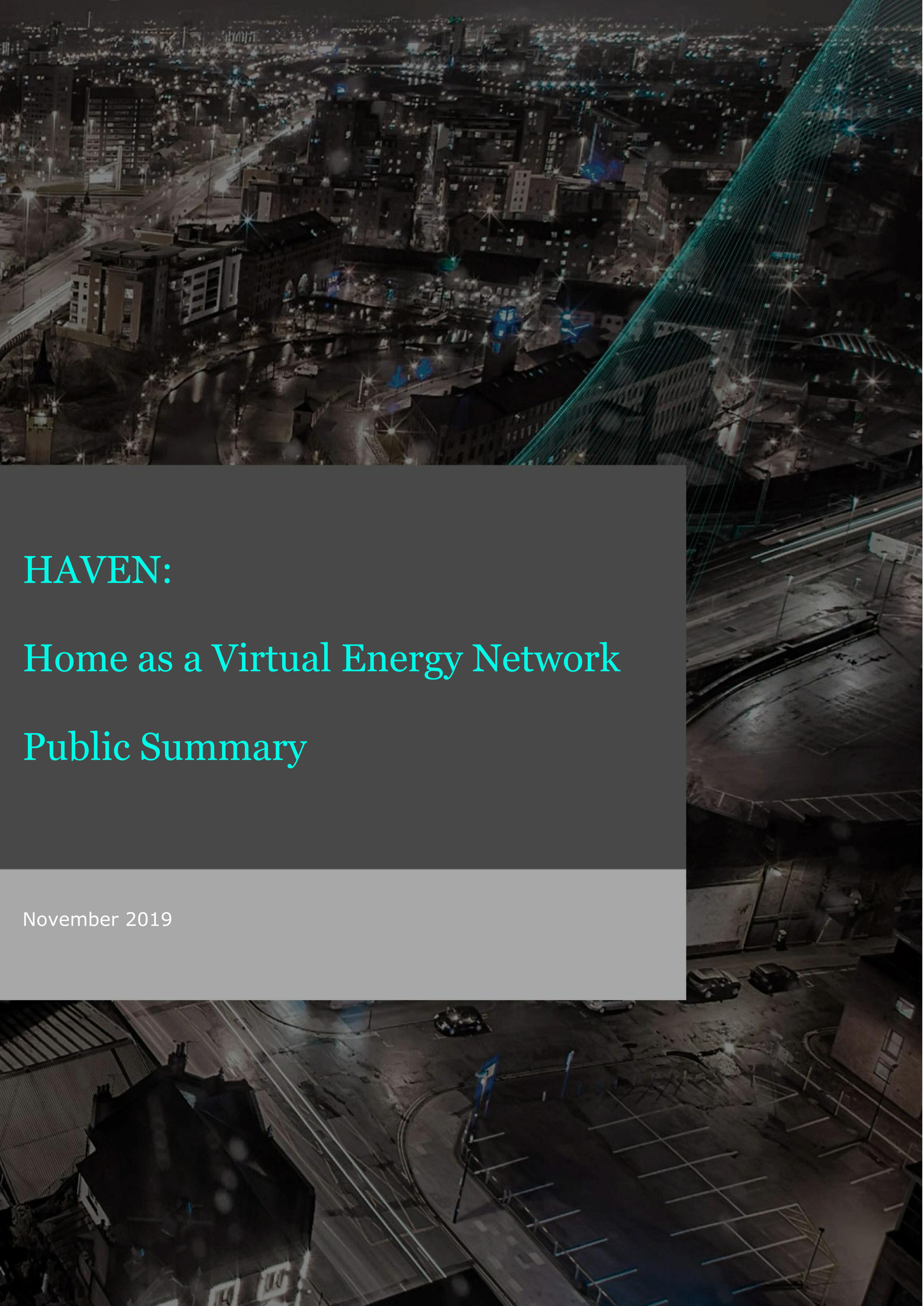

HAVEN:

Home as a Virtual Energy Network

Public Summary

November 2019

Executive Summary

The HAVEN (***Home as A Virtual Energy Network***) feasibility study examined the value that vehicle-to-grid (V2G) and vehicle-to-home (V2H) enabled EVs could provide to electricity suppliers and consumers within the context of a domestic home energy network of storage and generation assets.

A dual approach was taken consisting of in-depth modelling alongside real-world testing of asset deployment. Independent modelling was undertaken by **Upside Energy** and **Good Energy** in order to explore a range of revenue streams that could be captured through optimal deployment of domestic storage assets.

The modelling undertaken by Upside Energy revealed that **a supplier optimising** for day-ahead (DA) market electricity prices and use-of-system revenues (DUoS, TNUoS) could capture an additional revenue of **~£100** through adding a V2G-enabled electric vehicle (EV) to a home energy network, compared to a charged-when-plugged-in base case. The total additional revenue available from optimising an energy network consisting of: *home battery, smart hot water tank, PV system and V2G-enabled EV* was **~£500**. The size of these revenues was most sensitive to the specific combination of assets and the size of the home battery. The presence and sizing of the PV array had very little effect on supplier revenues compared to the baseline.

From a consumer perspective, a consumer operating on a flat price profile wishing to maximise self-consumption of PV could expect an additional revenue of **~£70** through adding a V2G-enabled EV - providing other energy storage assets (e.g. a home battery) are present to allow charge shifting between assets. A V2G-enabled EV used in isolation offers very few opportunities for increasing self-consumption of PV since it is generally absent during times of peak PV generation. Consumers operating the full energy network could expect total revenue of **~£300** through increased self-consumption of PV. From the consumer perspective, these revenues are most sensitive to the specific combination of assets and the size of the PV array. The revenues are relatively insensitive to the home battery size when comparing the Tesla Powerwall 1 and 2 due to their large capacities. From both a consumer and supplier perspective, modest increases in relative revenue are available with increasing load and when combining dwellings into a community where energy can be shared across dwellings.

Modelling undertaken by Good Energy considered revenues available to a consumer by optimising in V2H mode against a day-night Time of Use (ToU) price profile, as well as additional revenues available from optimising in V2G mode to capture Dynamic Firm Frequency Response (DFFR) and Balancing Mechanism (BM) revenues. The results revealed that a V2H-enabled EV could capture an additional **~£30-£100** through optimising against the ToU price profile, depending on the asset combination, compared to a base case where a smart charger is used. When including BM and DFFR revenues in V2G mode, total revenues of **~£100-£150** could be captured, depending on the asset combination.

Ground-truthing of the models in a real-world testing facility revealed that assets respond in non-uniform ways when combined in a domestic energy system, and at present, the installed control algorithms do not lend themselves to coordinated, cross-asset control. Hence, realisation of the revenues calculated in the modelling work will require further developments in the coordination and control of multiple assets linked in an energy network.

Overall, the results reveal that while significant revenues are available from coordinated control of domestic storage assets, additional revenues available from a V2G/V2H-enabled EV are modest as despite its large energy capacity, the EV is often absent from the home. This makes the investment case challenging for V2G/V2H-enabled chargers until hardware costs are reduced. In the meantime, a portion of these revenues may be better accessed through modulation of EV charging times.

Contents

1. Background: Project Summary

With a projected 34 million electric vehicles (EVs) expected on UK roads by 2040[1], it is clear that significant changes to the electricity sector are on the horizon, both in terms of demand, and the provision of flexibility. As well as increasing demand, EV batteries can provide significant flexibility to the grid and hence value to suppliers and consumers. However, this value must be considered in the context of consumers' wider lifestyle and other storage and generation assets.

The aim of this feasibility study was to examine the value that vehicle-to-grid (V2G) and vehicle-to-home (V2H) enabled EVs could provide to electricity suppliers and consumers within the context of other energy storage systems (e.g. home batteries, PV arrays, smart hot water tanks), in a domestic setting under a range of usage scenarios. The study takes a dual approach of in-depth modelling of different combinations of storage and generation assets, alongside real-world testing of asset deployment in a testing facility designed to emulate a typical domestic setting.

The benefit of this dual approach is that it provides an estimate of the theoretical value available from different combinations of assets alongside an appraisal of how realistic it is to capture this value given current, commercially available assets and control algorithms.

The modelling was completed by project partners Upside Energy and Good Energy, and the modelling approach and assumptions made were developed independently. The benefits of this approach were to remove (or at least identify) bias that may come from choice of input data, assumptions or modelling approaches, and to allow comparison between independent models.

Revenue streams for the Upside Energy modelling were based on day-ahead (DA) electricity market arbitrage and use-of-system (UoS) prices at the distribution network level (DUoS) and transmission network level (TNUoS). The electricity market is undergoing a period of transformation, and as such, revenue streams are in a state of flux. For example, we have recently seen the extrinsic value of Dynamic Firm Frequency Response (DFFR) declining as the market becomes saturated alongside increasing interest in revenues from the Balancing Mechanism and Capacity Market[2]. Hence Upside Energy decided to focus on DA and UoS

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[1] National Grid, Future Energy Scenarios, 2018. Available from: http://fes.nationalgrid.com/media/1363/fes-interactive-version-final.pdf

[2] Aurora Energy Research, GB distributed and flexible energy market outlook, May 2019.

revenues to provide a useful baseline for which reliable historical price data were available with the caveat that revenue streams will continue to evolve going forward.

Good Energy's focus was on the economic benefit to households when deploying V2H and V2G technology in conjunction with solar PV arrays, domestic battery, and a Profile 2 Time of Use (TOU) tariff where the price per kWh is different between day and night-time usage. Revenue streams based around TOU, DFFR, and Balancing Mechanism (BM) formed the core of their analysis. Given their customer focus, Good Energy chose these revenue streams rather than energy arbitrage to avoid the operational and consumer challenges associated with passing wholesale prices through to end consumers. In relation to TOU, the Profile 2 tariff was selected as the TOU tariff of choice as it is possible for utilities under the smart meter rollout to switch customers seamlessly from a Profile 1 tariff to a Profile 2 tariff without having major implications on the trading desk.

The Profile 1 tariff is the most common tariff in the UK where the price per kWh is the same regardless of the time of the day. Lastly, the current DFFR market is saturated with suppressed market prices while BM requires participating assets to be 50 MW plus. However, there is value in exploring these market avenues due to the ongoing market changes where the threshold for BM will be dropped in 2020 from 50 MW to 1 MW as part of the Trans European Reserve Exchange (TERRE) project; whereas the Firm Frequency Response will experience a significant change as of 2021 with the launch of the Manually Activated Reserves Initiative-Manually-activated Frequency Restoration Reserve (MARI-mFFR) project. This initiative will create a wider real-time fast response market which should benefit flexible assets in the UK that are currently competing in an increasingly saturated DFFR market.

The different revenue streams that were chosen by the two modelling approaches:, DA, DUoS and TNUoS and BM, DFFR and a TOU domestic tariff, while not allowing for direct comparison of the result sets, are entirely complementary and together cover the whole range of likely revenue streams, broadening the scope of the study.

2. Research Questions & Testing Approach

The HAVEN project consortium identified the following research questions:

- What is the financial benefit of optimising a V2G-enabled EV alongside different

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combinations of assets, (e.g. benefit of an EV compared to a home battery, benefit of orchestrating control of multiple assets, etc.)?

- How does value change when adding storage assets to PV and non-PV households from both a supplier and consumer perspective?
- Which revenue streams provide the most value and how does this depend on the asset combination (e.g. are some assets better at capturing UoS revenue)?
- Under which asset combination-configurations does a V2G enabled EV add the most value compared to configurations with a unidirectional charging EV.
- How can assets be used to maximise independence from the grid and does the amount of energy consumption and the way the energy is consumed have an impact on the financial benefits?
- How does value change when we consider a community rather than a single dwelling?
- How do revenues change when considered from a supplier and consumer perspective?

In addition, the project considered different usage scenarios to explore how these impacted the above research questions:

- High and low household electricity usage, high and low EV usage.
- Space and water heating provided by a heat pump.
- Variable battery and PV array sizes.

The research questions were tackled by creating robust models of a variety of home energy storage configurations and using them to determine the value available from each configuration.

Modelling results were then ground-truthed through testing asset deployment in the unique testing facility of the Salford Energy House (SEH). These tests were aimed at understanding how asset control might function in a real-world scenario, how a V2G enabled EV interacts with other storage and generation assets, the characteristics of V2G operation and battery charge and discharge, and the practicality of shifting charge between assets.

The Salford Energy House is a unique test facility based at the University of Salford. The use of the SEH was proposed as an effective way of establishing a rapid demonstrator to explore the challenges of V2G, as well as the wider issues of control and interoperability of energy storage, production and consumption within a domestic setting. The assumptions within the modelling could thus be directly investigated at a single dwelling level to allow for robust analysis of issues and risks.

The main benefits of the use of the SEH for the HAVEN project were as follows:

- The SEH is an existing property with the energy storage, production and consumption assets in place, allowing for rapid deployment of demonstration experiments.
- The property is within controlled conditions allowing for repeatability.
- The property is under control within a laboratory environment, which means that changes can be rapidly made, compressing the time required to set up and undertake different experiments.
- The property is highly monitored and provides a high level of detail on the systems, internal environment and energy flows using existing infrastructure.
- The property is highly characterised, with a measured performance of the building fabric.
- This is reflected in a calibrated model, which can be used to establish long term performance.

The following assets were sourced and installed in the SEH specifically for the HAVEN project:

- Tesla Powerwall 2 (13.5 kWh)
- Honda Power Manager V2G enabled EV charger
- Nissan Leaf 40 kWh (loaned from E-Car Club)
- Mixergy hot water tank (180 ltr)
- Nibe Air Source Heat Pump (VMM 320)

3. Data and Assumptions

EV Usage Profiles

EV usage profiles were sourced from a publicly available database created through the My Electric Avenue (MEA) field trial[3] - only profiles from the MEA control group were considered in the HAVEN study.

Profiles corresponding to a driver making a regular weekday morning trip (e.g. commuting or school run) were extracted from the database to be representative of low, medium and high usage following the approach below:

- Profiles with a total annual trip distance close to the 25th, 50th and 75th percentiles (low, medium and high usage), with respect to the whole data set, were extracted.
- The above profiles were refined to include only those with a trip between 7am and 9am on >90% of weekdays.
- Finally, three profiles were selected from the above, based on data coverage, to represent low, medium and high usage over a 12-month period spanning August 2014 to July 2015

Table 1: Summary of EV profiles

Profile	Total Annual Distance (km)	Total Annual Energy Use (kWh)
Low	10,210	1,840
Medium	13,780	2,160
High	18,630	2,890

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[3] http://myelectricavenue.info/ Accessed: May 2019

The raw data included a record of times when the vehicle was plugged in and charging, and when it was driving, in addition to the total energy used for each trip. Since the vehicle may be plugged in for longer than the recorded charging time (e.g. after full charge is reached), the plugged-in time was considered to span the period from when charging was initiated until the next recorded trip. A further assumption was made that the EV was plugged in between midnight and the time of the first trip the following day so as to be available for import/export overnight. In addition, all charging was considered to occur at home. These assumptions were based on the reasoning that for a scenario where a user was trying to maximise value from their vehicle they would leave it plugged in whenever it was at home.

Good Energy's EV profile assumes an EV owner working from 9am to 5pm, where the car is available for charging at home from 6pm until 7am. Hence, the EV is unavailable during the day and any monetization opportunities are limited to the period between 6pm and 7am. The roundtrip energy consumption of the car is assumed to be 8 kWh per day which reflects high utilisation and may not be representative of the average energy consumption of EV's on the road

Electricity and Hot Water Demand Profiles

Average electricity consumption profiles were derived from the National Energy Efficiency Data Framework[4] which describes the home energy usage for c. 50,000 households.

Three usage profiles were derived from the data (low, medium, high), chosen to represent the 25th, 50th and 75th percentiles respectively. These profiles were based on dwellings without electric space heating. The CREST[5] model was then used to identify representative usage profiles at a half-hourly resolution, and these were scaled to match the annual consumption target. Hot water consumption profiles were extracted from the same CREST profiles as the electricity consumption without further scaling.

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[4] https://www.gov.uk/government/collections/national-energy-efficiency-data-need-framework Accessed: May 2019

[5] Eoghan McKenna and Murray Thomson. 2016. High-resolution stochastic integrated thermal-electrical domestic demand model. Applied Energy, 165:445. http://dx.doi.org/10.1016/j.apenergy.2015.12.089

Table 2: CREST load profiles (net of hot water consumption) used in the modelling

Profile	Consumption (kWh/yr)	Dwelling Occupants
Low	2000	2
Medium	3100	2
High	4550	5

For Good Energy's modelling, they aggregated data of 19 households was used to model revenue streams from DFFR and BM, the data was procured from Good Energy's existing database and reflects the annual consumption of households in Central Scotland.

Heat Pump Load Profile

A representative heat pump (HP) electricity load profile was obtained from the Low Carbon London (LCL) Heat Pump Power Quality Monitoring Trials[6] using the following procedure:

- To align the heating profile with the CREST electricity demand, the total annual heating and hot water thermal load was extracted from the CREST Medium load profile and converted to an equivalent HP electricity load using a system performance factor of 2.458. This resulted in an equivalent HP electricity load of 2400 kWh/yr.
- The HP load profile with the closest annual load to 2400 kWh/yr was extracted from the LCL database and a further scaling factor of 0.64 was applied to match the annual load exactly to that extracted from the CREST profile.

PV Data

Synthetic PV generation data was obtained from NREL SAM[7] based on 20-year average weather data for the UK. The data was at an hourly resolution and so a linear interpolation was used to generate half hourly data to align with the settlement periods. The original

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[6] https://data.london.gov.uk/dataset/low-carbon-london-heat-pump-load-profiles Accessed: May 2019.

[7] Blair et al. (2015), System Advisor Model, SAM 2014.1.14: General Description, NREL/TP-6A20-61019 Available from: https://sam.nrel.gov/

data set was for a 10 kWp PV array and so a scaling factor was applied to the 2 and 4 kWp arrays considered in this study.

Good Energy obtained the annual generation half hourly data for two PV systems, 2 kW each, to support the appraisal of synergies between solar PV arrays and V2H/V2G technologies. The geographical location of the solar systems was a key factor in the selection of the data. The intention was to capture extremes in system performance to enrich the insights into the depth of collaboration between solar PV arrays and V2H/V2G technologies. As such, the collected data was from a system in the Cornish South Coast and another system in the North of Scotland. By studying these two distinctive locations in the UK, a range of potential financial benefits that may occur for households has been captured.

Pricing Data

For the supplier-focused modelling, market and use-of-system prices for 2018 were used as this was the most recent year available. Day-ahead (DA) market prices were obtained from EPEX SPOT[8]. DUoS rates for North West England (Electricity North West)[9], as shown in Table 3, were applied as these were found to be broadly representative of the UK. TNUoS rates[10] for Zone 4 (North West) of £43.81/kW (HH Demand Tariff) and £28.86/kW (Embedded Export Tariff), were also applied for the reason above.

Table 3:DUoS rates for North West England, 2018

	Red	Yellow	Green
LV Import (p/kWh)	6.623	1.341	0.604
LV Export (p/kWh)	6.450	0.944	0.121

For the consumer-focused modelling, average electricity retail prices were taken from Eurostat[11], representative of 2018. This resulted in a price of 0.1839 EUR/kWh. As of June

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[8] https://www.epexspot.com/en/ Accessed: May 2019

[9] https://www.enwl.co.uk/about-us/regulatory-information/use-of-system-charges Accessed: May 2019

[10] National Grid, 2018. Final TNUoS Tariffs for 2018/2019. Available from: https://www.nationalgrid.com/sites/default/files/documents/Final%20TNUoS%20Tariffs%20for%202018-19%20-%20Report.pdf

[11] https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers Accessed: May 2019

2019, this equated to a flat rate of 0.1575 GPB/kWh

The Feed-in-Tariff (FiT) generation and export rates have been taken from Ofgem, where the FiT Generation rate reflects the average price between April 2018 and March 2019 for systems with a maximum capacity of 4 kW and middle energy efficiency requirement rating. As for the FiT Export rate, the selected rate reflects systems installed on or after 1st of August 2012.

Table 4: FiT prices

	FiT Generation Rate	FiT Export Rate
p/kWh	3.64	5.38

Good Energy's Profile 2 electricity tariff was used in the analysis, where the night unit rate was assumed to be applicable from midnight to 7am.

Table 5: Tariff details

Night Day Rate	Day Unit Rate	Standing Charge
10.17 p/kWh	16.73 p/kWh	29.04 p/day

The DFFR intraday windows are separated into 4-hourly Electricity Forward Agreement (EFA) blocks beginning at 23:00. In the context of the research study, it is assumed that an EV will participate in the block from 7pm till 11pm and from 11pm till 3am. The remaining hours from 3am till 7am, the car is assumed to be charging for commuting purposes. The DFFR values for day and night were taken from National Grid and are summarised in table 6 below. As for the throughput of the battery which reflects the amount of energy exported and imported during DFFR, the calculated value is 0.053 kWh per hour and is based on data provided by Good Energy supply chain for large scale batteries.

Table 6:DFFR prices

Scenario	Day	Night	Day & Night
Period	7pm to 11pm	11pm to 3am	7pm to 3am
p/kW/h	0.685	0.516	0.6

The following scenarios have been developed to simulate the participation of the EV in the BM market:

- Scenario #1: No DFFR

  It is assumed that the EV is attempting to participate in the BM market from 6pm until 7am

- Scenario #2: DFFR-Day

  It is assumed that the EV is participating in the BM market from 6pm until 7pm and from 11pm until 7am and in DFFR from 7pm until 11pm

- Scenario #3: DFFR-Night

  It is assumed that the EV is participating in the BM market from 6pm till 11pm and from 3am till 7am and in DFFR from 11pm till 3am

- Scenario #4: DFFR-Day and Night

  It is assumed that the EV is participating in the BM market from 6pm till 7pm and from 3am till 7am and in DFFR from 7pm till 3am

4. Modelling

The domestic energy system was modelled using a mixed-integer linear program developed at Upside. Four different assets were modelled: (i) Mixergy hot water tank, (ii) PV array, (iii) Nissan Leaf EV in combination with a Honda Power Manager (PM), and (iv) Tesla Powerwall 2 home battery. The PM is a two-way EV charger capable of V2G, V2Home and DC charging through a CHAdeMO (CHArge de MOve DC charging) interface.

The assets were modelled in 16 different combinations corresponding to each asset being active or inactive in order to explore combined and individual effects of each asset. The combinations are shown graphically in Figure 1.

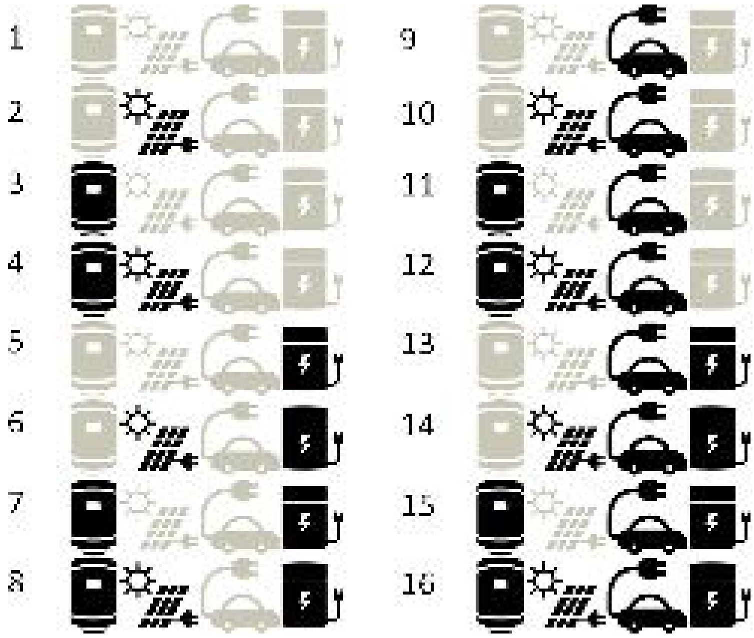

Figure 1: Schematic of 16 asset combinations used in modelling12

Asset parameters in the model were defined to reflect the physical assets installed in the Salford Energy House (SEH), with the exception of the PV array which was sized to be representative of a typical domestic installation. To provide some protection against excessive battery degradation in the optimisation model, the Powerwall and EV batteries were limited to one charge/discharge cycle per day. In the case of the EV this limit was applied in addition to any driving load. A brief summary of the asset parameters is presented in Table 7.

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[12] Image source: Electric car by icon 54, electric boiler by Fabio Rinaldi, solar panel by Luis Prado, Powerwall by Peter van Driel from Noun Project.

Table 7: Summary of asset parameters used in modelling. *Values were varied to consider edge cases

	Grid	PV*	Mixergy Tank	Powerwall*	Nissan Leaf / Honda Power Manager
Maximum Import	16 kW	-	3 kW	3.68 kW	5.5 kW
Maximum Export	3.68 kW	4 kW	-	3.68 kW	5.5 kW
Total Capacity	-	4 kWp	180 ltrs	13.5 kWh	40 kWh

Table 8 outlines the use cases considered along with their aims. The use cases are split into two categories: (i) Maximise Economic Return where the aim is to maximise revenue through optimal use of the assets and (ii) Maximise Grid Independence where the aim is to minimise import from the grid. For the latter category, only the consumer-focussed modelling is applicable since it would be unlikely to be in the interests of a supplier to support consumers' independence from the grid.

Table 8: Summary of use cases considered in the modelling

	Use Case	Aim	Focus
	Core Cases, with 16 Asset Combinations	Use assets to maximise economic return.	Supplier, Consumer
	Edge Cases - variable load, with all assets present	Investigate the effect on revenue of variable load, variable EV driving cycles and the use of a heat pump.	Supplier, Consumer
	Edge Cases - variable battery and	Investigate the effect on revenue of varying the size of	Supplier, Consumer

Maximise Economic Return	PV sizes, with all assets present	the battery and PV array.	
	Community Cases, with all assets present	Maximise economic return to local community using assets and allowing energy sharing between dwellings.	Supplier, Consumer
Maximise Independence from Grid	Core Cases with 16 Asset Combinations	Use assets to maximise independence from the grid.	Consumer
	Community Cases	Use assets and sharing of energy between dwellings to maximise independence of local community.	Consumer

An agile testing approach was devised to probe specific asset behaviours observed in the modelling. This approach offered more flexibility and lower risk while still adding significant value in ground-truthing the models. The resulting testing approach is summarised in table 9.

Table 9: Testing outlines for Salford Energy House Tests.

	Test Outline	**Aim**
U1	**All assets active** and available to discharge under a variable household load. Individual tests of 1-2hrs.	Understand how assets are prioritised, how they see the load and how they respond and interact.
U2	**Response time of Power Manager** to variable load. Introduce load spikes of progressively reduced duration and monitor response.	Understand how quickly asset responds to changes in load.

U3	**Response time of Powerwall** to variable load. Introduce load spikes of progressively reduced duration and monitor response.	Understand how quickly asset responds to changes in load.
U4	**V2G** run a schedule repeatedly activating V2G (controlled or no house load) and verify export in house meters.	Check V2G activates and understand it's characteristics - e.g. constant, variable, time-delayed etc.
U5	**Asset-Asset Charge Shifting.** Set Nissan Leaf to charge during period of peak electricity price, observe whether Powerwall discharges to Leaf. Reverse process.	Understand whether charge shifting is possible, probe its characteristics.
U6	**Power Manager charge-discharge cycl**e under constant load. At least top 30% SoC but as deep as possible in the time.	Understand non-linearities in EV battery response, particularly close to full.
U7	**Powerwall charge-discharge cycle** under constant load. At least top 30% SoC but as deep as possible in the time.	Understand non-linearities in Powerwall battery response.

5. Results

Good Energy

Figure 2 shows the financial benefits that may arise under each scenario of the EV configuration when considering a solar PV system in the South of the UK. The x-axis reflects the original annual household consumption for each of the 19 households, in other words it reflects their energy consumption with no EV, or any other technology embedded into their house. The y-axis indicates the potential annual savings for each household under various asset configuration scenarios, using as a baseline a household with an EV car and a unidirectional charger as part of their baseline energy consumption.

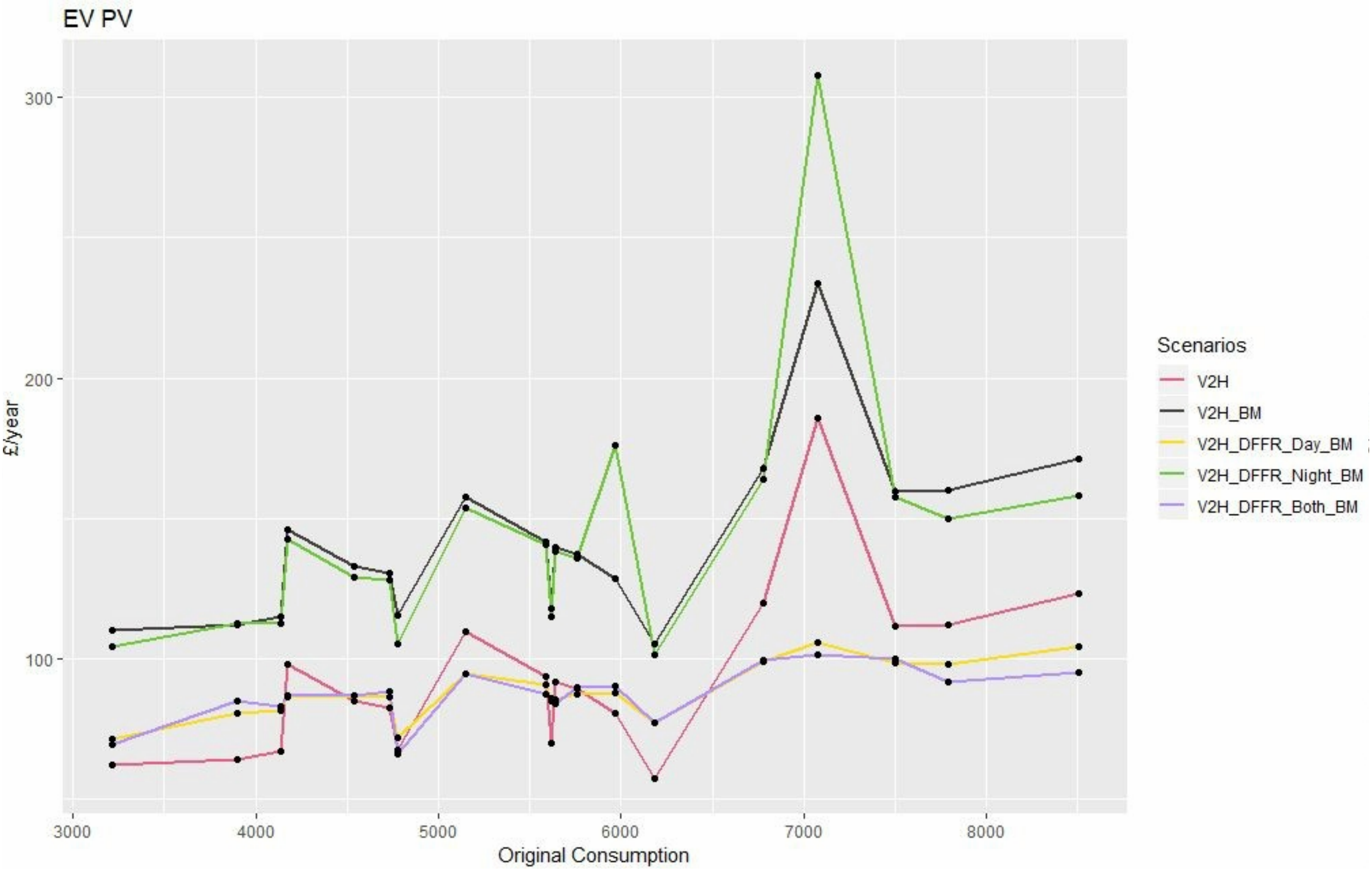

Figure 2: Financial benefits for the "EV+PV" configuration for each scenario.

Each dot on this graph answers the following question:

What is the financial benefit that households with different energy needs can achieve by replacing a smart charger with a bidirectional charger, across different scenarios?

The following sections address three key areas, the difference in the financial benefits that may arise from different PV generation, the financial benefits for the V2H scenarios and the financial benefits for the V2G scenarios. Only the best scenarios for each configuration and household are presented and discussed.

PV-included configurations

Figure 3 shows the financial benefit per annum for both low- and high-PV systems when used with an EV V2G technology and with and without a Home Battery (HB).

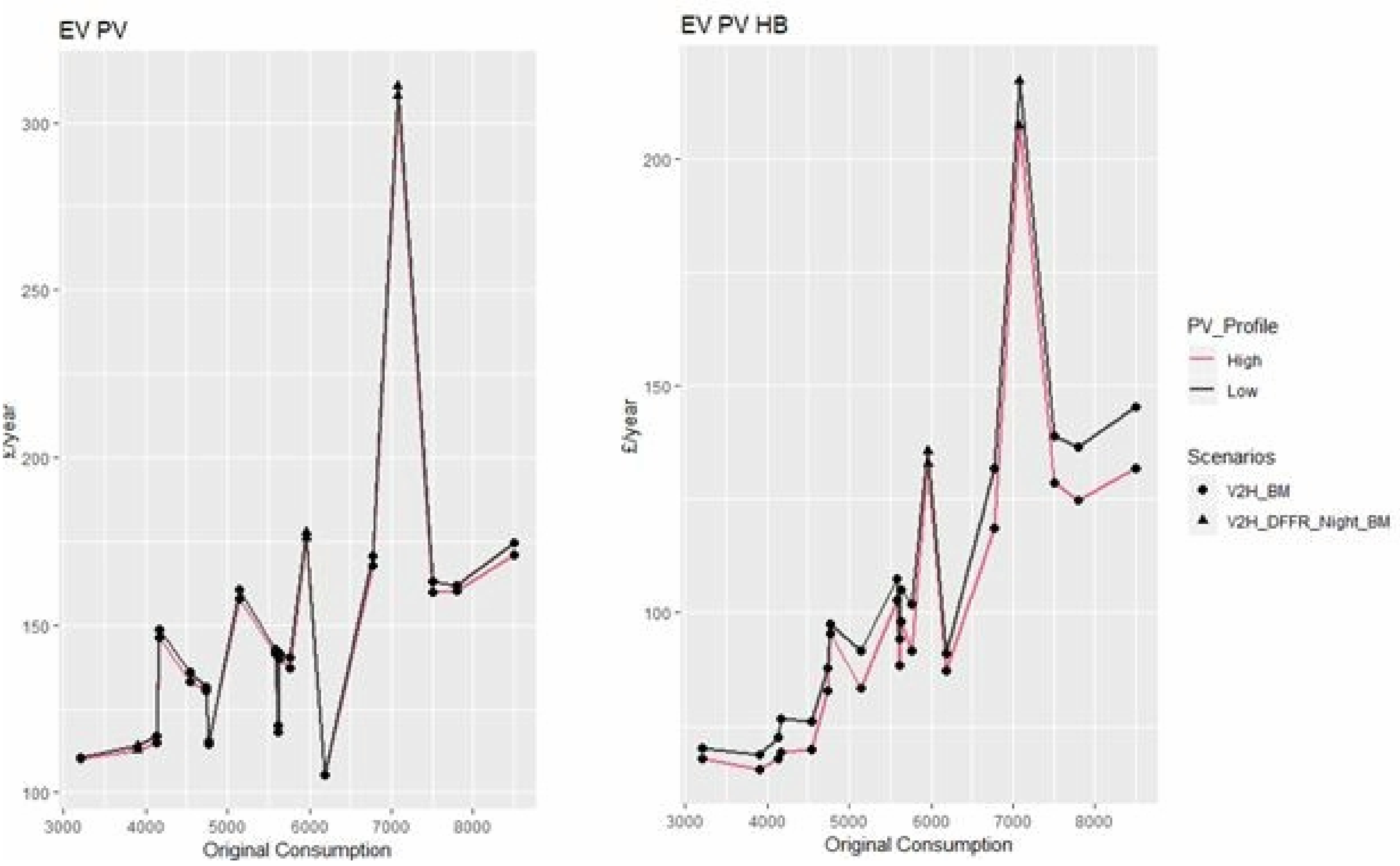

Figure 3: Financial benefits for the "EV+PV" and "EV+PV+HB" configurations and their scenarios for high and low PV generation.

For the purposes of the modelling one system is reflective of a high generation system installed in the South of the UK, whereas the other system is reflective of a low generation system located in the North of the UK.

Households with a lower generation PV system have a marginal advantage against households with a higher generation PV system. This is due to the V2G having a greater role in supporting the house energy demand due to lower PV generation.

The average difference for the “EV+PV” configurations is **£1.72** per annum and the average difference for the “EV+PV+HB” configurations is **£6.85** per annum.

For the remainder of this section the PV related results will be represented by the average price of the low and high PV scenarios.

V2H Financial Benefits

Even though V2H configurations are the easiest to implement from a household and EV owner perspective, they deliver lower financial benefits when compared to the V2G scenarios.

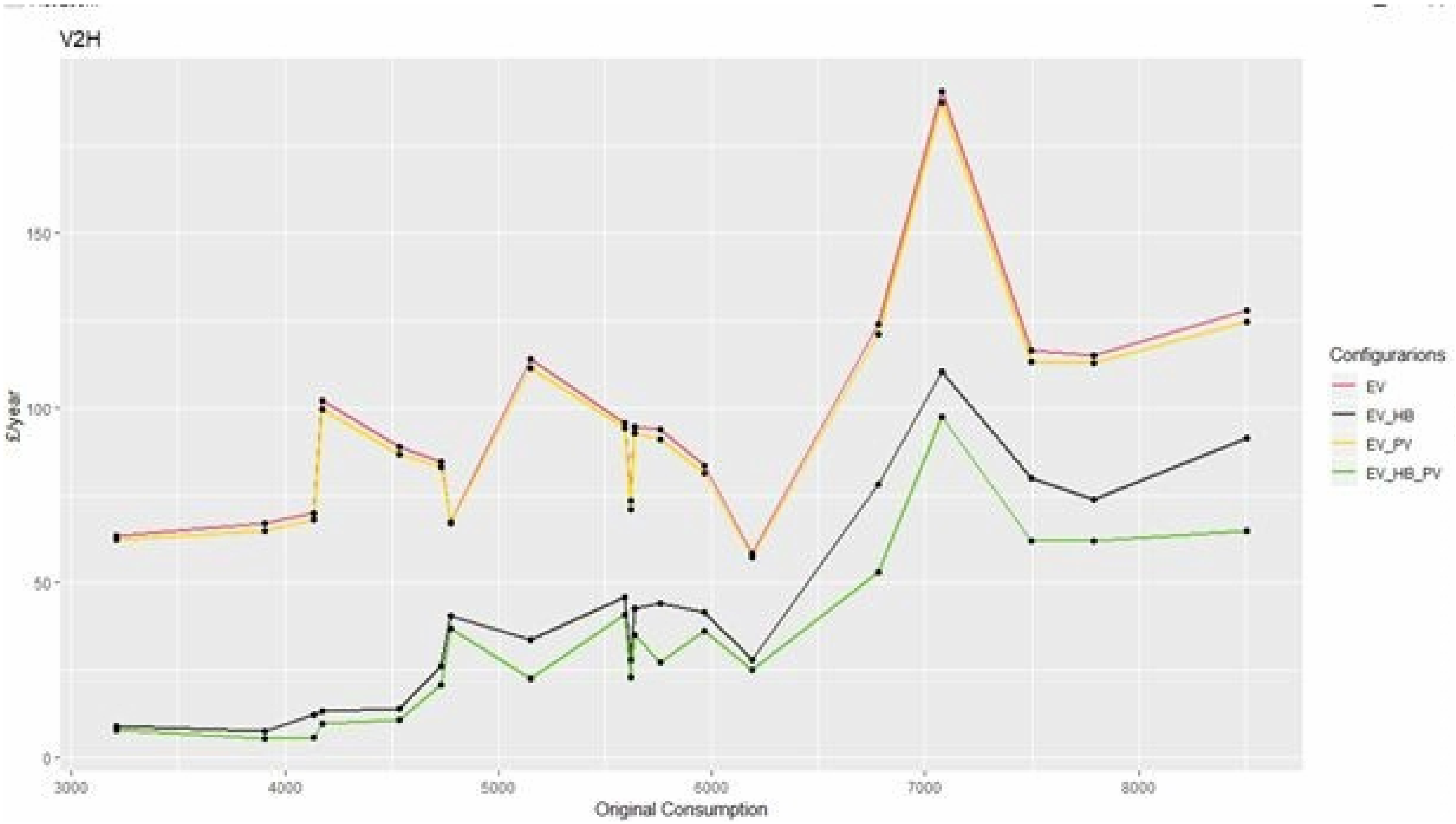

Figure 4: Financial benefits for each configuration under the V2H scenario.

From Figure 4, it is apparent that the financial benefit of a household without a home battery is significantly higher. That is because the home battery is in competition with the EV and the added value of the V2G charger. In addition, the V2H system delivers similar financial benefits with and without the PV system, the reason for this is that the EV is not available to capture excess energy for much of the time that the PV system is generating.

It should be highlighted that there is a positive relationship between the household original energy consumption and the financial benefits. In other words, the benefits tend to be higher for households with higher energy consumption. However, Figure 4 shows that this is not always the case. The reason for this is that, in addition to the magnitude of the annual energy consumption of the house, the timing of energy consumption also affects the financial benefits.

Table 10 shows the minimum, average and maximum financial benefit for each configuration. It is evident that even though there is a financial benefit in having a V2H charger, the payback does not justify the purchase of a bidirectional charger unless its cost is at parity with a unidirectional charger.

	EV	**EV HB**	**EV PV**	**EV HB PV**
Min £/year	58.5	7.5	57.6	5.4
Mean £/year	96.4	43.1	94.3	34.1
Max £/year	190.7	110.3	187.6	97.3

Table 10: Minimum, average and maximum financial benefit for each configuration

V2G Financial Benefits

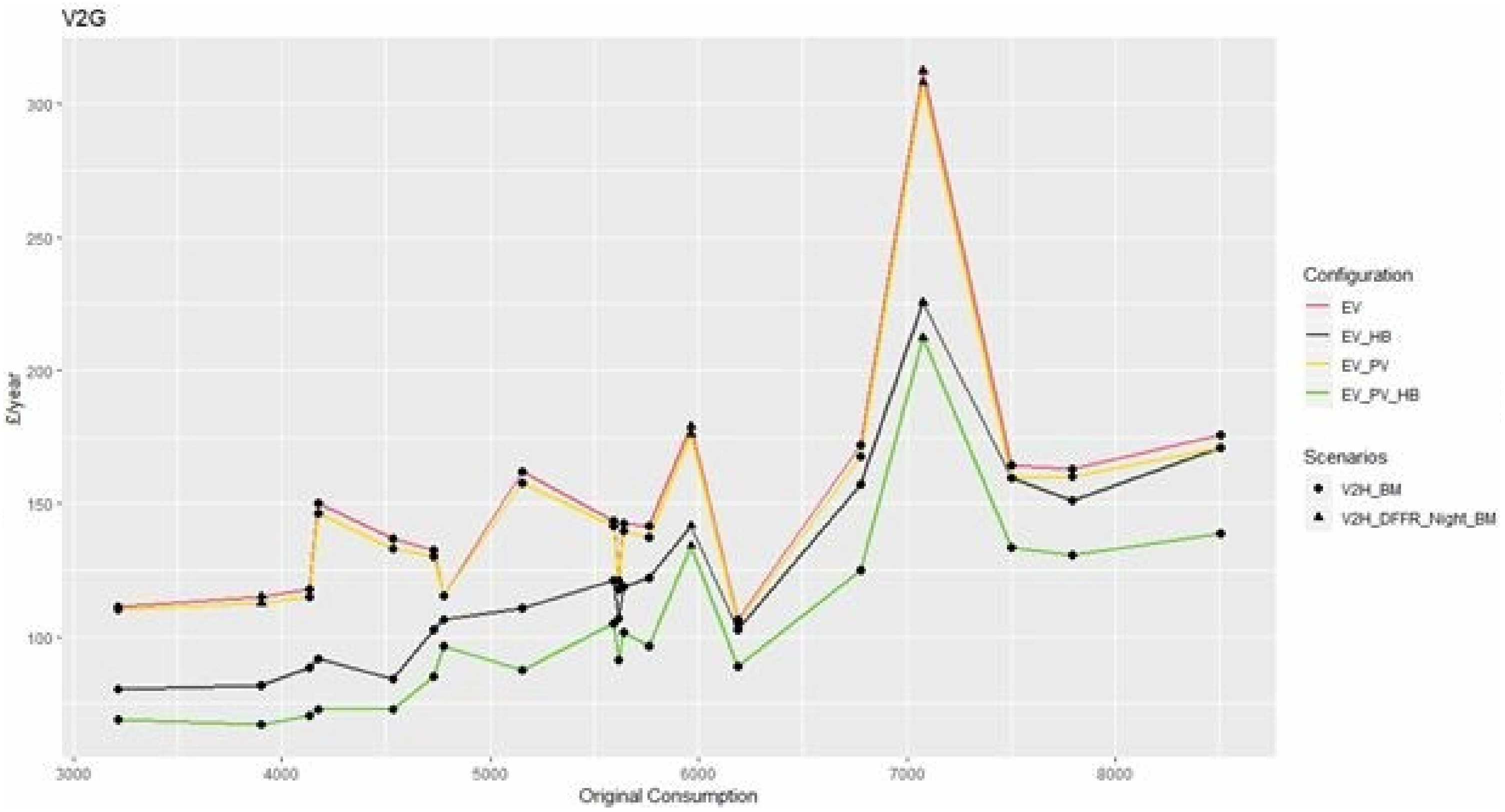

Figure 5: Financial benefits for each configuration and the best scenarios for each household.

Figure 5 above highlights the financial benefits for various scenarios when considering the V2G technology. For the majority of the households the optimal scenario is the "V2H_BM" where the V2G charger goes beyond supporting the house and actively participates in the BM market. However, for some households the optimal scenario is the "V2H_DFFR_Night_BM" which means the V2G is participating in DFFR from 11pm till 3am as well as taking part in the BM in the remaining hours where the EV is available and connected to the V2G charger. The discrepancy between the two scenarios for different households is down to how the energy was consumed from 6pm until 7am and is reflective of each individual household's behaviour.

From Table 11 it is apparent that the financial benefits and payback periods are significantly better than a bidirectional charger with no access to DFFR and BM. Nevertheless, the payback periods remain high and would require the bidirectional charger to reach cost parity with a unidirectional charger.

	EV	EV HB	EV PV	EV HB PV
Min £/year	106.5	80.2	105.6	67.2
Mean £/year	150.8	122.4	147.8	104.3
Max £/year	312.6	225.7	308	212.1

Table 11: Minimum, average and maximum financial benefit for each configuration

Upside Energy Results

Supplier/Consumer Focused Results

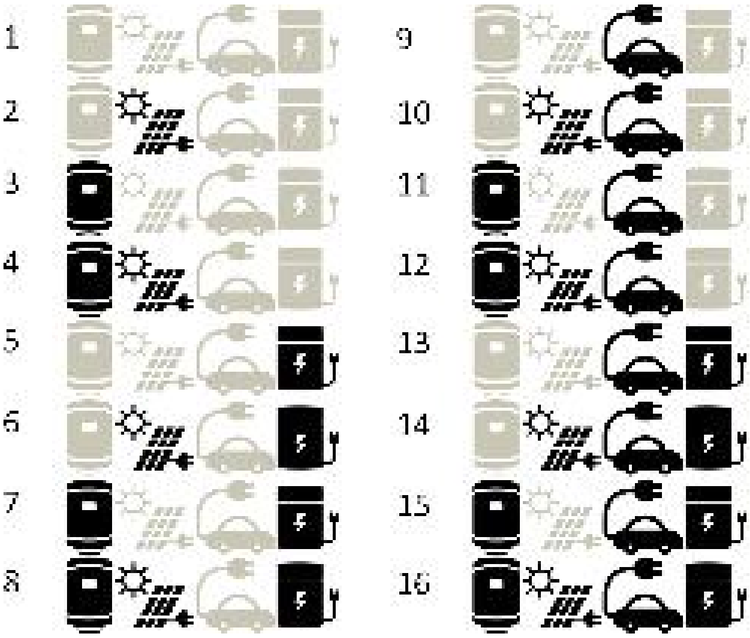

Figure 1: Schematic of 16 asset combinations used in modelling

Maximise Financial Return (Supplier)

Aim: Use assets to maximise economic return, regardless of grid-independence or self-consumption.

The most lucrative asset combinations are cases 13-16 which yield revenue of close to £500/yr. The next most lucrative are cases 5-8 which yield approximately £400/yr. In both these groups, the majority of the revenue comes from DA trading and DUoS with a smaller but significant amount from TNUoS. These cases correspond to all the cases where there is a Powerwall present, indicating that this is a major contributor to the revenue from a supplier perspective. In cases 5-8 there is no EV, while in cases 13-16 there is an EV present indicating that the EV adds an additional revenue of approximately £100/yr.

In the remaining cases, where there is no Powerwall present, revenue is significantly reduced. For cases 9-12 where storage is available via the EV, revenue does not exceed £150/yr. For these cases there is a marked reduction in DUoS revenue and zero TNUoS revenue since the EV is often absent during high value DUoS and Triad periods. It should be noted that while the EV has a very large energy capacity, the ability to extract value from this is limited by the low domestic export limit and the absence of the vehicle for much of the day.

Interestingly, the additional revenue from adding a Powerwall to a dwelling is very similar whether PV is installed (case 6) or not (case 5). This is because the battery is fully utilised through trading in the DA market and no additional value can be captured through further optimising the PV usage.

The Mixergy has a much smaller impact on revenue compared to electrical storage, providing revenues of around £24 (cases 3 and 4).

Maximise Financial Return (Consumer)

Aim: Use assets to maximise economic return through self-consumption of PV.

The most lucrative asset combination is case 16 which includes all assets and yields revenue of just over

£300/yr. Cases 8 and 14 are the next most lucrative, with revenue close to £250 both these include a Powerwall. Cases 4, 6 and 12 have revenues close to £150 and all include either a Powerwall or a Mixergy. This implies that in addition to the Powerwall, the Mixergy is also a significant source of consumer revenue. It should be noted that this result depends on a base case including a non-optimised electric hot water tank, comparison with a gas boiler may lead to very different conclusions. Case 10 shows the lowest, non-zero revenue of £12 and includes only a PV and an EV. These results indicate that both the Mixergy and Powerwall are valuable in increasing utilisation of PV. Using these assets in combination increases value but with diminishing returns. An EV used in isolation with a PV array adds very little value (£12) in the domestic context (assuming a commuter drive-cycle) since it is mostly absent during periods of PV generation.

Interestingly, when an EV is used in combination with a Powerwall, the added value from the EV is significantly higher at close to £70 (comparing cases 6 and 14).

Salford Energy House Results

Test	Outline	Aim	Findings
U1	**All assets active** and available to discharge under a variable household load. Individual tests of 1-2hrs.	Understand how assets are prioritised, how they see the load and how they respond and interact.	Assets do not always respond at full power, when another flexible asset is also responding.
U2	**Response time of Power Manager** to variable load. Introduce load spikes of progressively reduced duration and monitor response.	Understand how quickly asset responds to changes in load.	Power manager responds to all load variations down to 1 minutely, although only partial load was seen for 1 minute spikes, indicating that this could be approaching the limit of its response speed.
U3	**Response time of Powerwall** to variable load. Introduce load spikes of progressively	Understand how quickly asset responds to changes in load.	Powerwall responds to all load variations down to 1 minutely spikes.

	reduced duration and monitor response.		
U4	**V2G** run a schedule repeatedly activating V2G (controlled or no house load) and verify export in house meters.	Check V2G activates and understand it's characteristics - e.g. constant, variable, time-delayed etc.	Power manager able to discharge up to the household limit, or up to the battery limit when there is sufficient household demand.
U5	**Asset-Asset Charge Shifting.** Set Nissan Leaf to charge during period of peak electricity price, observe whether Powerwall discharges to Leaf. Reverse process.	Understand whether charge shifting is possible, probe its characteristics.	Load shifting is possible from the Nissan Leaf to the Powerwall and from the Powerwall to the Nissan Leaf.
U6	**Power Manager charge-discharge cycl**e under constant load. At least top 30% SoC but as deep as possible in the time.	Understand non-linearities in EV battery response, particularly close to full.	EV charging power reduces when state of charge over 95%
U7	**Powerwall charge-discharge cycle** under constant load. At least top 30% SoC but as deep as possible in the time.	Understand non-linearities in Powerwall battery response.	Powerwall charging power reduces when state of charge is over 97%

Table 12: Results from SHE tests.

6. Conclusion

The two independent modelling approaches (Upside Energy, Good Energy) differ in their approach and assumptions as outlined below:

- Relative revenue gain is calculated against different EV baselines, either charge when plugged in or smart charging,
- Different markets were considered: either DA, TNUoS and DNUoS (Upside Energy), or ToU, BM and DFFR (Good Energy),
- Different input data sets were used for consumer tariffs, PV, household demand, EV usage profiles etc.

Despite these differences, the calculated revenues from the different approaches, while not directly comparable, are of a similar order of magnitude. This increases confidence in the results and provides an insight into the range of revenues that could be available under different assumptions, broadening the scope and generalisability of the study.

What is the financial benefit of optimising a V2G-enabled EV alongside different combinations of assets, (e.g. benefit of an EV compared to a home battery, benefit of orchestrating control of multiple assets, etc.)

The Upside modelling shows the financial benefit of V2G optimised households with different asset combinations for a supplier and consumer focus, as compared to a non-optimised case. In all cases the EV creates revenue; approximately an additional **£100/year** for the supplier case and an additional **£60-70/year** for the consumer case. The EV is capable of providing considerably less revenue than a home battery despite its large capacity, due to its limited availability and the domestic export limits. The Mixergy adds limited value in the supplier focused case. Coordinated optimisation of all assets provides revenue of up to **£500/year**.

The Good Energy modelling shows the financial benefit of V2G optimised households with different asset combinations for different revenue streams, as compared with an optimised smart charging EV. The revenues possible from the V2G EV are in the range of **£30-100/year** when energy is only exported to the home (V2H), and **£100-150/year** when energy is exported to the grid.

How does value change when adding storage assets to PV and non-PV households from both a supplier and consumer perspective?

For both sets of modelling results where there is access to non-flat energy prices (either DA, BM or ToU) it is shown that the presence of PV only improves the revenues by a relatively small amount compared to the same asset combinations without the PV. This is because the majority of the revenue comes from trading/flexibility services or smart charging, so storage size and availability are the key factors.

However, when there is a flat energy price (Upside Energy modelling, consumer focus), the presence of PV has a significant impact on the revenue since the benefit comes from using the storage assets to increase self-consumption. In this case it is the combination of the PV and storage, when correctly sized, that provides revenue. Due to the EV being absent from the home for many of the PV generating hours, the additional revenue provided by the EV in the consumer focussed case is just £**12/year** but this increases to **~£70/year** when the EV is coordinated with other assets that allow load shifting.

Which revenue streams provide the most value and how does this depend on the asset combination (e.g. are some assets better at capturing UoS revenue)?

The EV and home battery have the greatest influence on which revenue streams provide the most value when considering DA and UoS revenues. When a home battery is present, TNUoS revenue of **~£100** is possible regardless of which other assets are present. This assumes that all three triad periods are captured. When the EV is present, DA revenue is higher than DUoS, and when an EV is not present the converse is true, but both offer significant revenues. The revenues possible for DUoS and TNUoS are likely to change in the future under the Targeted Charging Review (TCR).

For the flat rate / load shifting case, both the PV and some storage must be present for revenue, with most of the revenue arising from the home battery, followed by the mixergy and the EV.

When the revenue streams are BM, DFFR and ToU, the revenue primarily arises from the BM and load shifting, however, for some households additional revenue can be raised in the DFFR market.

Under which asset combination-configurations does a V2G enabled EV add the most value compared to a unidirectional charging EV?

For both the V2H ToU only and V2G (ToU, BM, DFFR) cases, the scenario where only the EV is present, results in the highest revenue. This is because a baseline with a unidirectional charger was used for comparison and hence much of the benefit of the PV and home battery is already captured in the base case. In terms of revenue, this asset combination is closely followed by the EV + PV case, and then EV + HB, and finally EV + HB + PV. This holds true for both V2H and V2G.

How can assets be used to maximise independence from the grid and does the amount of energy consumption and the way the energy is consumed have an impact on the financial benefits?

With a consumer focus, the revenue is derived from minimising imports from the grid with an import reduction of up to ~34% possible through optimisation of storage assets to maximise self-consumption of PV. Hence, from this perspective, both revenue generation and grid independence are compatible. This is not true when considering other revenue streams e.g. DA, BM, DFFR, as they require importing and exporting at different times, which results in significant increases in the overall energy imported/exported. This could have knock-on effects on the Distribution Network Operator (DNO) if adoption is widespread or concentrated in clusters.

In general, import reduction is less than export reduction due to storage efficiency losses.

How do revenues change when considered from a supplier and consumer perspective?

A supplier focus allows access to revenue streams not directly available to the consumer (DA, UoS, DFFR, BM), and so the revenues are higher. In addition, the home battery is the most important asset when viewed from a supplier perspective, whereas the PV combined with any storage asset is most important when viewed from a consumer perspective. In the case of a ToU tariff, a storage asset is able to generate revenue for a consumer without the presence of PV.

How do the following impact the above research questions: High and low household electricity usage; high and low EV usage, Space and water heating provided by a heat pump; Variable battery and PV array sizes?

For the DA and UoS revenues, the electrical, heat and EV loads had little impact, as most of the revenue is derived from the size of the storage. There is however a tendency towards larger revenue from higher load and EV usage. It is likely that the availability of the EV may have a bigger impact on revenue than the driving load. Heat pump load and PV generation have very little impact on the revenue. The converse is true for the consumer focus where the PV size has more impact on revenues than the load profiles or battery size, indicating the Powerwall 2 is oversized, but again the largest influence comes from the specific combination of assets. This indicates that the results are generalisable to a range of different households.

When comparing to the base case of the smart charger, the high PV output generates less revenue than the low PV case, indicating that the additional benefit of the V2G charger is less for higher PV output. The revenues also tend to increase with the electrical consumption, but this will vary from home to home, with, for example, the time when the energy is used, also having an impact on revenues.

Ground-Truthing

- In the real-world, assets respond in non-uniform ways when combined. Installed control algorithms attempt to optimise individual assets for the consumer, rather than coordinating multiple assets for either home or grid support. In addition, they do not allow the precise control required for optimal dispatch. Suppliers/aggregators should work with Original Equipment Manufacturers (OEMs) to ensure accessible controls are incorporated into assets.
- There are some technical differences between modelled and real-world charging behaviour close to 100% SoC meaning models will tend to slightly overestimate available flexibility.
- Charge shifting between assets is technically possible in the real-world and models show it can be an optimal strategy for utilising PV generation.