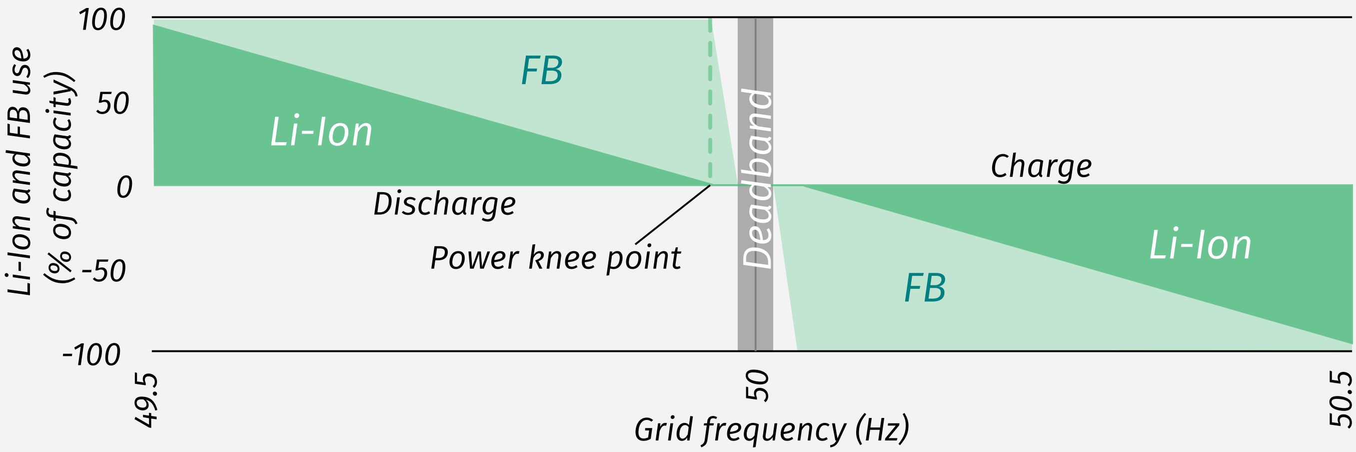


Figure 4.5: Dynamic FFR response curve

Frequency response using a hybrid battery system

One of the objectives of the hybrid battery was to investigate the benefits, or otherwise, of operating the two different chemistries together. Li-ion batteries are known to have a higher round trip efficiency than vanadium flow systems, but conversely shorter lifetime. Therefore, combining them could allow improved overall economic performance. For example, the flow battery might be prioritised to deal with the rapid power fluctuations associated with low power frequency response delivery, where round trip efficiency is less important, whereas the larger Li-ion battery could focus on the higher power and higher efficiency requirements of the trading markets. The hope is that doing so could reduce the amount of cycling of the Li-ion battery, resulting in an extended life before module replacements are required.

Habitat's flow battery commissioning process included stacking of frequency response curves for each battery, demonstrating that it is possible to operate the two different chemistries together to provide a combined frequency response service. However, due to the delays in gaining approval to operate the overall hybrid battery in the frequency response markets, it has not been possible within the ESO project timescale to commercially operate the total system together and hence evaluate the potential benefits. This work will continue beyond the project end date, and EDF Renewables together with Habitat Energy will find the optimum operating balance across both systems.

Financial performance

The following charts present a 'dashboard' for the Li-ion battery's activity over the first 19 months of operation and give some insight into how and in which markets the battery has operated.

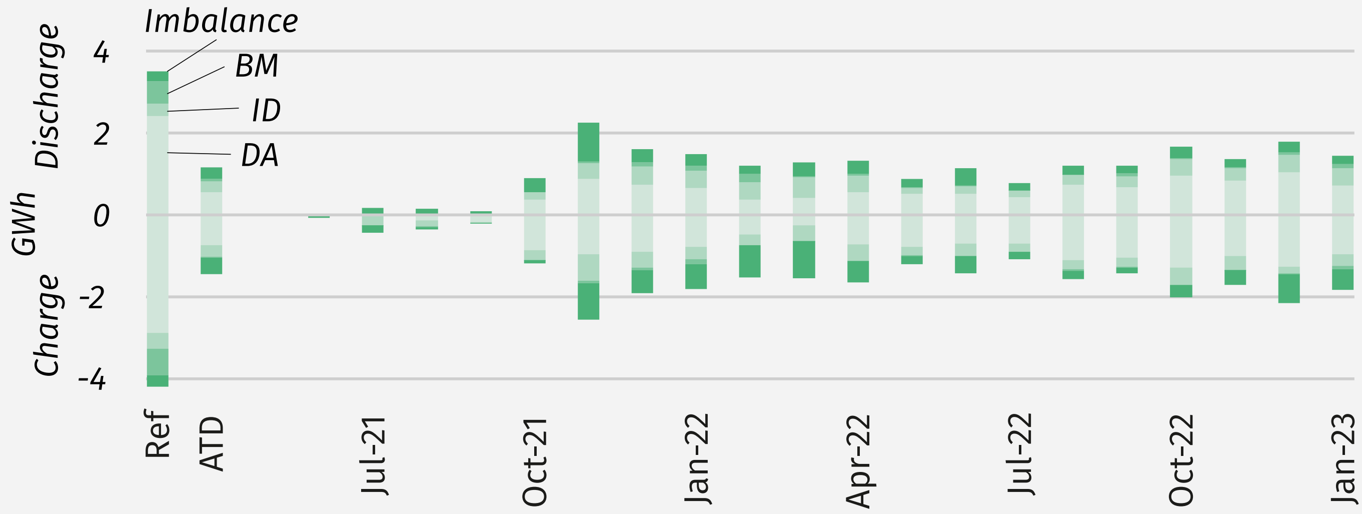


Figure 4.6: Trading volumes in different markets for charging and discharging

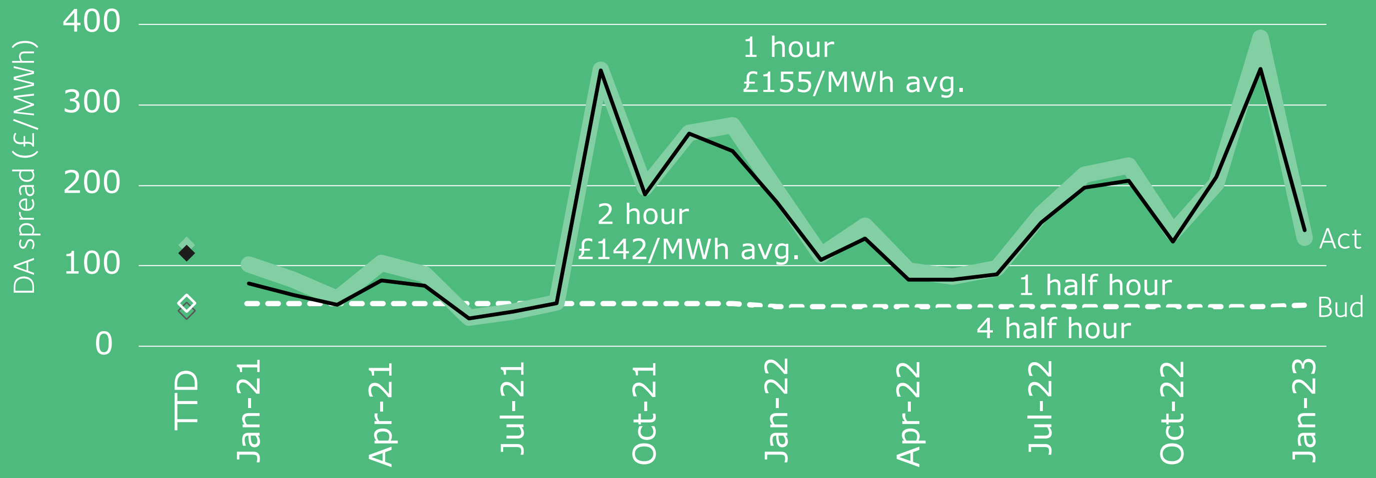


Figure 4.7: Market volatility

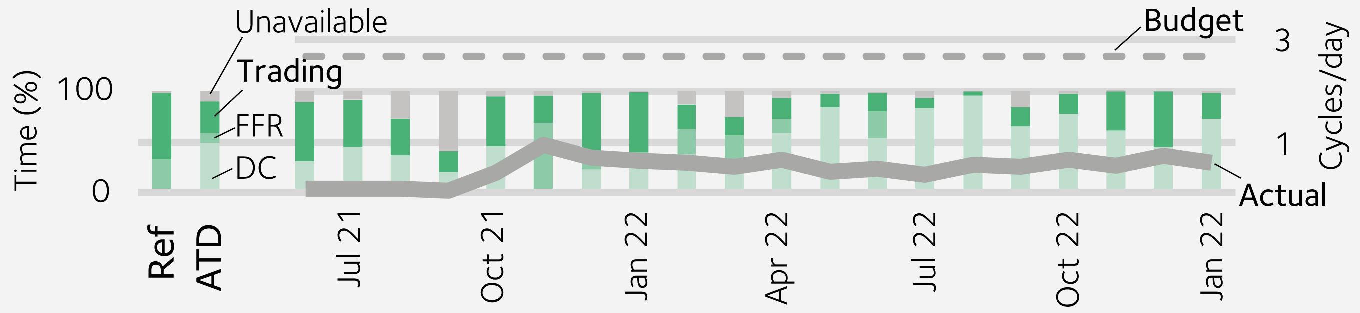


Figure 4.8: Storage cycles (lines) and share of time in different markets (bars)

	VOLTAGE* (V)	CAPACITY* (Ah)	ENERGY* (kWh)	V_{MIN}* (V)	V_{MAX}* (V)
Cell	3.7	100	0.368	2.70	4.2
Module	81	100	8.1	70.4	91
Rack	972	100	97	845	1096
Bank	972	3300	3206	845	1096
Rack	972	59400	57708	845	1096

Table 4.1: Lithium-ion battery properties (*nominal)

Li-ion efficiency

In this section we provide analysis of the technical performance of the ESO battery, focusing primarily on the larger Li-ion system. The Li-ion system consists of 18 battery banks, with each bank containing 33 racks connected in parallel. Each rack has 12 modules connected in series, and each module contains 12 prismatic NMC-based Li-ion cells each of 100 Ah capacity. The system is summarised in Table 4.1.

To test the battery capacity, a cycling procedure was applied at commissioning. After several warm-up cycles, the battery was charged from 0% to 100% state of charge (SOC), then discharged to 0% SOC to see how much of the stored energy could be retrieved. In Figure 4.9, the resulting accumulated energy for one battery bank (ESS-1) is available on discharge.

With an approximate 2.7 MW charging power and 2.8 MW discharging power measured at the AC side (upstream of the inverter, downstream of the transformer), we note that 3.04 MWh of the total 3.35 MWh charging energy was able to be discharged at the AC side. The difference of 0.31 MWh was 'lost' as heat during the process. Therefore, this battery bank has an AC-to-AC round-trip efficiency of 90.7% at these conditions and power level (note, excluding transformer losses). On the DC side, 3.29 MWh energy was used to charge the battery and 3.12 MWh of this energy was retrieved from the DC terminals at discharge. Therefore, the DC-side was responsible for 0.17 MWh of the losses, hence the DC-to-DC round-trip efficiency is 94.7% in this test.

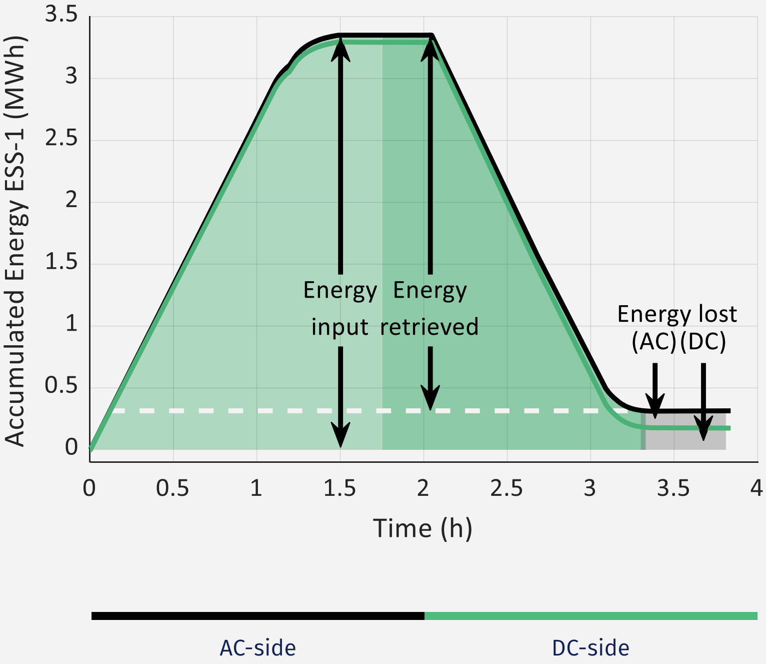


Figure 4.9: Battery commissioning data

The Li-ion system consists of 18 battery banks, with each bank containing 33 racks connected in parallel.

Battery degradation simulations

Grid-scale batteries are long-term assets with substantial capital costs, but they gradually degrade over time, resulting in reduced energy storage capacity. This significantly impacts the associated costs of a battery energy storage system, and therefore understanding and optimising battery life is an important part of optimising the revenue streams derived from the batteries (Kumpeteli & Howey, 2022).

It is crucial to quantify how batteries behave and age under various conditions, since this enables accurate assessment of financial returns, risk mitigation, and the development of effective management algorithms. Ageing is complex and influenced by many factors, including temperature, current, state of charge, and time. Capacity fade and power fade are common ways to quantify ageing, with capacity fade being the primary focus in this project.

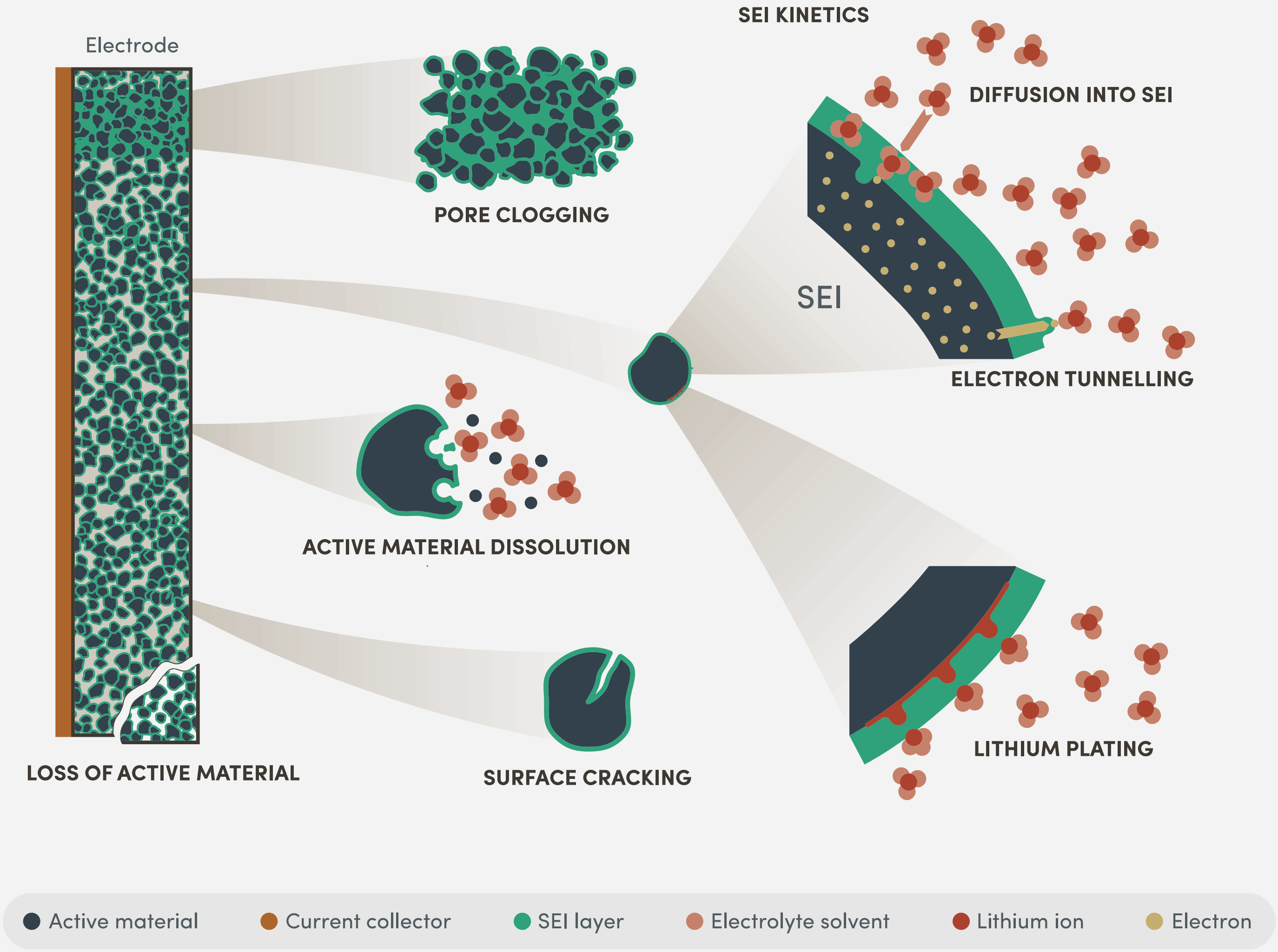


Figure 4.10: Li-ion battery ageing involves multiple complex mechanisms (Reniers et al., 2019)

To predict the lifetime of a battery, various modelling approaches exist—from simple empirical models to advanced physics-based models, with some even incorporating cutting-edge machine learning techniques. Simple models offer rapid computation but are essentially just curve-fitting measured data; advanced models prioritise accuracy and transparency but may require expert knowledge and specific difficult to obtain input data (Kumtepeli et al., 2019). Machine learning approaches can enhance the accuracy of degradation models by learning unknown or unmodelled dynamics, but only if suitable data sets are available. Regardless of the approach, high-quality experimental data is required for both calibration and validation of these models.

In this project, the team at Oxford University's Department of Engineering Science used physics-based models of degradation to understand the link between operational profiles and ageing. Here, the single particle model, a simplified electrochemical model, was employed for its ability to simulate individual battery cell performance and provide results against diverse load cases. It is not always necessary to simulate every separate ageing mechanism; for instance, lithium plating is predominantly associated with fast charging and low temperatures, and can be omitted in temperature controlled lower C-rate applications like grid storage systems.

Essentially, battery storage capacity relates to the amount of useable lithium that can be moved back and forth between the electrodes. Capacity fade occurs when lithium becomes inaccessible due to mechanisms such as solid electrolyte interphase (SEI) layer growth, where lithium ions and other materials adhere to the anode surface permanently and no longer participate in energy storage. Furthermore, the expansion and contraction of materials during charging and discharging create stress, leading to cracks, loss of porosity, and the loss of connection to active material. This also exposes new surfaces for SEI layer formation (Reniers et al., 2019; 2021; Reniers & Howey, 2023).

The workflow for the Li-ion ageing studies (Figure 4.11) was as follows. First, the appropriate battery model was selected, and usage data from EDF Renewables and Habitat Energy obtained. Then, degradation was assessed under three scenarios:

- **Ancillary services,** where the battery is mainly operated to support grid stability via frequency response. The current profile in this case exhibits many small, frequent pulses. These are the battery's active response to frequency deviations, supplying or absorbing power as needed. In this scenario, the battery operates at relatively low power levels, making rapid adjustments to maintain grid frequency.
- **Merchant operation,** or energy trading, i.e., buying electricity when prices are low and selling when prices are high. Consequently, the current profile is characterised by fewer oscillations and more prominent higher power trapezoidal patterns, with large current values up to 1C.
- **Mixed operation,** which combines elements from both ancillary services and merchant operation, resulting in a superposition of the respective current profiles. This scenario highlights the battery's versatility, illustrating its capacity to simultaneously provide frequency response to the grid while participating in energy arbitrage activities.

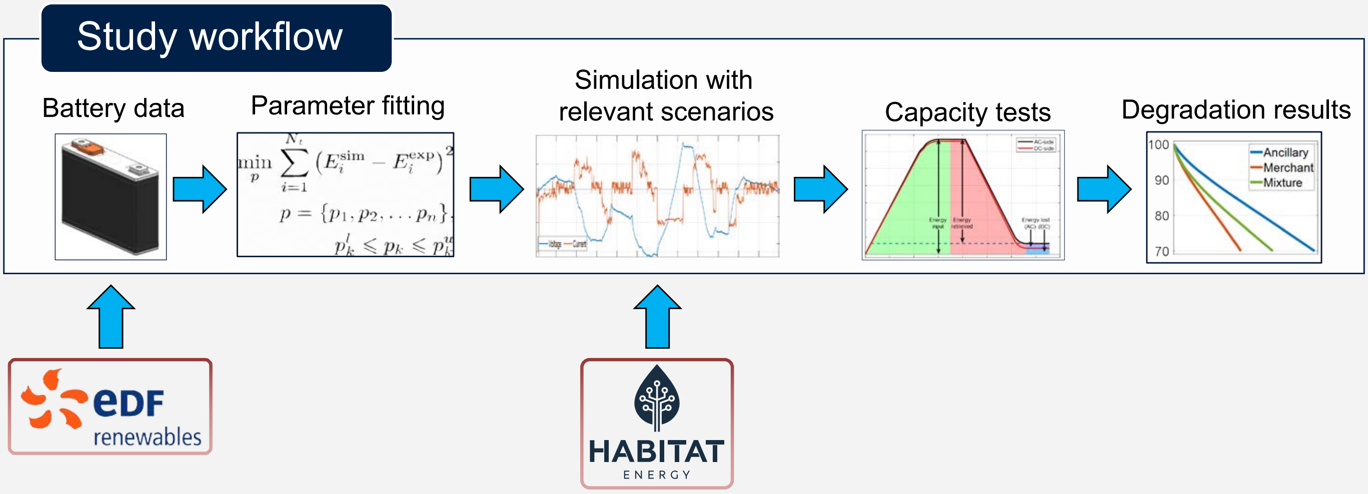


Figure 4.11: Workflow for testing battery degradation in different case scenarios

Each scenario used two days of representative measured data supplied by Habitat Energy and EDF Renewables. Important quantities such as cell voltage, current and temperature ranges in an individual battery module are illustrated for each case in Figure 4.12.

Further characteristics of the data are given in Table 4.2. In this table, C-rate is a common metric used to quantify the intensity of cycling, and is the inverse of battery duration; i.e., 2C would be equivalent to a half hour full charge or discharge.

Table 4.2: Summary of supplied usage data

		ANCILLARY	MERCHANT	MIXED
Daily cycles:		0.26	0.86	0.59
SOC	Min:	23.9%	20.0%	24.7%
	Avg:	44.2%	56.5%	58.1%
	Max:	64.5%	97.2%	83.1%
C-rate	Avg:	0.21	0.07	0.05
	Max:	0.17	0.56	0.25

Daily cycles:
This metric represents the average number of charge-discharge cycles per day for the data of each scenario. The ancillary scenario has the lowest daily cycles at 0.26, while the merchant scenario has the highest at 0.86, and the mixed scenario falls in between with 0.59 daily cycles.

State of Charge (SOC):
Given minimum, average, and maximum SOC values, it is possible to analyse the magnitude of SOC swings as well as whether the battery is used in low or high SOC conditions. Here, merchant operation has the widest SOC swing and ancillary services operation the narrowest, with mixed operation in-between. Both merchant and mixed operation show a relatively high average SOC compared to ancillary services.

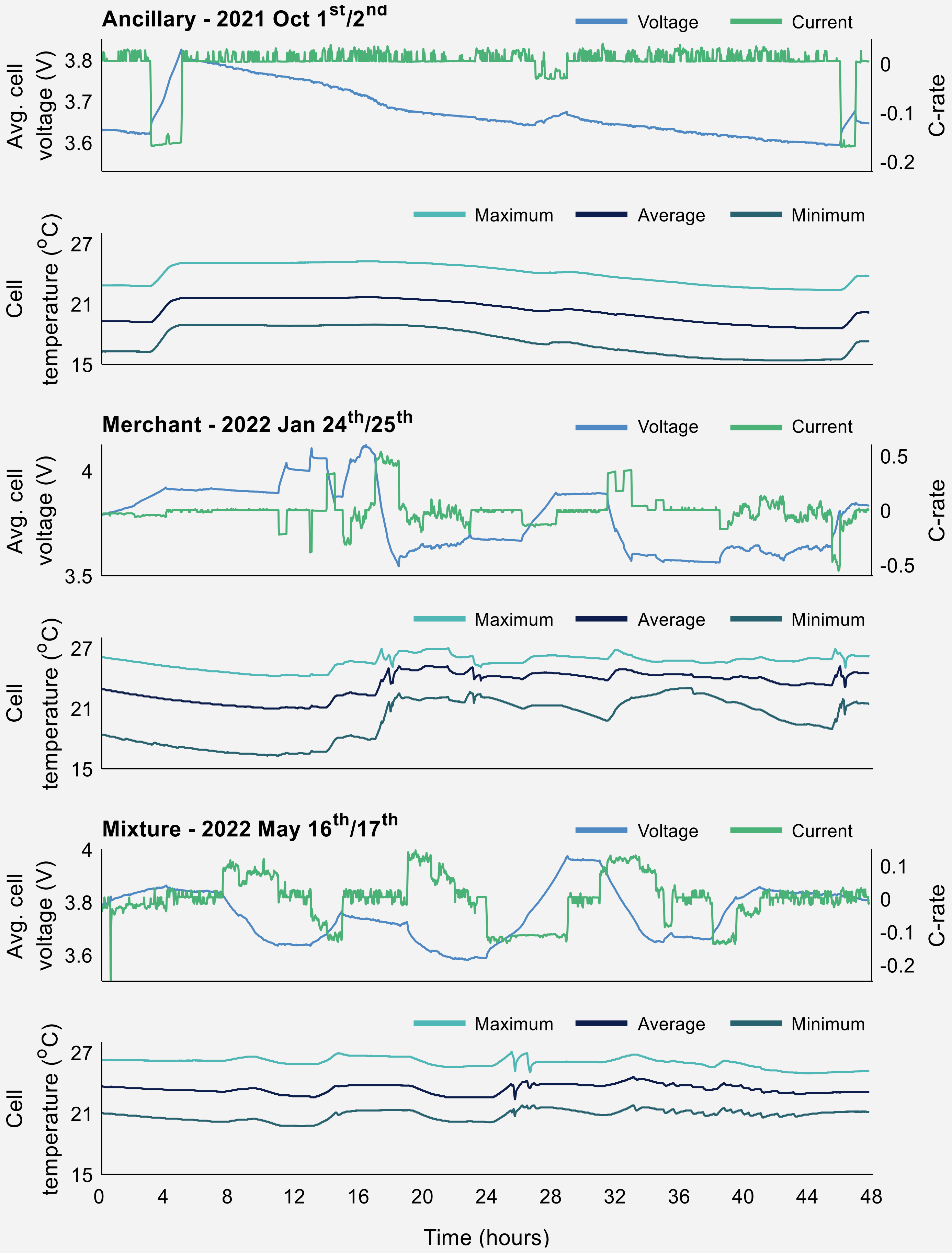


Figure 4.12: Measured usage data under three different usage scenarios

C-rate (charge or discharge rate):
Ancillary services exhibit the lowest maximum C-rate, whereas merchant trading has the highest and the mixed case is in-between.

In summary, the table indicates that merchant trading experiences the highest number of daily cycles and maximum SOC, while ancillary services have the highest minimum and average SOCs, and the lowest maximum C-rate. The mixed scenario has intermediate values across the metrics, highlighting its blended nature, combining aspects of both ancillary and merchant scenarios. These characteristics provide valuable insights into the performance and potential degradation of batteries operating under each of these conditions, allowing for informed decisions on battery management and optimisation.

By repetitively feeding the current profiles shown in Figure 4.12 into the digital-twin battery degradation simulation software developed by the Engineering Science department at the University of Oxford (Reniers & Howey, 2023), we obtained corresponding ageing simulations which are given in Figure 4.13.

It is evident in these results that the ancillary services scenario likely offers the longest battery life in terms of calendar time. However, when considering life versus full equivalent cycles, it becomes apparent that this scenario also has the lowest battery utilisation. In contrast, the merchant scenario has the shortest battery lifespan but this is because of much higher utilisation. The mixed scenario effectively combines the benefits of both scenarios by extending battery life (in calendar years) but maintaining similar utilisation levels (in number of cycles) as the merchant case.

It is important to note that the results are based on a relatively small amount of usage data and calibration data for the modelling, and do not account for effects such as manufacturing variability and the impact of temperature control and non-uniformity. Consequently, the absolute values of battery lifespan and number of cycles may deviate from this, but nevertheless, this analysis still provides valuable comparative insights for assessing the performance under different operating conditions.

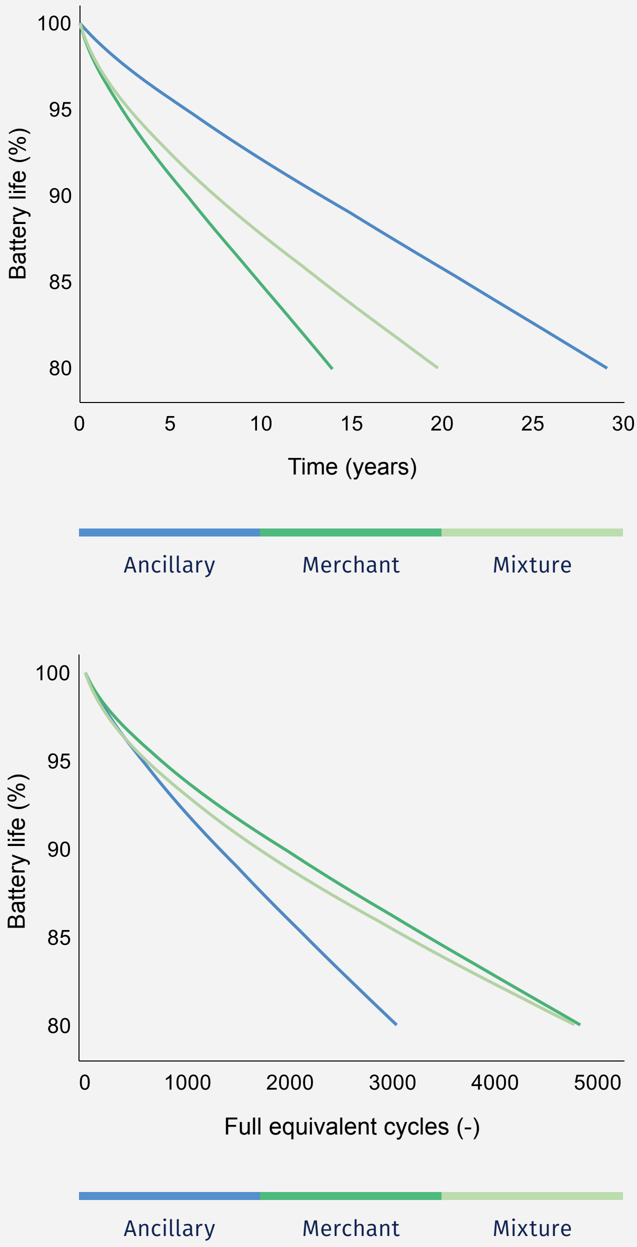


Figure 4.13: Battery degradation simulation results

Key points from degradation simulations

- In this project, Oxford University developed ground-breaking new simulation capabilities for Li-ion degradation that do not exist in any current software. Their software is open source and is being used by others around the world.
- It was found that operating a grid battery in frequency response, rather than energy trading, appears generally beneficial for Li-ion cell lifetime, because there are fewer overall cycles. However, this could also be seen as over-engineering (the cells "die" because of calendar aging, rather than cycle ageing).
- Stacking frequency response and trading may give the best of both worlds—reasonable lifetime and good use of the asset.
- Access to sufficient battery cell data and usage data, which may be confidential or not available at a sufficiently granular level, is a challenge for this kind of study.

Summary

A wide range of lessons have been learnt during the construction and operation of the battery and these are already being applied to the next two EDF Renewables projects currently under construction in Coventry and Birmingham.

ESO is the first project to connect a 'small' (50 MW) generator to National Grid's transmission network, which is conventionally used to connect large power plants. It does this by interfacing at 13.5 kV to a tertiary winding coming off one of the substation's main 400 kV/240 MVA supergrid transformers. This 'first of a kind' connection created not only supply chain challenges for National Grid (i.e., an entirely new type of transformer was required), but also raised questions and challenges during the commissioning process required to bring a battery into operation. In contrast, a 50 MW battery connected to the distribution network might expect two days of testing with the distribution network operator. EDF Renewables also introduced a new battery provider (Wärtsilä) for the first time into the UK. The original programme had allowed six weeks for commissioning. However, because this was a first-of-its-kind project, commissioning took nearly four months. Wärtsilä had to make changes to their control system to adapt to shifting requirements, and National Grid had to adjust their commissioning and testing protocols in real time as they learned more about the asset. On EDF Renewables' second site the commissioning phase was able to be completed within the target time of six weeks.

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Key achievements: Hybrid battery

- Demonstrated the UK's first transmission-connected battery.
- Opened up the UK transmission market – there are now multiple GW of transmission connection applications with National Grid.
- First connection to a tertiary winding on a National Grid UK supergrid transformer.
- Multi-MW demonstration of vanadium flow batteries and one of the world's largest hybrid battery projects.
- New productised modular vanadium flow battery, incorporating overdrive function, now being deployed in other projects, both in UK and overseas.
- Developed optimisation and trading engine, with transmission-connection focus.
- Demonstrated value of Grid Ancillary services and trading resulting in almost £200m of further committed investment in grid scale batteries by EDF Renewables.
- Digital twin software built by University of Oxford enables simulation of degradation-impact of different usage profiles.
- Demonstration of "stacking" of lithium-ion and flow battery frequency response curves to support ancillary services.

Lessons learned: Hybrid battery

- Energy Storage remains classed as a generation asset by NG-ESO/OFGEM, resulting in generation related transmission use of system (TNuOS) charges.
- 24/7 Manual desk is required to operate transmission connection – we do not feel this is necessary for 'smaller' transmission connected assets, such as this.
- Transmission asset registration is challenging - we propose a lead party's asset trader should be able to register separate from the lead party (asset owner).
- Changes to grid services and market requirements are highly dynamic and require constant adaptation of an optimisation tool such as Habitat's OTE.
- Gaps between procurement specifications (inverters/transformers) caused a significant issue in transformer damage during testing – combining these is essential.
- A broad asset warranty envelope is essential for maximization of revenues by the trading entity (EDFR/Habitat).
- Grid services markets are very dynamic, and agility and flexibility are necessary in adapting to increasingly granular market requirements.

Chapter 5

CO$_2$ savings from battery operation

Initial CO_2 savings estimated at the start of the project

- 20.1 $ktCO_2$ /year saving in 2021
- 44.2 $ktCO_2$/year by 2032 in total, where 15.1 $ktCO_2$/year of the saving is attributed to the battery operation

This section focuses on estimates of the carbon emissions associated with the battery system operation since 'go-live' and explores the broader impacts of energy storage on grid operational emissions.

It was orginally estimated that the ESO project would lead to 20 $ktCO_2$/year saving in 2021 and 44 $ktCO_2$/year by 2032 in total, with 15.1 $ktCO_2$/year of the saving attributed to the battery operation. However, integrating more energy storage into the power grid does not necessarily guarantee reduced carbon emissions. The relationship between storage operation and emissions is more complex and depends on the mix of generation in a country.

In some circumstances, adding more storage may increase the carbon intensity even if the storage is lossless (Reuse et al., 2021; Pim et al., 2021). For a grid battery to reduce carbon emissions, it should be charged via low-emissions sources and displace high-emissions sources when discharging. Therefore, the local generation mix, volume of energy charged or discharged, and market dynamics play a role in determining the actual net CO_2 savings or emissions.

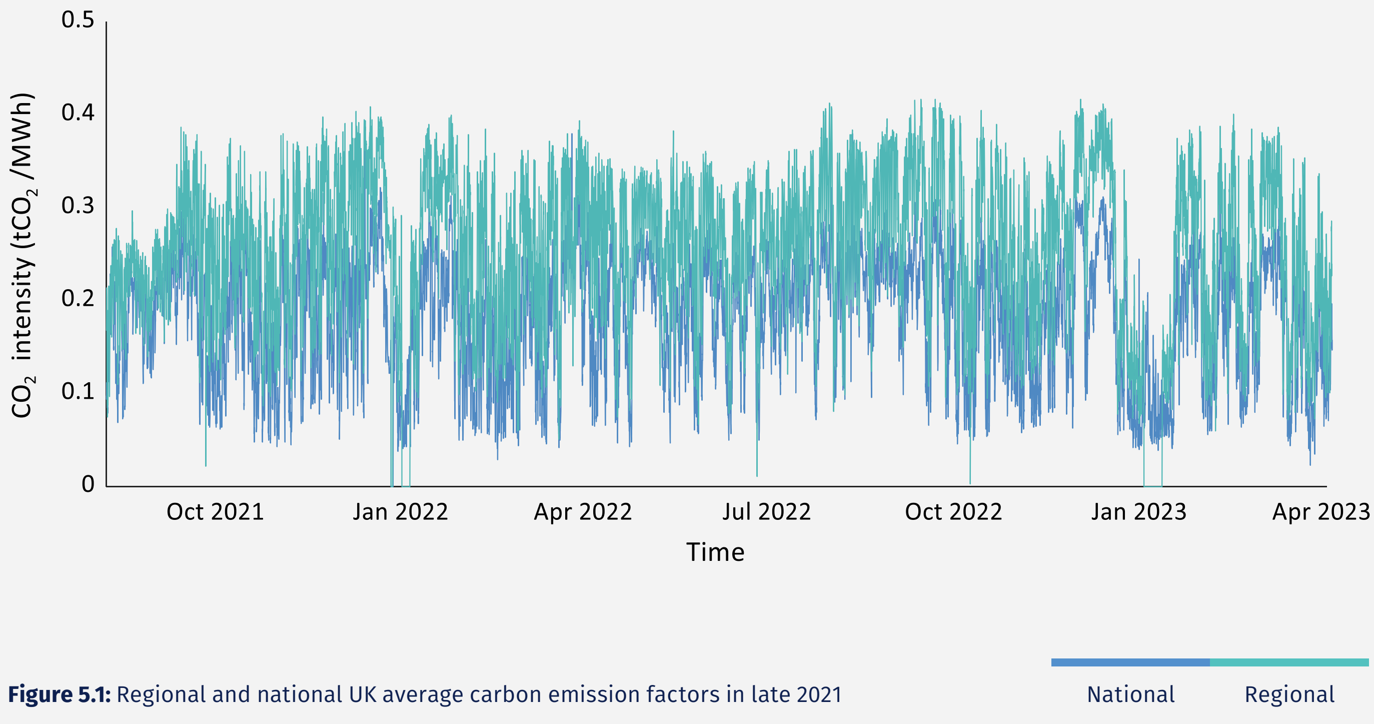

Figure 5.1: Regional and national UK average carbon emission factors in late 2021

To estimate CO_2 emissions associated with battery dispatch accurately, a detailed model of the transmission grid and market is required, and this was out of scope of this project. Alternatively, so-called marginal emissions factors (MEFs) may be considered; these estimate the change in the grid generation CO_2 intensity due to changes in the load (Hawkes, 2010). However, the marginal behaviour of the grid is difficult to model and requires many assumptions. On the other hand, the current and historical generation mix of the grid is easily available. By assuming that each generation source may be described by a carbon emissions factor, one can calculate the average carbon intensity of the entire grid mix, known as the average emissions factor (AEF). Although AEFs may misrepresent the carbon emissions corresponding to an intervention (Beuse et al., 2021) and are only available for a retrospective analysis, they are straightforward to obtain. Therefore, AEFs are used here to undertake an analysis to describe the battery carbon emissions in broad terms so far, before wider implications for battery storage on grid decarbonisation are considered in the subsequent sections.

CO_2 impacts based on average emissions factors

In the UK, national and regional AEFs are calculated by National Grid ESO and available from the Carbon Intensity website (**carbonintensity.org.uk**) as total CO_2 emissions per total electricity generated over some time period,

$$\text{AEFs} = \frac{\text{total } CO_2 \text{ emitted from electricity generation}}{\text{total electricity generation}}$$

The AEFs used in this report are shown in Figure 5.1. Here, regional data describes the south England region including Oxford. Since the regional and national data differ, the regional data was used to calculate battery-related carbon emissions. The battery input or output energy for each time interval was multiplied by the corresponding regional carbon intensity factor; i.e., for a given time interval.

Lastly, the emissions at each time interval were summed to obtain cumulative carbon emissions. The battery power and corresponding cumulative carbon emissions for the period between 9 August 2021 and 22 March 2023 are given in Figure 5.2. The low AC-side power readings prior to October 2021 are due to the installation and commissioning. From November 2021 onwards the system is in continuous operation, with moderately higher utilisation during winter months.

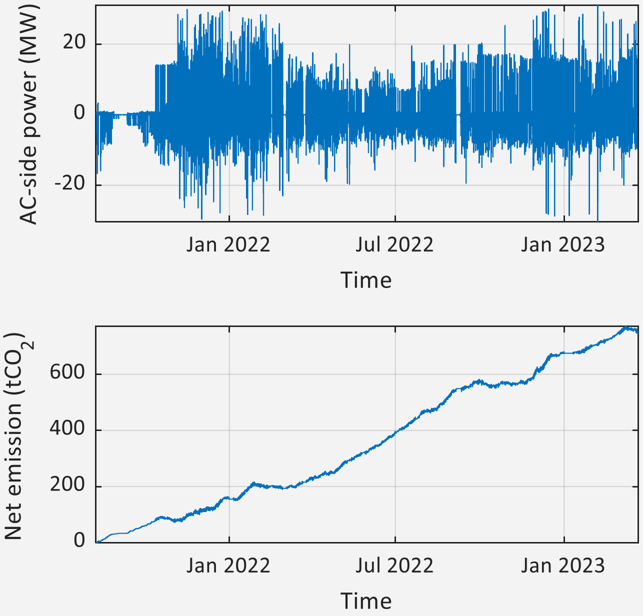

Figure 5.2: Battery power measured at the site meter (positive values denote discharge or power output), and corresponding cumulative net carbon emissions

The operation of the system is governed by merchant decisions at market prices and grid frequency, rather than emission factors.

Figure 5.3 shows how poorly the average emission factor correlates with the charge and discharge patterns.

In this simple initial analysis, the differences in average emission factors between charging and discharging are therefore not sufficient to compensate for the emissions attributable to round-trip losses.

Net-emissions associated with the ESO battery system therefore show a small but steady increase equating to approximately 450 tCO_2/year when using this metric.

As Figure 5.4 shows, periods with high utilization have the highest operational efficiency.

December 2021 and October 2022 saw some of the highest usage, and the net emissions in Figure 5.2 are therefore reduced during those periods.

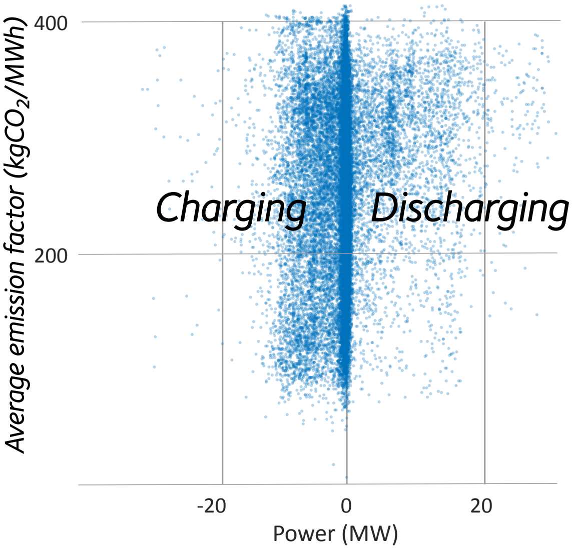

Figure 5.3: There is no correlation between market driven charge and discharge patterns and average emission factors

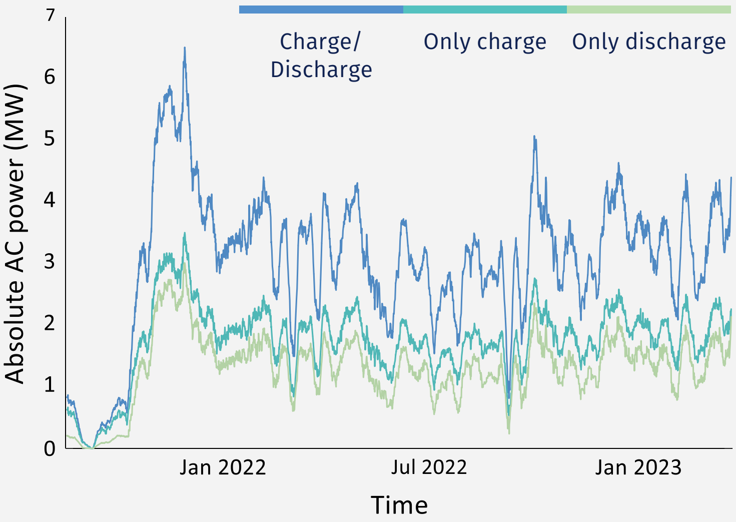

Figure 5.4: Weekly average absolute battery power from 2021 to March 2023 showing its utilisation

CO_2 impact from operating in frequency response markets

Part of the reason for periods of low utilisation is that the Li-ion battery spent much of its time supporting the ancillary services/frequency response markets, which offered the best revenues at the time. As a result, the number of cycles was far lower than originally expected, averaging under 1 cycle a day, compared to the initial expectation of up to 3 cycles (for merchant trading).

While this has positive effects on battery cycle life, it also means that tHe auxiliary loads of the battery, particularly cooling and ventilation, have a much greater impact on the direct energy-related carbon benefits realised.

Operating a battery should, in principle, provide significant carbon savings due to imports often taking place during times of low cost, which are expected to largely correlate with non-peak generation times, when renewables on the grid are generating at surplus. Export would be expected at peak times when energy prices are high, but also when fossil fuel generation is increased to provide the required peak demand. However, there is a level of auxiliary power required to operate the battery (e.g., thermal management) and if the volumes of energy cycled by the battery are low, as is mostly the case when delivering frequency response services, then the carbon savings of importing greener energy to export during carbon intensive peaks is eroded. This has been found to be the case here during periods of grid services operation.

Potential CO_2 savings from avoided spinning reserve

The preceding paragraphs, however, do not tell the full story. There is an alternative and potentially much larger carbon impact associated with the battery operation in ancillary services—specifically, replacing the need for spinning reserve. This effect is not captured by the average emissions factor estimation method and needs to be calculated separately.

Spinning reserve is a type of ancillary service for the power grid that is usually provided by combined cycle gas turbine generators (CCGTs). In this situation, such generators are operated below their full load output to provide headroom for frequency response. This results in a reduced fuel efficiency, which by our calculations, based on real examples, is equivalent to approximately 940 tonnes CO_2/MW/yr for the ESO battery. Displacing a part-loaded CCGT with a battery offering frequency response therefore delivers CO_2 savings. If 20 MW of the battery input/output power operates in the FR and FFR markets, then savings of approximately 18.8 ktCO_2/year can be achieved. When accounting for emissions related to the operation of the battery and round-trip losses, the net saving is 15.8 ktCO_2/year. In practice, the ESO system operated between 70% and 80% of the time in frequency markets, such that this saving is a conservative estimate of the potential carbon impact. The extent to which system operation and markets might be affected in the long term is discussed in the next section.

Figure 5.5 shows how the spinning-reserve related carbon savings from offsetting 20 MW of part-loaded CCGT plant dominate the overall savings of the ESO battery. The difference between net CO_2 savings (♦) and CCGT offset (green line) are the result of emissions attributable to trading under average emission factors, which are positive but small by comparison.

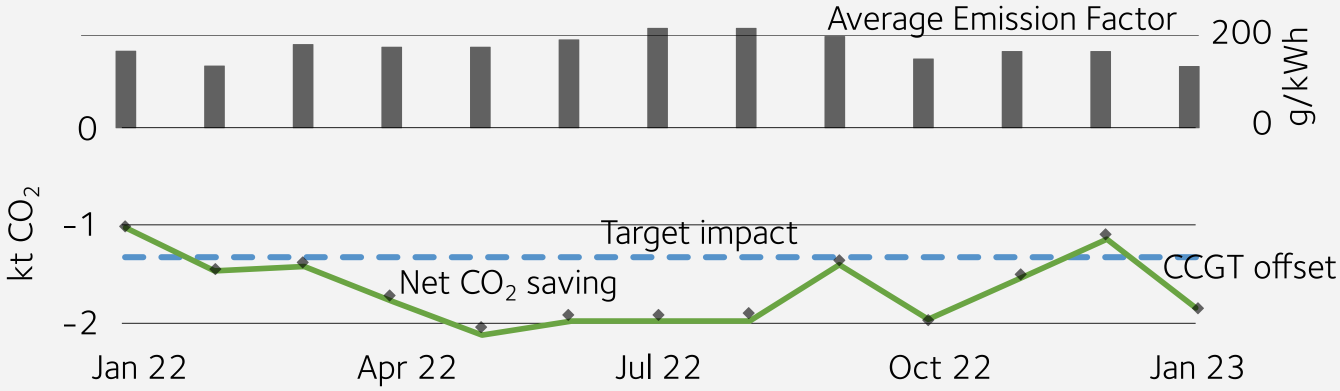

Figure 5.5: Net CO_2 savings (♦) are dominated by CCGT emission offsets (line)

Long term impacts of storage on emission factors

The complexity of estimating the CO_2 savings from storage has been the subject of intense deliberation within the ESO project team and has resulted in the writing of a journal paper and a new, successfully-funded, EPSRC/UKRI project focused exclusively on this topic.

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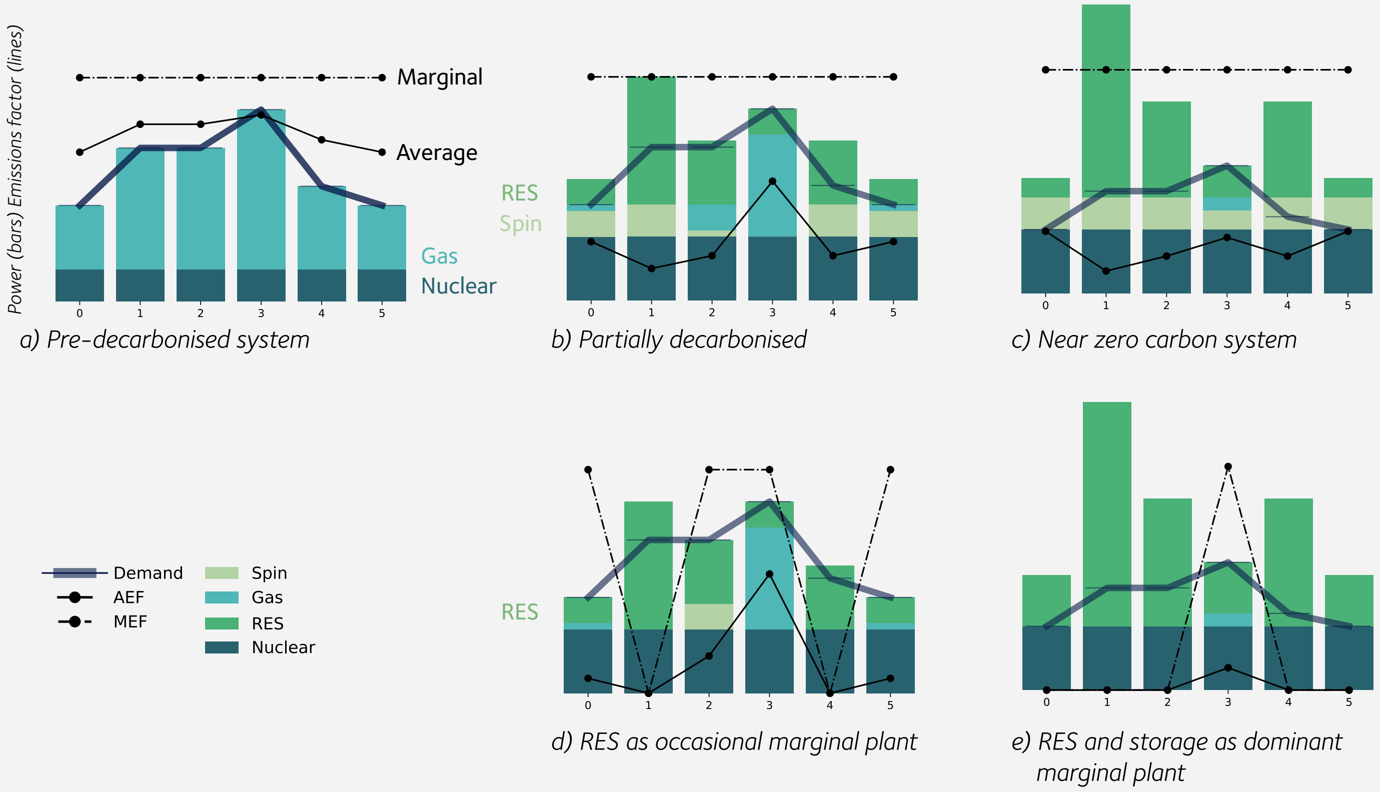
Figure 5.6 gives a cartoon example of the possible changes to average and marginal emissions as a power system is decarbonised. In a fossil fuel dominated system (a) the average emissions (solid line) follow the same shape as overall demand. High demand results in the highest share of fossil-fuelled plant being used and therefore the highest average emissions. The difference between highest and lowest emissions is small, making it more difficult for storage to claim carbon reductions between these periods.

In a partially decarbonised system (b) the variability of average emission factors is greater. At times when renewable output dominates (such as time period 1, average emissions are lowest, such that storage can claim significant carbon reduction when charging during this time, and then discharging later (e.g. period 3) to offset higher emissions.



a) Pre-decarbonised system

b) Partially decarbonised

c) Near zero carbon system

d) RES as occasional marginal plant

e) RES and storage as dominant marginal plant

Figure 5.6: Illustrative example of the effect of decarbonised generation on emission factors ($gCO_2/kWhe$). Spin = spinning reserve, RES = renewable energy sources

However, as the system is further decarbonised (c), and low carbon generators dominate for most of the time, average emission factors become permanently low. This mutes the signal indicating when and where flexibility is needed and makes storage appear to be 'less beneficial' for carbon, despite its potentially crucial role in enabling this system to operate securely.

An alternative means to attribute emissions from interventions in the power grid generation and demand mix is the marginal emissions factor. While the average factor considers all emissions from all sources and divides these by the total output, the marginal factor is only concerned with the marginal plant—the source of the last unit of electricity that was required or avoided because of changes in supply or demand, including the charging or discharging of storage.

In period 1 (b) renewables had to be curtailed, in part to enable sufficient thermal spinning reserve to remain on the system. Had the conventional spinning reserve been replaced with 'part-loaded' renewables and storage (d), these would provide downward flexibility by turning a larger share off, but also upward flexibility thanks to the remaining headroom above the blue demand line. However, there are limits: insufficient renewables expected in period 3 still necessitates conventional spinning reserve or storage to start up that period.

The effects on marginal and average emissions, and thus the savings attributed to storage, are significant. Average emissions are reduced, because less spinning reserve is dispatched. More importantly, the marginal emissions become more meaningful as a signal for the environmental impact of storage and other flexibility options. Load shifts towards periods 1 and 4 become appropriately recognised. These signals can encourage appropriate deployment of storage, and the signals remain valid even in highly decarbonised systems that have a small amount of fossil fuel generation remaining, such as shown in (e).

Short run marginal costs and short run marginal emissions are strongly linked, such that commercially operated flexibility measures are more likely to deliver environmentally beneficial outcomes. In such a future system, some renewables curtailment will become a necessity (Jenkins et al, 2018). It is not economically efficient to avoid all curtailment in a system with high penetration of renewables. Storage has the ability to capture zero-carbon, zero-marginal cost output from renewables that would otherwise have to be curtailed, i.e. wasted. Despite round-trip losses, storage can therefore improve the overall system efficiency and reduce the cost, even when current short-term indicators may suggest a carbon increase.

For strategic investments, short term market signals may not always deliver sufficiently fast or far-sighted outcomes (Gagnon et al., 2022). This is especially true when one reflects on the rapid learning rates for solar, wind and energy storage systems. System models that can explore future tensions in system operation at longer timescales could provide a key complement to inform such decisions and to explore options with respect to counterfactual scenarios.

As a result of the ESO project, the Oxford team has secured additional funding from EPSRC/UKRI to explore in greater depth the carbon impacts of storage and the importance of placing it in the best locations on the national grid in more depth.

Short run marginal costs and short run marginal emissions are strongly linked, such that commercially operated flexibility measures are more likely to deliver environmentally beneficial outcomes.

Lessons learned

This section has given an analysis of battery operational carbon emissions based on average emissions factors, and introduced the need for wider system benefits and longer term decarbonisation strategies to be considered for a better understanding of the system impact of storage in decarbonised power systems.

Battery operation in frequency response markets provides valuable system services, but the carbon attributed to traded volumes is small and may not make up for the emissions attributed to auxillary loads and losses. However, if spinning reserve capacity can be reduced by storage, then there are considerable carbon benefits from not running gas turbines inefficiently.

ESO has resulted in follow-on funding for further research to explore the impact on carbon emissions of temporal and locational aspects of storage on the grid. These will build on the lessons gained from operating batteries in different markets. It will also consider the carbon benefit of optimal siting and operation of storage assets.

When operating in markets where traded volumes are greater, the carbon benefit of storage is also improved.

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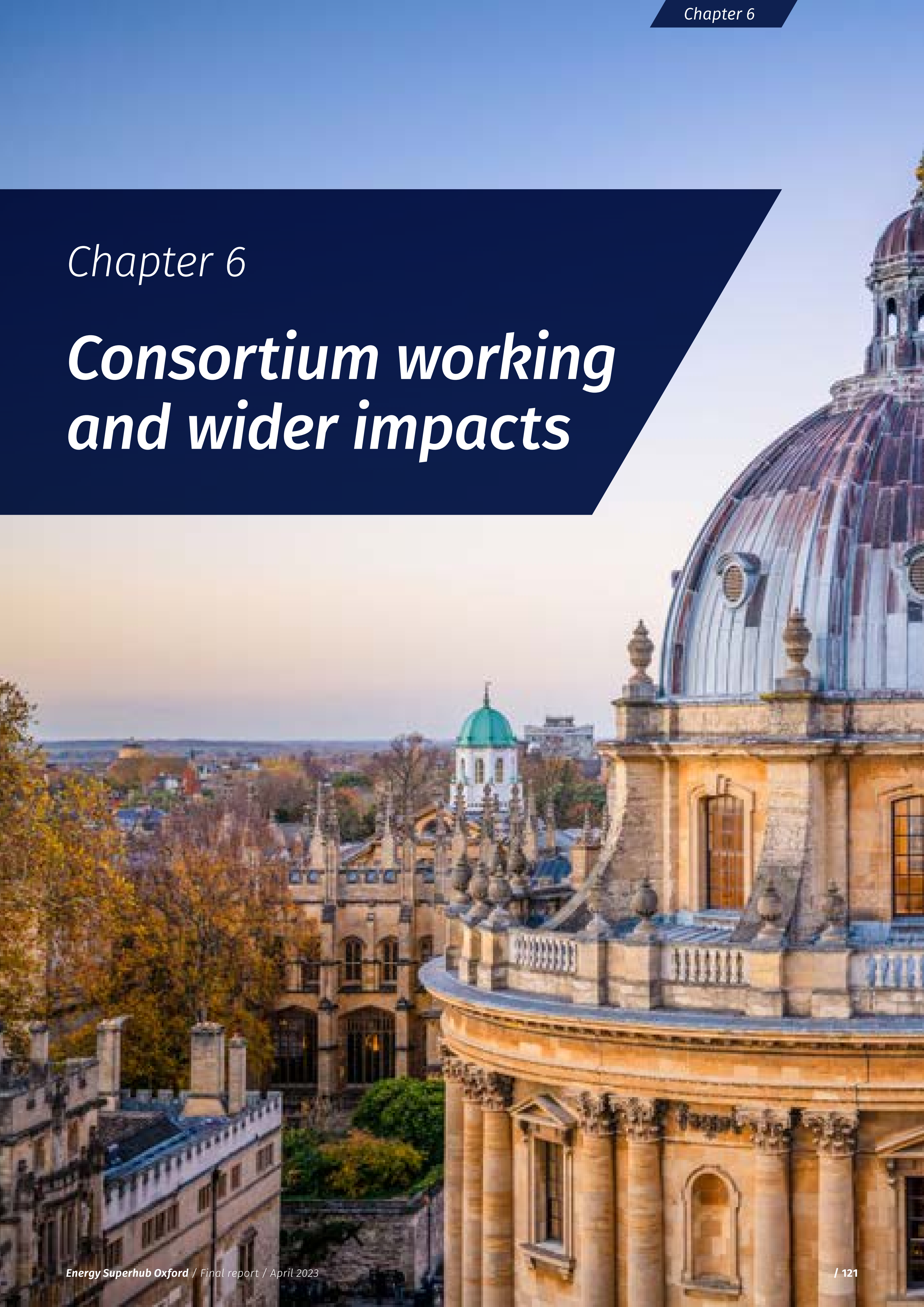

Chapter 6

Consortium working and wider impacts

The ESO consortium has been praised by Innovate UK for overcoming a series of challenges and obstacles. While the previous discussion of the transport and heat work packages outlined several of these, this section adds further examples, and reviews the partners' ability to adapt.

Financial sustainability

At the project outset, there was a significant risk associated with the financial outlooks for the SME partners: Pivot Power, redT and Habitat. The closure of any of these would have delivered a catastrophic blow to ESO. However, by mid-2020, each of their medium-term futures had been secured.

Habitat successfully raised investment; Pivot Power was taken over by EDF; and redT merged with Avalon to create Invinity. One project partner said that these arrangements worked out 'incredibly smoothly' and 'better than we could possibly have hoped'. They attributed part of this success to the profile given to each firm by their involvement in ESO.

Achieving financial stability is a key marker of success for the three SMEs on the project. However, the mergers also led to a loss of agility and flexibility which can be a benefit of being small. Pivot Power, for instance, report that the processes associated with corporate investment, technical and commercial management, have led to cost increases and more complex decision-making and approval processes. However, these have also led to significant improvements in project investment planning, health and safety management and other areas.

There is no doubt, however, that these strategic structural changes have secured the future of the businesses and their ability to deliver on their development pipelines. EDF Renewables (formerly Pivot Power) has now committed investment for seven projects, totalling £240 million. This demonstrates the viability of the transmission connected model, and five of the projects have been directly enabled by ESO.

Similarly, Invinity Energy Systems, following the merger of redT and Avalon, were able to redesign and combine their respective products, creating the third generation VS3 product deployed under this project. This product has gone on to be deployed in the UK and elsewhere. Invinity is now developing its fourth generation product, targeting the cost reduction necessary to compete with other battery storage technologies.

During the project, Habitat energy has also been acquired by Quinbrook, significantly broadening their market horizons for the OTE product.

Kensa also took a strategic investment from Legal and General to support its future investment plans.

Structural changes such as these are a part of any business's strategic development and are to be expected during a multi-year project such as ESO. The fact that all of these have been successfully negotiated and have supported the success of the ESO project should be considered a success for the project.

Formalising collaborative arrangements

During the bid phase, only high-level agreements were put in place between project partners. With minimal experience of working together, a significant initial risk facing the consortium was whether mutually beneficial commercial arrangements could be formalised.

These were subsequently achieved, specifically between EDF Renewables (formerly Pivot Power) and Habitat Energy and Invinity. The EDFR/Habitat Agreement related to Habitat's optimisation of the battery on behalf of EDFR, while the EDFR/Invinity agreement was a formal a contract for purchase and long-term service arrangements for the flow battery itself.

It has proven challenging for Oxford City Council to formalise legal agreements relating to the private wire, charging infrastructure, and data. In overcoming barriers and pushing for progress, several partners highlighted the determination and persistence of the OCC Officer leading their work on ESO. As well as this, one partner pointed out that OCC's pro-environmental political and executive leadership has helped to raise the profile of the project, and decarbonisation efforts more broadly. One learning documented by OCC was the need for more senior council representation on similar projects in future.

The public/private nature of this joint team has been repeatedly highlighted by all partners as a strength. While businesses and local authorities have different approaches to decision making, procurement and project implementation, the collegiate culture in the consortium helped maintain momentum, often in the face of significant obstacles. Examples of effective collaboration include securing planning approvals, land agreements, design and construction planning. As partners seek to replicate their innovations elsewhere, each recognise the importance of local authorities in enabling the effective and efficient deployment of smart, local energy systems.

The hope is that learnings from Oxford will mean that projects can be a success even where local authorities possess less experience and expertise with regards energy innovation. However, there is a need for national coordination to ensure that lessons from ESO and the wider PFER programme are effectively disseminated.

As partners seek to replicate their innovations elsewhere, each recognise the importance of local authorities in enabling the effective and efficient deployment of smart, local energy systems.

Ofgem's review of the Transmission Demand Residual

In November 2019, Ofgem completed its 'Targeted Charging Review', which sought to review the ways in which the costs of operating, maintaining and upgrading the electricity grid are spread across consumers. As part of this review, it concluded that the charges associated with the 'Transmission Demand Residual' (TDR) should be levied on a fixed based for final demand consumers.

The implications of this decision were potentially catastrophic for ESO, putting at risk the economic viability of the hybrid battery and private wire connection. If Ofgem chose a single band solution, the charges (in £/MWh) levied for all users connecting to the transmission network would be highly uneven. As shown in the table (right), a 2- or 4-band solution would distribute costs more fairly, according to demand.

With support from the ESO partners and the local MP, EDF Renewables were proactive in lobbying for a 4-band solution, highlighting the strategic importance of transmission-connected storage for developing smart, local energy systems and meeting net-zero goals. In their CMP343 consultation, Ofgem issued a 'minded-to' decision for the 4-band solution, to be implemented in April 2023. This outcome was highlighted by IUK as a significant success for the consortium. One lesson learned from this process is that innovative projects such as ESO, featuring the first storage asset connected to the transmission grid in the UK, are bound to encounter regulatory barriers, as they push the boundaries of energy system governance. While the CMP343 outcome was favourable for ESO, a similar regulatory decision went against the project, as Ofgem turned down Kensa's application for 'Demonstration Action' funding through the Energy Company Obligation.

£/MWH	BAND	SMALLEST USERS	LARGEST USERS	RANGE
1 band		471	1	470
2 bands	1	248	3	246
	2	18	4	15
4 bands	1	85	4	15
	2	14	5	9
	3	10	6	4
	4	18	4	15

Monitoring and Evaluation

The PFER programme involves several organisations with a monitoring and evaluation remit. In addition to IUK's monthly and quarterly monitoring, and stage-gate processes, EnergyRev is an academic consortium focusing on researching the barriers and opportunities associated with smart, local energy systems, using insights from Demonstrator projects such as ESO.

The Energy Systems Catapult's Energy Revolution Integration Service (ERIS) evaluated the projects against seven criteria, including investability, scalability and replicability; while Ipsos Mori were appointed to evaluate the impact of the PFER programme as a whole.

In the early stages of ESO, confusion was expressed by partners about the respective roles, scope and focus of these organisations. Several evaluators offered assistance to the projects, but partners struggled to see the potential value-added. Consulting with other evaluators, the Oxford University team adapted its objectives in accordance with its expertise and comparatively limited resources, producing a Framework for Assessing Project Impact with six objectives (see Introduction). ESO project partners valued our proactive engagement with EnergyRev, ERIS and Ipsos Mori. In an interview, one consortium member said they'd appreciated how this had reduced the 'calls on our time'.

Having multiple evaluators focusing on an individual project is unusual in energy innovation projects. Whereas under-evaluation is a more common issue, we explored the potential for over-evaluating projects in an **academic conference paper** published in 2020. This highlighted the benefits of multiple evaluators having different perspectives, objectives, audiences, and added scrutiny. However, it also flagged the potential downsides associated with having overlapping remits, overwhelming quantities of data, and consultation fatigue.

ESO has received several awards, including a Special Contribution to Net Zero by the Association for Decentralised Energy, the Innovation Award at the British Renewable Energy Awards, and a special recognition award for Energy Strategy at the EVIES (an EV industry ceremony).

Other PFER evaluators provided positive feedback: this discussion paper led them to review their own practices and scopes of work.

When questioned about the level of scrutiny and performance management exercised by Innovate UK, ESO partners were unanimously positive. They accepted the need for close monitoring and being held to scheduled milestones and deliverables, given the significant public investment made. Several partners highlighted the understanding and flexibility of the project monitoring officers (MOs) with respect to scope changes.

Oxford City Council - the difference that ESO has made

In 2019, Oxford declared a Climate Emergency and set a goal to become a net zero carbon city by 2040, and a net zero carbon council by 2030. Energy Superhub Oxford (ESO) has been fundamental in developing and supporting this journey. Key headline items include electrification of 25% of the council's fleet and of 25% of the city's Hackney cabs, and the creation of the largest and most powerful EV charging hub in the UK.

What has been just as valuable is the learning and upskilling in the Council in the following key areas:

- Becoming more agile in supporting the benefits of public and private sector partnership to achieve scale and innovation deliverables at the speed needed to achieve net zero goals.
- Increased knowledge, confidence and support from Senior Leadership to formalise its role and adopt a strategy to mandate the Council's role in the provision of EV Infrastructure (EVI) for the city to achieve net zero, resulting in EVI delivery moving to business as usual, with targeted roll out programmes and increased council resource to support the programme.
- Understanding the importance of data (for example around fleet usage) which has resulted in the council financing systems that collect and collate the data needed to inform decarbonisation action.

Being the first to do something is not easy, it requires creation of a 'new pathway' forward, the ability to negotiate obstacles, alongside dedication and resilience. The positive good will, collaboration and team work from all those involved, including ESO partners, internal council teams, external contractors and partners; has produced this superb outcome, showing what can be achieved by joint public and private sector partnership.

Oxford has been and will continue to support other local authorities who are interested in undertaking a similar journey, whilst continuing to be a testbed for innovation and a model for cities around the world.

Skills and capabilities

One theme which emerged from interviews with partners was how different stages in the lifecycle of projects such as ESO require different skillsets from the staff involved.

For instance, the ability to pull together such a diverse consortium for the bid required unique influencing skills, whereas the inception and team-building phases require patient diplomacy. In its final stages staff shifted mode, into data analysis and dissemination. In interviews with consortium partners, several respondents spoke of the positive 'chemistry' in ESO, which may be partly a result of having faced and overcome significant adversity together.

The EnergyRev consortium has conducted in-depth research on the **skills needed for successful 'smart local energy systems'**, drawing on interviews and data from ESO, while a separate report for Innovate UK authored by Regen identified **skills and policy gaps**.

Key Achievements: consortium working

- Involvement in ESO helped to secure the financial security of the three SME partners
- A range of new products and business models were tested and advanced
  - Transmission connected batteries with private wire (EDF Renewables)
  - VS3 modular vanadium flow battery (Invinity)
  - Development of Optimisation and Trading Engine for transmission connected services (Habitat)
  - Smart Heat Pump controls and Integrated heat/pump/heat battery (Kensa)
- Oxford City Council have gained expertise around Fleet electrification, leading to additional roles and closer executive team working
- Demonstration of successful public/private collaboration

Summary of lessons learned: consortium working

- Involvement in ESO helped to secure the financial security of the three SME partners.
- Political and executive support for local authority staff is essential, and engagement with senior leaders should begin at project outset.
- Although there have been some significant scope changes, partners have worked together closely and efficiently.
- The ESO battery is the first transmission-connected storage asset in the UK. Its financial viability depended critically on Ofgem's review of the Transmission Demand Residual.
- The ESO consortium effectively lobbied for a 4-band solution.
- The skills and capacities needed for different stages of projects such as ESO vary widely. The ESO team have adapted well to different phases.
- Re-use of legal & commercial documentation will prevent "re-inventing the wheel" in future projects.
- Partners were satisfied with project governance arrangements, including monitoring, scrutiny and paperwork requirements.

Chapter 7

Conclusion

Energy Superhub Oxford has delivered a range of innovations, spanning power, heat, transport and storage. It has helped to demonstrate and accelerate the smart, sustainable energy transition at a local level, and many of the activities initiated by Energy Superhub Oxford will continue to grow beyond the timescale of the project.

ESO has faced a series of challenges and setbacks which have been described in the chapters above. Most notably, COVID-19 led to temporary pauses across work packages and extended disruptions to the procurement of essential equipment, goods and services. With the help of a funded extension, the consortium mitigated the effects of the pandemic with a range of creative solutions.

The UK energy market has faced unprecedented turmoil, with a price crisis precipitating the need for government support for all households and many non-domestic bill payers. This severely impacted ESO's plan for dynamic heating, and substantially changed the operating model for the hybrid battery.

ESO has also faced challenges associated with Brexit and policy reform with respect to power and storage markets, and renewable heat.

Despite these serious disruptions, ESO has met many of its original objectives. The 48 MW lithium-ion battery is operational and providing a range of services to the national electricity grid. The 6.9 km private wire is installed and providing high-powered charging for 42 charge-points in Redbridge Superhub. Ground-source heat pumps equipped with smart controls have been deployed and tested in social housing. And uptake of ULEV taxis has exceeded even the most optimistic estimates.

?

This conclusion focuses on addressing two overarching questions:

1

Has ESO demonstrated the value of a smart local energy system?

2

What lessons can be learned from ESO to replicate its successes elsewhere?

Has ESO demonstrated the value of a smart local energy system?

In this section we look separately at each of these words – smart, local and system, in reverse order.

Is ESO an integrated system?

In its call for PFER Demonstration proposals, Innovate-UK specified the need for integrated, multi-vector projects, embedded in a local area. Here we consider how this 'integrated' aspect of the brief was met by ESO.

The ESO proposal outlined two key ways in which integration would be achieved.

Firstly, the connection to the National Grid transmission network was central to multi-vector integration. Despite major concerns resulting from Ofgem's Targeted Charging Review, the 60 MW connection was secured. This is the source of power for the hybrid battery, deployed at the Cowley sub-station, as well as for the private wire which was successfully constructed around the edge of Oxford, providing high-voltage power for the EV Superhub and Oxford Bus Company. ESO has clearly demonstrated the effective integration of power, storage and transport services, deployed at a local level. While each of these activities are led by different actors, consortium members supported one-another through the installation process. Moreover, by securing £200m investment for similar projects elsewhere in the UK, EDF-Renewables (previously Pivot Power) have demonstrated the viability of this smart-local energy system elsewhere.

Secondly, an Optimisation and Trading Engine (OTE) would be developed by Habitat, operating across work packages. At the project conclusion, the OTE is successfully operating the grid-connected lithium-Ion battery, and its financial performance has far exceeded expectations. However, technical issues have meant that the operation of the lithium-ion and flow batteries in tandem has not yet been proven.

Further, at an early stage it was decided that the OTE would not be the correct tool for optimising EV chargers and heat pumps. Habitat have instead provided a simulation for the optimisation of OCC EV chargers, and Kensa chose to work with a specialist heat software developer to optimise its heat pumps (later developing this capability in-house). The heat activities proceeded without practical integration with other elements of the project. Finally, both Pivot Power and OCC initially had ambitions of operating EV charging points themselves. As the project evolved, and Pivot merged with EDF and OCC investigated the practicalities associated, a strategic decision was made to procure the services of existing charge-point providers.

Is ESO local?

While the infrastructure and technologies deployed by ESO are geographically concentrated in and around the city of Oxford, its impact spans geographical scales: from national energy markets, to EV chargers for drivers from across the region, to electric taxis across the city, and low carbon heating in one Oxford suburb.

The transmission-connected battery operates in national power markets, helping to maintain grid frequency and responding to intermittent sources of generation. Yet it has brought local benefits too. The business case for securing a 60 MW connection at the Cowley sub-station was built around the dual purposes of storage and EV charging, and the 10 MW dedicated to the private wire was enabled by the co-installation of the hybrid battery.

The private wire has significant local benefit. At project inception, constraints on the local distribution grid had been hindering the installation of new grid connections for technologies such as rooftop solar and EV chargers, and was said to be a barrier to introducing electric buses into the city. The private wire helps to overcome these constraints without the need for investment in upgrading sub-stations. Initially, the only use case included in the scope of the project was for EV chargers at the Redbridge Superhub, but later the route was extended to provide the Oxford Bus Company with a 6 MW connection. This will enable the electrification of buses in Oxford and help reduce air pollution in the city. In future, additional supply-points are expected to be installed, and potential customers include Stagecoach and logistics companies.

Our research with Superhub users has highlighted its impact on a regional scale, with over 55% of users travelling from outside Oxfordshire. The Superhub supports EV use on the major road network, and its rapid charging capabilities were highly valued by users.

Support for the electrification of ODS vehicles and Hackney taxis have a strong local character. Substantial consideration was given to which of ODS vehicles would be best suited for electrification, and this includes the location of individual drivers' homes as well as analysis of typical routes and routines. Oxford taxi drivers were also consulted throughout the project, and the reallocation of ESO funds towards the provision of a £5k grant was in response to local need. This proved to be influential in boosting the speed of uptake of electric taxis, which has exceeded all expectations.

Lastly, heat pump installations have brought local benefits by delivering energy savings for social housing tenants. They have also demonstrated the viability of ground arrays even in an area with relatively unfavourable geology. But the principal aim of the heat work package has been to test and demonstrate the potential for dynamic, price-responsive heating in the domestic setting. This has national and international implications, and while the project has not delivered definitive conclusions, it has helped advance this strategic goal.

> *Heat pump installations have brought local benefits by delivering energy savings for social housing tenants.*

Is ESO smart?

The **EnergyRev research consortium defined 'smartness'** as involving the use of 1) information and communication technologies, 2) automation and self-regulation, 3) machine learning, and 4) decision-making.

ESO's hybrid battery epitomises smartness, as the optimisation and trading engine incorporates machine learning to make micro-decisions about battery operation as it partakes in power markets.

The algorithms used to optimise heat pumps for time-of-use price signals have also been developed using machine-learning, and use mobile phone networks to enable remote operation.

Other elements of the project have faced barriers to the full implementation of 'smartness', as envisaged at the outset. This includes the optimisation of ODS EV chargers, which has instead been simulated by Habitat, and shown to have potential for cost and carbon savings. The uptake of advanced telematics equipment and analysis by taxi drivers was also lower than expected, although the lack of this intelligence appeared not to dampen interest in ultra-low emission vehicles.

ESO has been fully smart where this is integral to the success of the innovation, primarily operation of the battery. Other elements of the project have succeeded without relying on all the anticipated smart elements, e.g. take up of electric taxis. Some elements of smartness trialled in ESO require further development before they are ready for commercial roll-out or user acceptance.

In summary

The concept of a smart, local energy system is not rigid. Compared with some **other projects** funded by the PFER programme, the version of a SLES demonstrated by ESO involves larger investments in infrastructure and large-scale technology. While it has exploited the synergies involved with the co-deployment of storage, power and transport innovations, its renewable heat activities were less well integrated. Some activities are more locally oriented than others, and involve 'smartness' in different ways.

Given the serious challenges faced by ESO, the project has demonstrated that many elements of smart, local energy systems can be robust to a changing economic and policy landscape, and deliver value to a range of users and stakeholders.

What lessons can be learned from ESO to replicate its successes elsewhere?

Battery

ESO has delivered the UK's first transmission-connected battery, and has paved the way for similar installations elsewhere. ESO overcame a major regulatory barrier and has proven its ability to operate profitably across markets. Replication is already underway, and EDF has plans for 40 installations across the UK.

Private wire and Superhub

Deployed alongside transmission-connected batteries, ESO has demonstrated the benefits of delivering high-powered EV charging in the city of Oxford. This model is being replicated in Coventry and Birmingham, and is suitable for the outskirts of many UK cities, especially where local grid constraints hinder the roll out of solar, EV chargers and heat pumps.

ODS fleet electrification

Local authorities throughout the UK are developing plans to electrify their vehicle fleets. ESO has demonstrated the viability of larger vehicle types such as the e-RCV, proving the benefits for urban areas in terms of particulate emissions and noise pollution. The project has also deployed EV chargers in drivers' homes: a novel solution for a flexible workforce. OCC has benefitted from Innovate UK funding to be an early adopter amongst local authorities. As costs come down, and availability of larger vehicle types increase, this project has helped to demonstrate the benefits of electrification. Modelling of flexible charging has shown its potential for cost savings, but this has not demonstrated through the project.

Taxi electrification

The taxi trade varies from city to city in terms of size, profitability, and the socio-demographic makeup of drivers. Much of the success of ESO's work on electrifying the fleet of Hackney cabs in Oxford can be attributed to the £5,000 grant offered to drivers, enabled by Innovate UK funding, and this limits the replicability of Oxford's success in other urban areas. However, other city councils will benefit from lessons learned by OCC, in developing effective communications with the trade, and its co-deployment of incentives (try before you buy, grant offer) alongside disincentives (zero emissions zone).

Flexible heat pumps

The use of a shared ground loop array to supply clean heat solutions to groups of social houses is a well-proven solution, with potential for replication across the UK. ESO has demonstrated that this can be successful even in areas with non-optimal geology. It has also demonstrated the technical viability of smart-controlled heat pumps. Trials have identified the conditions for user acceptance of flexible heating, and helped to scope areas for further research and development. ESO has shown that smart-controls can be an attractive proposition for social housing providers given the potential for savings on running-costs. However, for wider deployment in new housing, more work is needed to convince developers of the benefits which would accrue to home-owners. Lastly, the successful trial of prototype heat-pump with battery systems in Sonning Common has convinced Kensa of its potential for scalability.

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