MLMI 10 Designing Intelligent Interactive Systems

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Introduction

Ownership of a battery electric vehicle has the potential to present homeowners with novel opportunities that are not currently being fully realised. Whilst this could simply be reducing household electricity bills, it could also be a means of increasing energy self-sufficiency or supporting the stability of energy delivery to one's street. The choice will depend on user's primary drivers, although few will have previously considered such possibilities. This design document initially explores the problem context before defining user-centred design requirements. Conceptual designs are developed and assessed, and the architecture of the most promising design further developed. A risk assessment is conducted, and methods for verifying and validating the chosen design are presented. Using this report, a detailed design could be developed and, crucially, further validation and verification conducted.

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1. PROBLEM CONTEXT

The number of battery electric vehicles (BEVs) registered in the UK increased by 76.3 % from 2020 to 2021 to around 382,000 [1], [2]. Under their most conservative future energy scenario, the National Grid predicts that there will be 4.7 million BEVs by 2030 [3].

The time of day at which BEV charging occurs could have significant implications for the electricity system [3]–[6]. It is estimated that 80 % of BEV charging takes place at home [6]. Many consumers are likely to plug-in their BEV when they arrive home from work (between 5pm and 7pm), which is already a peak time of demand for the National Grid. Supporting the additional load would require significant levels of investment, both in the networks that transport the electricity and in electricity generation capacity. The costs of this would ultimately be borne by consumers.

Further, since the mid-2000s, government policies that aim to reduce carbon dioxide emissions in the energy system have led to rapid growth in renewable power sources and small-scale, local energy generation [3]. Under certain scenarios, it is predicted that there may be ten times more solar panels on rooftops by 2050 compared to today [3].

Smart technologies, such as smart chargers and smart tariffs, are already helping consumers engage with the electricity market by shifting their consumption to times of lower demand, and save money in the process [4], [6]. Smart tariffs include: tariffs where costs vary by the time of use (TOUTs), based on the cost of electricity; export tariffs, for those with generation technology such as solar panels; and tariffs designed for consumers with low-carbon technology (such as BEVs) to ensure they can charge at the cheapest times [4].

Digitalisation is viewed by National Grid Electricity System Operator (ESO), who are responsible for maintaining grid stability in the UK, as essential to managing an energy system with smart and flexible demand [3]. The Automated and Electric Vehicles (AEV) Act 2018 mandates that all BEV chargers sold and installed in the UK have smart functionality and meet minimum device-level requirements [5], [7]. However, without careful control of assets, aggregated demand side technologies responding directly to price signals could cause large fluctuations in the Grid's frequency. For example, a whole street of electric vehicles simultaneously drawing power from the grid in response to system price reductions could cause local and regional network issues. More granular control, including randomisation of response times, will be needed to avoid causing system operational faults [3].

As more consumers start to own BEVs, it is thought that smart charging, Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) uptake will increasingly help to manage higher demand and greater renewable supplies on the electricity system [3], [4]. Proof of concept trials of such systems have already begun [8]–[12], however these are at an early stage, comprise small numbers of participants, and have limited features. A 2019 government report predicted V2G would become commercially mainstream in around 2024 [6].

Therefore, this could be an ideal time to introduce an innovative new combined V2H and V2G product, which will be termed Vehicle-to-Everywhere (V2E) in this report, that assists BEV and home owners to make informed choices in a complex space of potential priorities:

- a desire to have their BEV fully charged whenever they may need to make an extended and/or unexpected journey
- exploiting smart tariffs to take advantage of opportunities to minimise household electricity bills
- obtaining the greatest possible benefit from their own sources of renewable electricity (e.g., solar panels) to reduce costs, realise personal net-zero emissions, and achieve energy self-sufficiency
- the requirement to support the reliable delivery of electricity to their street, city, and country
- the opportunity to make money by exploiting time arbitration opportunities, as is already being explored by grid-scale battery operators [13]

The above problem scenario led naturally to the following solution neutral problem statement.

1.1. Solution Neutral Problem Statement

Enable home and BEV owners to maximise the financial, energy self-sufficiency and societal opportunities presented by their BEV's battery and any renewable electricity generation sources they own.

2. REQUIREMENTS SPECIFICATION

2.1. Problem Definition

Researching the problem context led to the high-level problem definition presented in Table 1. This would be updated based on the outcome of user-centred design research (Section 2.2).

Table 1: High level problem definition.

Who?	Homeowners with a BEV
What?	Facilitate electricity delivery to the BEV, and from the BEV to the home/grid. Integrate demand predictions for both the owner's BEV and household electricity consumption with forecasted electricity prices, supply from domestic renewable sources (e.g., solar panels), and demands on the local/national Grid. Enable owners to make informed decisions, aligned with their primary drivers, regarding what the system prioritises.
Why?	Enable users to maximise the potential of their BEV's battery to achieve their financial and energy-related goals, while supporting stability of the National Grid.
Where?	In the home.
When?	The system will operate continuously. User interaction will occur when setting up the system, connecting and disconnecting their BEV, updating preferences, analysing system performance, and when the system needs information, requires a decision, or makes a recommendation.

2.2. User-Centred Design Research

2.2.1. Target Audience

Given the volume of data and trade-offs that could potentially be presented to users, the product risks being very complex. Understanding user's interests, desires and drivers will be vital for determining the most important features that the initial product should ship with and display, and which features could be targeted towards more advanced users and/or made available at a future date via software updates.

<u>Demographics:</u> These are intentionally broad to capture a wide range of views for this nascent product.

- **Ages**: 25-60 (capture broad ranging attitudes and views)
- **Gender**: Any (product is not targeted towards a particular gender)
- **Education**: Mixture of high-school level and university-level (viewpoints from diverse backgrounds; varied interests and priorities)
- **Relationship**: Mixture, ensuring large households are represented (demands on vehicles and electricity will be highest and most varied)
- **Location**: Any (broad ranging views and motivations; will rural users give higher priority to having a fully charged vehicle?)
- **Income**: £25k+

<u>Behaviours:</u>

- Home and BEV owner
- Makes use of their BEV at least 3 times a week
- Could approve the installation of a V2E charger, which their household would have sole access to (i.e., does not live in a flat or development with shared chargers)
- Responsible for paying the household energy bills, and incentivised to see these reduced
- Range of altruistic tendencies: for example, those who would go to the rescue of a neighbour/colleague whose car has broken down, and those who would not
- Range of risk appetites: for example, those invested in stocks as well as those who view market involvement as too risky

<u>Technology Use and Experience:</u>

- Familiar with the use of smart interfaces, such as smart phones
- Willing to engage with smart tariffs and smart chargers; some users will ideally have direct experience with these
- Some users should have their own solar panels or other renewables
- Basic understanding and acceptance of the possibility to use their BEV's battery to store electricity for a range of potential benefits

In addition to the target audience, it would be important to gather feedback from experts. These could be from the ESO, electricity suppliers, and/or those familiar with the operation of the National Grid.

2.2.2. Personas

The personas in Table 2 segment the potential users of the V2E system and will be useful in later stages of the design. Features can be tagged with one or more of these personas, and the target audience recruited appropriately.

As illustrated in Figure 1, users will likely fall somewhere between personas. Ideally the target audience will contain a mixture of individuals from across the "persona space." Methods will need to be devised to help determine roughly where in the space individuals reside. It's possible that further personas could arise from user-research.

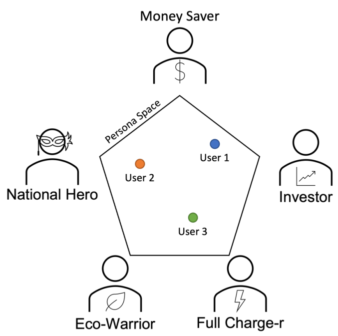


Figure 1: V2E user personas and persona space.

Table 2: Persona definitions.

Persona	Primary Motivation
Money Saver	Minimising household electricity bills.
Full Charge-r	Keeping their BEV at high capacity.
Eco Warrior / Proudly Independent	Maximise consumption of their own renewable generation; minimise consumption from the National Grid.
National Hero	Enjoys seeing the contribution they're making to ensuring the stability of the local/national electricity network.
Investor	Would like to utilise their BEV's battery to engage in time arbitration opportunities.

Table 3: Potential interview questions for target audience members.

Question	Information Gained
"What is the minimum capacity you want your BEV's battery to have at all times?"	Before asking further questions, determine if users often have an a-priori acceptance threshold that is < 100 %.
"If the battery could be used to reduce your household electricity costs by 10 %, would you accept a 10 % lower minimum capacity?"	Now present the user with a scenario whereby lowering the minimum capacity provide a benefit – how does this impact their thinking?
"If {the National Grid/your street} were facing a shortfall in supply, would you be happy to be paid market price for 10 % of your battery capacity to be used to help meet this?"	How many would be happy to do so, and, more interestingly, how many would be willing to accept market price rather than some premium above this?
"If there was an opportunity to earn money by *attempting* to buy and store electricity when the price is low and sell when it is high, would you want to take part in this, even if you could potentially lose money?"	Most users are unlikely to be familiar with time arbitration principles/opportunities – gauge appetites for taking such risks

2.2.3. Methods Employed

User-research would primarily take the form of *interviews*. Initially this might focus user's existing experience with charging their BEV, how they currently pay for electricity, and the experience and opinions they have of smart tariffs and smart charging. This could then evolve into a focussed discussion regarding their feelings towards using their vehicle for energy storage, and ultimately the goals of the product itself. Table 3 provides examples of the questions that could be asked.

Interviewees could also be asked to keep *diaries* of the journeys they make and the battery capacities at the start and end of their trips. A small number of field visits could be conducted to elucidate frustrations users have with their existing BEV charger: is it easy to forget to charge the vehicle? Do they only plug their vehicle in when the battery is below a certain capacity? Do they tend to unplug their vehicle once it is charged to ensure it is not still consuming electricity?

2.3. Functional Analysis

2.3.1. FAST Diagram

The Functional Analysis System Technique (FAST) [14] diagram shown in Figure 2 was constructed to provide a graphical overview of the product's functional requirements. It helped expose the sub-functions that will be required, and so reduced the risk of key requirements being overlooked. The diagram should be updated with learnings from the user-centred design research.

2.3.2. Function Elaboration

Two related functions which warranted additional elaboration were **Generate Recommendations** and **Make Decisions**. These are at the heart of the product offering, and the product's success will be dependent on their performance. Figure 3 provides further in-depth analysis, considering many facets of how these functions will operate.

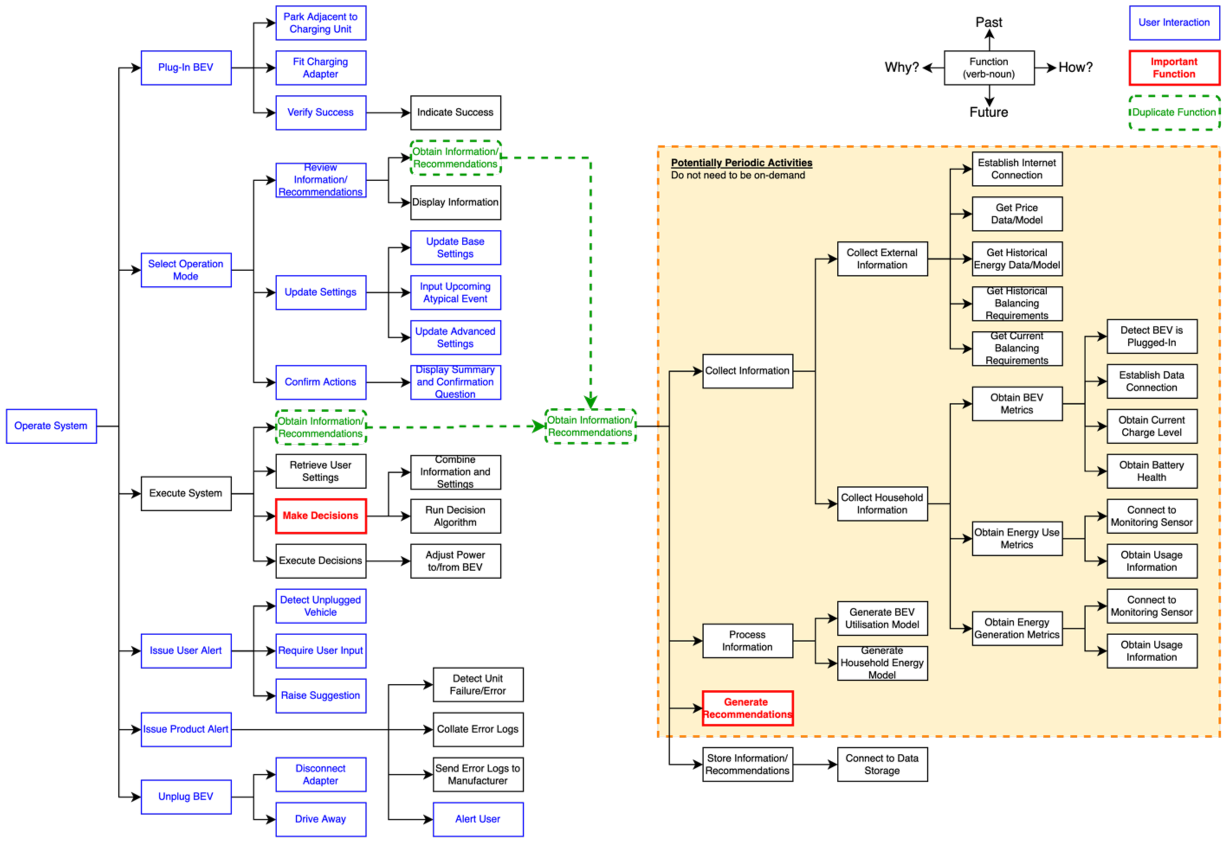


Figure 2: FAST diagram.

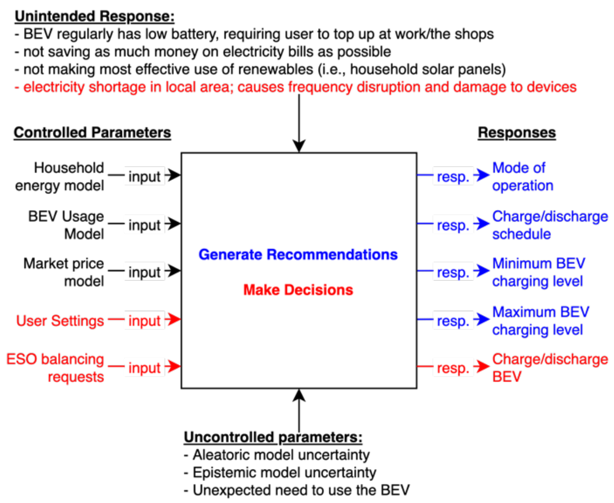


Figure 3. Elaboration of Generate Recommendations and Make Decisions Functions. Blue text indicates points applicable to only Generate Recommendations; red text applies to Make Decisions.

2.3.3. Functional Requirements

From the FAST diagram, the subset of key functional requirements shown in Table 4 were documented. A justification for each requirement is included in brackets, and all items are intended to be testable. The source for all the requirements is shown as AC, the report author. Requirements would typically be developed by a team and may also arise from user-centred research. Sources would normally therefore be more diverse. Each requirement has been given a unique identifier to aid with traceability, and so better adhere to IEEE Standard 1059.

2.4. Regulatory Requirements

The product must adhere to the UK Government's Electric Vehicles (Smart Charge Points) Regulations 2021 [15]. Regulatory requirements in this space are evolving, and the UK Government plans a second phase of legislation that will mandate BSI PAS 1878:2021 and 1889 [16], [17]. ISO 15118-1:2019, which defines the standards for communication between BEVs and chargers, should also be followed [18]. Further, installations must be carried out in accordance with several standards and regulations [19]; the design of the V2E system must take these into account.

2.5. Matrix Checklist

The matrix checklist in Figure 4 was used as an aid to identify requirements that had not surfaced from the functional analysis. Those for which some requirements had already been specified in Table 4 are shaded in green. Those shaded in blue have requirements defined in Table 5. No items were thought to be unapplicable to this product, however only a small subset could be covered due to space constraints.

3. CONCEPTUAL DESIGN

3.1. Function Modelling

The functional requirements elucidated by the FAST diagram were used to generate the function model for the V2E system shown in Figure 6. This clarified that the system can be decomposed into five modules, which could reside in separate devices or be combined into a single unit:

- **BEV Charging Module**: The unit that connects to the BEV, regulates power flows, and obtains information from the vehicle.
- **Processing Module:** Has overall responsibility for collecting information, generating/applying models, making recommendations, and taking decisions.
- **User Interface Module**: The user interface.
- **Mains Electricity Monitoring Module:** Senses consumption.
- **Renewable Electricity Monitoring Module:** Senses generation.

3.2. Criteria Scoring

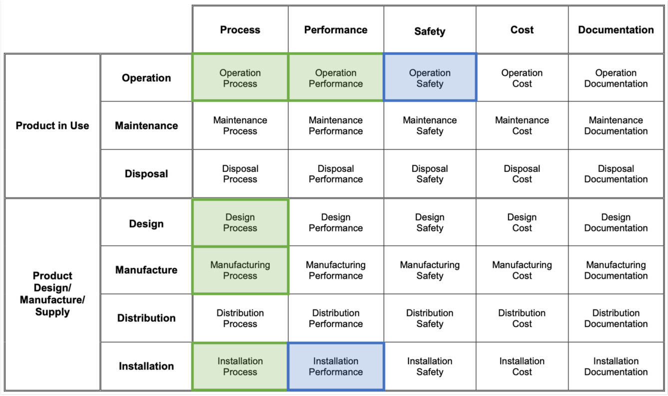
For this initial evaluation, the simple set of criteria functions shown in Figure 5 were employed. Types A and B reflect simple linear relationships between assessed quantities and values. Type C reflects a non-linear behaviour, where small changes within a narrow quantity range yield significant changes in value. For example, interface ergonomics could be measured via throughput, where values above a threshold score more highly, but further incremental improvements do not yield similar score increases. Type D reflects criteria possessing a "Goldilocks' zone". For example, increased product customisability yields higher scores, up until a user becomes overwhelmed with options.

Table 4: Functional requirements arising from the FAST diagram. Key: # = unique identifier; T = type = Demand/Wish; W = weighting; S = source (AC is report author).

#	T	W	Functional Requirement	S
			Park Adjacent to Charging Unit	
1	W	M	- Device *should* have a motion-activated light and/or screen (visibility)	AC
2	D	H	- Installation instructions *shall* specify charging unit be installed 1-2 m above ground (visibility)	AC
			Fit Charging Adapter	
3	D	H	- Charging unit *shall* be manufactured with CHAdeMO DC connector type (only type that currently supports V2G/V2H [6])	AC
4	W	M	- Cable *should* be 5 m in length (ease-of-use)	AC
5	D	H	- Charging unit *shall* deliver power to the BEV at 7 kW (industry standard for fast home charging)	AC
			Collect External Information	
6	D	H	- Device *shall* be able to connect to the internet (access APIs, download updates, send analytics)	AC
7	D	H	- Device *shall* have access to Supplier/ESO pricing data, or a suitable model (pricing model)	AC
8	D	H	- Device *shall* have access to historical energy data, or a suitable model (peak demand model)	AC
9	D	H	- Device *shall* be able to retrieve information from the ESO/supplier regarding *historical* balancing requirements (peak demand model creation)	AC
10	D	H	- Device *shall* receive notifications from the ESO/supplier regarding *current* balancing requirements (support network requirements)	AC
			Obtain BEV Metrics	
11	D	H	- Device *shall* be able to establish data connection to BEV (BEV utilisation model creation)	AC
12	D	H	- Device *shall* be able to determine BEV charge level (BEV utilisation model creation)	AC
13	W	H	- Device *should* be able to determine BEV battery health (incorporation into recommendations)	AC
			Obtain Energy Use Metrics	
14	D	H	- Device *shall* have an electricity consumption censor (energy consumption model)	AC
15	D	H	- Device *shall* have data connection to censor (energy consumption model)	AC
			Obtain Energy Generation Metrics	
16	D	M	- Device *shall* have censors to monitor output from any renewable generation sources (energy generation model)	AC
			Generate BEV/Household Energy Utilisation Model	
17	D	H	- BEV utilisation model *shall* correctly predict vehicle use within 30-minute window, 70 % of the time (BEV utilisation model)	AC
18	D	H	- Household energy utilisation model *shall* correctly predict demand level 80 % of the time (household energy utilisation model)	AC
			Generate Recommendations	
19	D	H	- Recommendations *shall* be justified and can be readily interpreted by 80 % of target audience members (system interpretability)	AC
20	D	H	- Target audience members *shall* agree with recommendation engine's decision 70 % of the time (maintain user's trust in the system)	AC
			Make Decisions	
21	D	H	- Decision engine *shall* achieve the following performance: user has sufficient charge for their journey 95 % of the time; lost savings opportunities $<$ £20/week 95 % of the time; able to accommodate requests of the ESO $>$ 70 % of the time (maintain user's trust in the system)	AC
22	D	H	- Reasoning for the decisions *shall* be logged for user review, which can be readily interpreted by $>$ 95 % of test users (traceability)	AC

Table 5: Functional requirements arising from the matrix checklist. Key: # = unique identifier; T = type = Demand/Wish; W = weighting; S = source (AC is report author).

#	T	W	Functional Requirement	S
			Installation Performance	
23	W	M	- Users *should* be able to perform initial device setup within 20 minutes	AC
			Operation Process	
24	D	H	- Users *shall* have easy physical access to an interface with the system	AC
			Operational Safety	
25	D	H	- Device *shall* have a method of detecting ingress of moisture	AC
26	D	H	- Device *shall* have at least one method of raising the alarm should a critical fault develop	AC



		Process	Performance	Safety	Cost	Documentation
Product in Use	Operation	Operation Process	Operation Performance	Operation Safety	Operation Cost	Operation Documentation
	Maintenance	Maintenance Process	Maintenance Performance	Maintenance Safety	Maintenance Cost	Maintenance Documentation
	Disposal	Disposal Process	Disposal Performance	Disposal Safety	Disposal Cost	Disposal Documentation
Product Design/ Manufacture/ Supply	Design	Design Process	Design Performance	Design Safety	Design Cost	Design Documentation
	Manufacture	Manufacturing Process	Manufacturing Performance	Manufacturing Safety	Manufacturing Cost	Manufacturing Documentation
	Distribution	Distribution Process	Distribution Performance	Distribution Safety	Distribution Cost	Distribution Documentation
	Installation	Installation Process	Installation Performance	Installation Safety	Installation Cost	Installation Documentation

Figure 4: Matrix Checklist. Green shaded items have been partly covered in the functional analysis. Example requirements from blue shaded items are provided in Table 5.

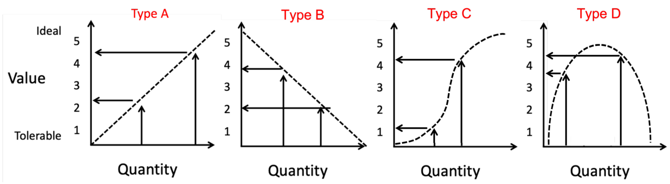


Figure 5. Criteria Scoring Functions.

3.3. Selection Criteria

The selection criteria shown in Table 6 were defined to evaluate concepts against. These criteria were selected based on the key requirements identified from the FAST diagram. The scoring function applied to each criterion is specified, as is a weighting between 1 and 3. Given the product should be as simple to use and interpretable as possible, higher weightings were given to the initial setup time, ongoing update requirements, flexibility/customisability, and model explainability. Sensing power was given the lowest weighting given that inter-day/inter-seasonal variance will likely be significantly larger than the noise in the sensor's readings.

3.4. Candidate Concepts

Potential function carriers for the sub-functions highlighted in red in the function model are presented in the morphological chart shown in Table 8. Permutations of these function carriers were used to define the concepts indicated with red, orange, and green dots.

3.5. Concept Scores

The red, orange, and green concepts identified were scored against the selection criteria using their assigned scoring functions, yielding the values shown in Table 7. The values were multiplied by the criteria weighting to yield the final weighted values. While this scoring was very approximate, and so the values will have significant error bars, there is still clear separation between the concepts.

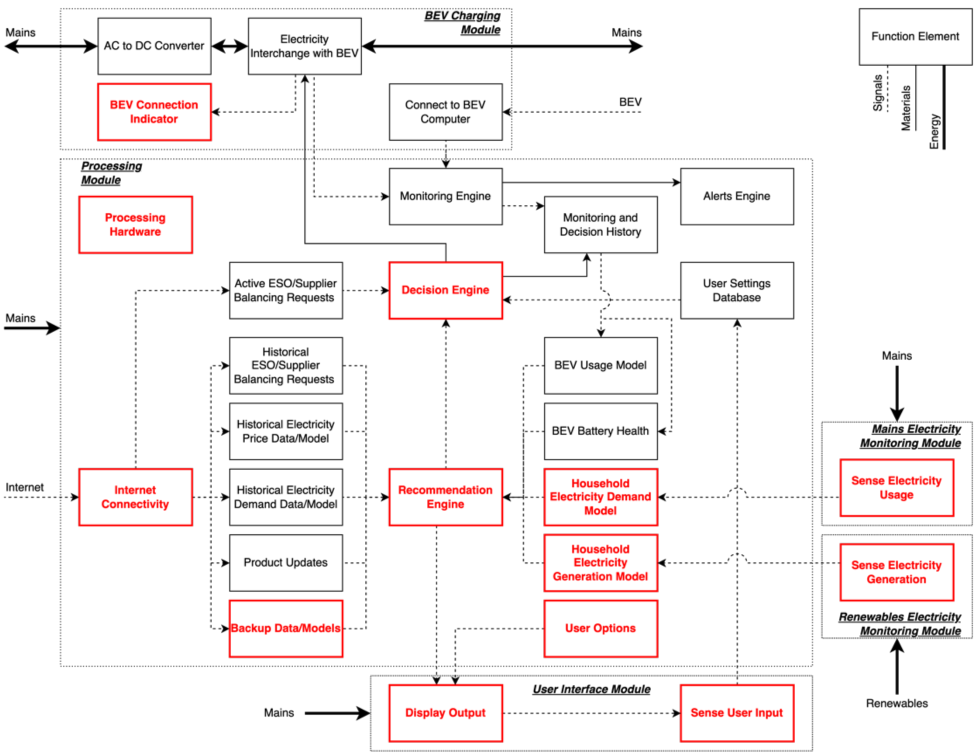


Figure 6. Function Model of the V2E System. Potential function carriers for red highlighted sub-functions are shown in Table 8.

Table 6: Selection Criteria. Key: CS=criteria scoring method used. W=weighting.

#	Name	Description	CS	W
1	Manufacturing/ Development Cost	Cost of manufacturing physical units and software.	B	2
2	Installation Time	How long it takes to install.	B	2
3	Initial Setup Time	How long it takes to setup.	B	3
4	Ongoing Update Requirements	Amount of time required to keep system up to date.	B	3
5	Ease of Access to Interface	Is the user restricted in where they can access the interface?	C	2
6	Interface Aesthetics	How pleasing the interface is to look at?	C	2
7	Interface Ergonomics	How easy is the interface to use?	C	2
8	Modelling Power	How powerful and flexible are the chosen modelling options?	C	2
9	Flexibility/ Customisability	Degree of product customisability possible.	D	3
10	Model Explainability/ Interpretability	Ease with which explanations for the recommendations/decisions can be produced.	A	3
11	Processing Power	Amount of compute available for training models.	C	2
12	Sensing Power	Level of sensing sensitivity.	C	1
13	Online/Continuous Learning	Can the models continuously learn, or will periodic retraining be required?	C	2
14	Robustness/ Resilience	How many potential failure modes are there? Are their fallback modes?	C	2

3.6. Concept Narratives

The red concept scored very highly on model explainability given its use of rule-based approaches: it would only be necessary to provide users with the rationale behind these rules. This simplicity will also reduce development costs, but does provide less modelling power, especially if the rule set is shallow. Processing and user interface modules are built into the charging unit, which helps reduce construction costs and installation time. Installation time is further benefited by electricity usage/renewables generation sensing being delegated to users; requiring them to manually input readings periodically. This, however, results in low ongoing update requirements and sensing power scores, and contributes to low initial setup and robustness scores. The small screen and use of menu buttons further reduces the initial setup time score and leads to low scores across all three interface criteria (5-7). The lack of a fallback solution impairs robustness. Thus, while this concept is in some senses the simplest, its simplicity would be burdensome to the user and likely result in a poor product experience.

The orange concept improves on all interface criteria by utilising a separate, touchscreen display. It also introduces the personas from Table 2 into the product. Users could directly choose the persona they feel most closely aligned to, or complete a survey to be assigned to a persona. Along with the improved user interface, this is likely to reduce initial setup time and should not require regular updating. The use of wired connections to the mains fuse box/source of renewables further reduces the ongoing update requirements and increases sensing power.

Table 7: Concept scores. Red and green arrows have been used to assist in identification of where trade-offs have been made from one concept to the next. Wt=concept weight; Val=criteria value; Wt Val=weighted criteria value.

Criteria	Wt	Red		Orange		Green		Ideal
		Val	Wt Val	Val	Wt Val	Val	Wt Val	Wt Val
1	2	5	10	3 ↓	6	3 -	6	10
2	2	5	10	2 ↓	4	3 ↑	6	10
3	3	3	9	4 ↑	12	4 -	12	15
4	3	2	6	4 ↑	12	5 ↑	15	15
5	2	1	2	3 ↑	6	5 ↑	10	10
6	2	1	2	3 ↑	6	5 ↑	10	10
7	2	1	2	4 ↑	8	5 ↑	10	10
8	2	1	2	5 ↑	10	4 ↓	8	10
9	3	1	3	3 ↑	9	5 ↑	15	15
10	3	5	15	2 ↓	6	4 ↑	12	15
11	2	3	6	5 ↑	10	3 ↓	6	10
12	1	1	1	4 ↑	4	4 -	4	5
13	2	1	2	5 ↑	10	3 ↓	6	10
14	2	1	2	3 ↑	6	3 -	6	10
Total			72		109		126	155

Table 8: Morphological chart.

Sub-func. \ Solution	1	2	3
Processing Hardware	Built-in to charging unit	Stand-alone processing unit	Data sent to cloud/supplier
Display Output	Built-in to charging unit; 6-inch LCD screen	Separate device; 10-inch LED screen	Mobile/tablet app
Sense User Input	Menu buttons	Touchscreen	Mobile/tablet app
Sense Electricity Usage/ Generation	Meter readings periodically provided by user	Wired connection to mains fuse box/source of renewables	Remote sensor gathers data and transmits via WIFI
User Options	Multiple screens of settings to be completed manually	User selects from pre-defined modes based on personas	Pre-defined modes, atypical events, and advanced settings
Household Energy Demand Model	Pre-trained model is selected based on user profile	Trained classifier: high/medium/ low based on time of day	Trained regression model
BEV Usage Model	Pre-trained model is selected based on user profile	Binary classification: BEV is in use or not	Regression model over battery capacity
Recommendation Engine	Rule Based	Content-Based Filtering	RL Algorithm
Decision Engine	Rule Based	Decision Tree	RL Algorithm
Internet Connectivity	Ethernet	WIFI	
Backup Data/Models	None – system can only charge BEV	Predefined action schedule, based on personas	Set of pre-defined models
BEV Connection Indicator	Auditory confirmation	Visual Confirmation	Mobile app notification

The more sophisticated screen and sensing will increase manufacturing costs and installation time but are likely to results in a significantly improved user experience. The RL modelling used in the recommendation and decision engines has the potential to be very powerful and can perform online learning from experience. However, it's actions would be challenging to explain to users, and it would gain experience from exploration in the real world, which runs the risk of users being left with a BEV lacking charge and/or a higher electricity bill. Shipping the product with a predefined action schedule, aligned to the personas, will increase robustness should issues arise with any model.

The green concept was given maximum points across interface criteria for its use of a mobile/tablet app. This allows users to monitor the system and update their settings from anywhere in the home, and allows the interface to utilise the power, flexibility, and high screen quality of modern devices with no hardware costs. It will, however, be imperative to ensure that high cyber security protection measures are implemented. Simpler content-based filtering and decision tree models are used by the recommendation system and decision engine respectively. Whilst these perhaps have reduced modelling power, their decisions should be more straightforward to describe to the user. The classification-based energy consumption/generation models have been exchanged for regression models, which should allow higher fidelity in recommendations and decisions. Based on this assessment, the green concept was selected for further development in embodiment design.

4. EMBODIMENT DESIGN

4.1. Product Components

The product is envisaged to comprise three components:

- **V2E charger:** the device that plugs into the BEV and regulates the interchange of electricity between the vehicle, home, and grid.
- **Sensors:** smart electricity meters that will record the power being drawn from the National Grid and produced by any sources of renewable generation. Wireless smart meters are now commonplace is UK homes; similar meters would be utilised here [20].
- **Mobile app:** the main method used to interact with the system

Figure 7 provides an overview of where each component would be installed in the home. The V2E charger would likely be mounted inside a garage or on an external wall. It would therefore need to be suitably weatherproof, which could be achieved via a sufficiently sealed unit construction. The electricity consumption sensor should be placed at home's connection point to the National Grid, and the generation sensor(s) at the output from any source(s) of renewables.

4.1.1. Charging Unit

A sketch of the main charging unit is provided in Figure 8. It is envisaged that this would be a square with side approximately 0.8 m. The CHAdeMO DC connector cable should be 5 m in length, such that users can easily reach their BEV's charging port from wherever they park. The unit will feature a small touchscreen displaying key information, such as the vehicle's current charge level, and the level the system is aiming for. It will be possible to perform very limited functions, such as indicating the battery should be fully charged or the system should shutdown. This screen is multipurpose: it indicates when the vehicle is connected; provides key information when the user is setting-off; and provides a minimal backup control method should WIFI connection be lost, or the user is otherwise unable to connect to the unit from the mobile app. A physical power button is provided for restarting or powering off the system should the screen cease to function. Further, a small set of indicator lights will provide minimal information in the case of a fault with the screen. Whilst the touchscreen does not need to be particularly high quality, it should be bright. The charger will have a built-in motion sensor to activate the screen. The main purpose of this is to make the unit more visible when the driver is parking so that the likelihood of collision is reduced. The unit will need to have a WIFI receiver so that it can connect to the energy sensors, collect data from the internet, and communicate with the user's mobile app. A moisture sensor inside the unit will be activated by water ingress. Finally, an in-built speaker can be used by the system to raise the alarm for serious faults requiring urgent user attention.

4.1.2. Mobile App

Rather than integrate a large, more sophisticated, and higher cost screen within the charging unit itself, the preference is for users to primarily interact with the system via an application on their mobile and/or tablet device(s). Users can interact with the system from anywhere in the home, and devices tend to have relatively high-quality screens, which would be costly to install in every charging unit. Further, users are likely to update their devices more regularly than they update their BEV charger, and so improvements in screen quality and interface design can be taken advantage of. Mock-ups of potential app screens are shown in Figure 9 and Figure 10. Attempts have been made to keep the screens uncluttered. Ubiquitous use of tool tips enables less information to be displayed initially. By clicking on the "i" icons users will be taken to separate pages with detailed descriptions, animations, and videos.

4.2. Algorithms and Data Sources

4.2.1. External Data and Models

Historic electricity price, demand and balancing requirement models are used by the recommendation and decision models. Price models will be used to plan periods when electricity will be bought from the National Grid and when it will be sold back to the Grid.

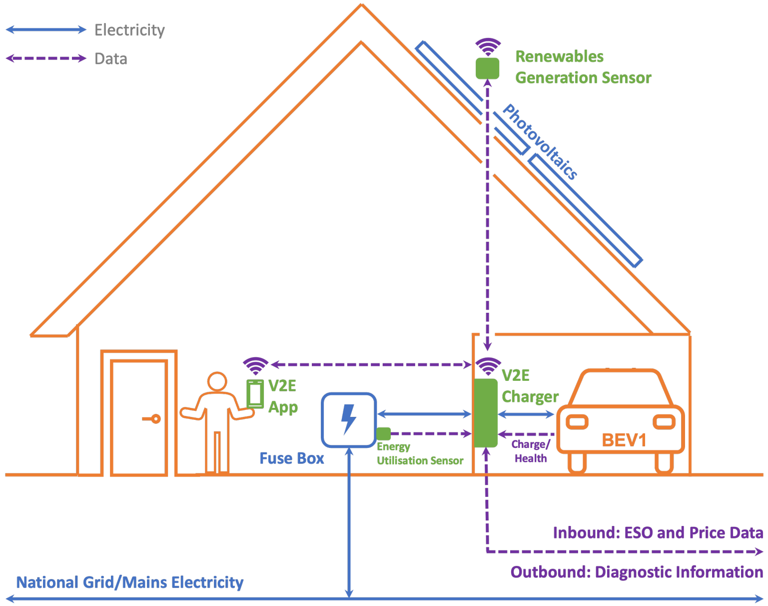


Figure 7: Placement of V2E components within a home.

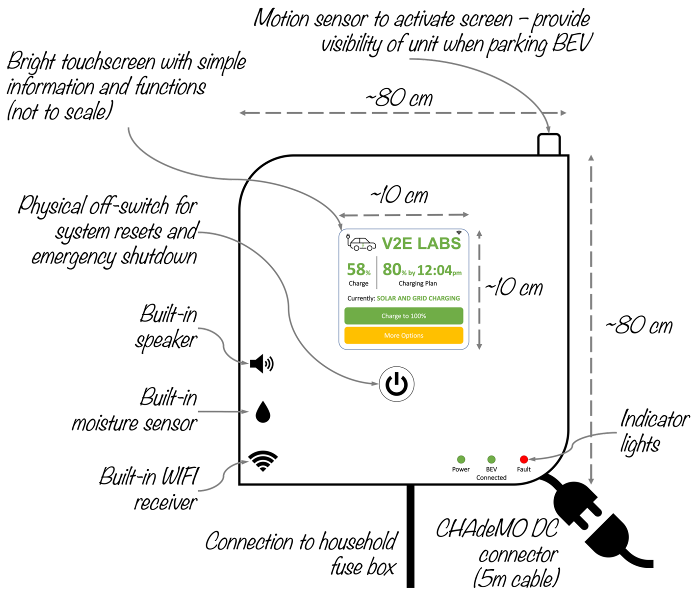


Figure 8: V2E Charging Unit.

Figure 9: V2E mobile app mock-ups.

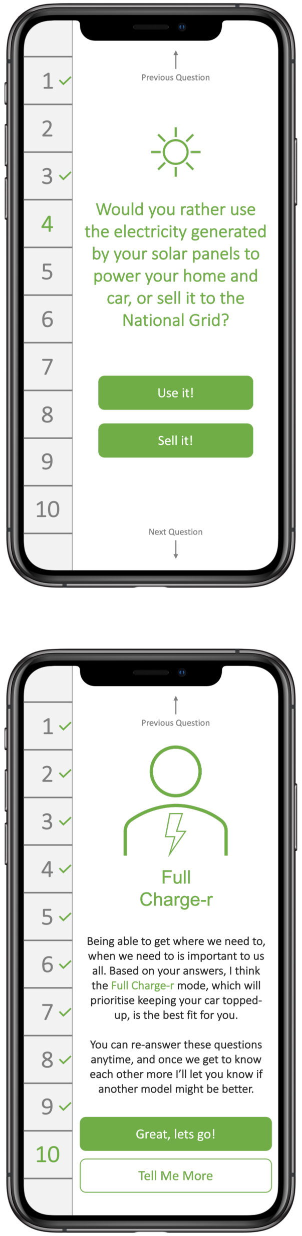


Figure 10: V2E setup screens.

For example, the model may indicate that electricity prices will be lowest from 1-4 am, and so the system will plan to charge the vehicle then. If performing time arbitrations, the battery could be charged to a higher capacity than the user requires such that excess electricity can be sold to the Grid at a time of high system prices the next day. Rather than have every charging unit train these models independently, it makes sense for them to be trained centrally and periodically distributed to the charging units via their internet connection. The units will be shipped with the latest available models, such that an initial lack of internet connection should not inhibit its operation. As time series data is being used, auto-regressive models could be trained. Alternatively, sparse Gaussian-process methods could be applied, allowing the uncertainty in predictions to be used by the recommendation and decision engines. A major source of the data will be the Balancing Mechanism Reporting Service (BMRS), which maintains a public-facing API that can be used to extract supply, demand, system price, and balancing information at a granularity of 30 minutes [21]. Many other services with lower granularity are also available from the ESO. Further pricing information would need to be sourced from electricity suppliers, such that a suitable model can be provided to users based on their particular supplier and tariff.

4.2.2. BEV Data and Models

The CHAdeMO charger type supports the CAN (Controller Area Network) communication protocol [22]. Compliance with the ISO 15118-1:2019 standard for vehicle to charger communication should enable data transfer with similarly compliant BEVs [18]. This will enable the charger to determine the current battery capacity and battery health. The charger will also maintain a history of when the vehicle is connected. A simple binary classification model could be trained to predict whether the vehicle is likely to be present in each 15/30-minute period. The output of this model would effectively describe the frequency with which the vehicle has been present in each period in the past. Discounting should be applied such that recent data is weighed more highly. Maintaining a history of BEV charge at the start and end of regular journeys would allow the charger to make a simple prediction of what the battery's capacity is likely to be when the vehicle returns.

4.2.3. Household Data and Models

Data would be provided via the installed smart sensors and regression models trained to predict demand and generation. It is hoped that these could be trained such that they are unique to each user, however this will depend on the specific regression method used, and the compute power of the unit. Proof-of-concepts would need to be conducted using data collected from real homes, and the performance of models trained using low-compute devices examined. If significant compute power is necessary to obtain reasonable performance it may be necessary to consider forwarding user data to a training server (which introduces additional privacy and cyber-security concerns), or it may be possible to instead generate a central library of models for different categories of typical users, and simply use the collected data to classify the user such that the appropriate model can be downloaded.

4.2.4. Recommendation Engine

The primary purpose of the recommendation engine would be to classify the user into a persona, which would then drive the decision engine's choices. Information about the user's energy and BEV utilisation combined with the models of external prices, demand and balancing requirements could be used to up/down-weigh certain personas. For example, if the user usually works at night then "Money Saver"/"Investor" may not be as appropriate as "Eco-Warrior," given their vehicle will be mainly plugged-in at home during the day when system prices and renewable generation from solar are typically highest. This information would need to be combined with information about the specific user/household. A content-filtering based approach may be suitable, where users are questioned about their preferences and opinions regarding the climate, helping others, taking risks, etc. Based on this information they could be clustered and aligned with personas. This process has the further advantage of potentially leading to the identification of additional/different personas.

4.2.5. Decision Engine

The decision engine must combine information from the models developed with user's preferences and any balancing requests from the ESO/suppliers to decide whether to charge the BEVs battery or discharge to the home and/or Grid. The use of a decision tree will enable decisions to be explained to the user, increasing their trust in the system.

5. RISK ASSESSMENT

5.1. System Boundary

The functional model in Figure 6 was used as the basis for defining the system boundary. However, as well as the owner of the BEV/home, it was important to consider the people and infrastructure the system is dependent on and could potentially impact. Primarily, this is the local and National Grid. The system should support the stability of the power network by receiving information/instructions from the ESO, and appropriately adjusting its behaviour. The negative impacts of this signal not being received were thus considered.

5.2. Risk Matrix

Figure 11 shows the risk matrix used to assign likelihoods and risks to each hazard identified. Definitions for each likelihood score and examples for each impact score are provided. Cells highlighted in red represent intolerable risks which must be mitigated before the product can be released to market. Excluding malicious activity, the system causing the death of a user once every 10 years would be unacceptable, given the monetary, reputational, and human costs involved.

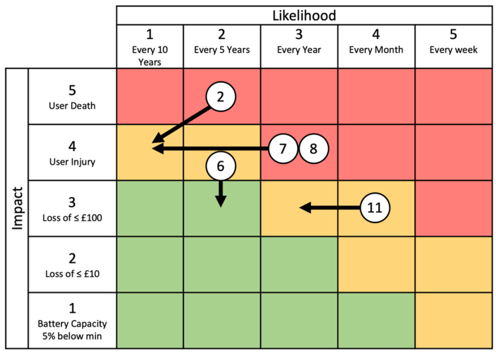


Figure 11. Risk Matrix. A selection of hazards identified via the SWIFT approach, referenced by their IDs from Table 9, are shown.

5.3. SWIFT

The Structured What-If Technique (SWIFT) [23], [24] was employed to identify relevant hazards and risks associated with many of the sub-functions in the functional model. The outcome of the analysis is shown in Table 9. The SWIFT method was chosen as it allowed the systematic consideration of each sub-function and the ways in which deviations from normal operations could occur. Any existing controls to mitigate each hazard were identified and resulting likelihood and impact scores assigned. Each risk was then ranked.

A selection of examples from Table 9 are shown in the risk matrix, Figure 11, referenced by their ID. The markers are placed at each risk's original location within the matrix, and the arrow indicates their final position. For example, water ingress to the system resulting in a fire or electrocution is unlikely to happen annually, but could lead to user death, which is unacceptable. By designing the unit to prevent water ingress, installing a moisture sensor, and automatically ceasing power transfer between the BEV and the home/Grid in the event of the moisture sensor activating both the likelihood and impact are reduced, moving the hazard into a tolerable position in the matrix.

6. VERIFICATION AND VALIDATION

6.1. VCRM

The verification cross-reference matrix (VCRM) shown in Table 10 specifies how a subset of the functional requirements from Table 4 should be verified. To aid traceability, the requirement IDs across the two tables correspond. The most challenging requirements to verify are likely to be those relating the performance of predictive models and the decision engine. Large quantities of data will be required, and it will be vital to assess a broad range of potential users and scenarios.

Table 9: SWIFT Risk Assessment. Key: L=likelihood, I=impact, R=risk ranking.

Sub-Function	What-if?	ID	Hazard	Relevant Controls	L	I	R	Action Notes
Processing Hardware	Electricity supply lost	1	Charging unit stops receiving signals and maintains current operation indefinitely		3	2	7	- Charging and processing modules share the same power source - Power interchange ceases if power to the unit is lost
	Water ingress to charging unit	2	Potential fault or fire, and risk of user electrocution	- Unit designed to prevent water ingress - Moisture sensor - In-built speaker	1	4	1	- Cessation of power interchange if moisture censor trips - Audible alarm, and screen flashes
Display output	Failure of in-built screen	3	User unable to interact with charger via screen	- Mobile application - Physical power switch	2	2	10	- Autodetection of system issues and automatic reboot
	User disables notifications in phone settings	4	Important information/ alerts are not seen by user		3	2	5	- Display alerts on charger screen - Prevent charging until critical alerts acknowledged
Internet Conn.	Connection Lost	5	Customer cannot access system via app	- In-built charging unit screen	3	2	6	- Critical information and functions available on charging unit screen
		6	Cannot receive instructions from ESO; device draws power during grid instability	- Device uses existing model of peak demand and avoids charging during these periods	2	3	4	- None – the only alternate option would be stop charging, but this would be an overreaction given the redundancy built into the Grid
	Traffic intercepted	7	Information about user's vehicle and electricity consumption is stolen	- Adherence to Schedule 1 of The Electric Vehicles (Smart Charge Points) Regulations 2021 [15], which specifies cyber-security requirements.	1	4	3	- Mobile app must be on the same WIFI network as the charger. This prevents the user from accessing the system whilst away from home, however users are unlikely to use the system when their vehicle is not plugged in.
	Malicious access/activity	8	Third-party accesses system and modifies settings resulting in lower charge and potential money loss		1	4	2	
Household Demand Model	Demand underpredicted	9	BEV undercharged at low market price; higher costs incurred		3	2	9	- Periodic model retraining - Measure divergence with fallback/typical model(s) - Use fallback model if divergence is above a certain threshold
	Demand overpredicted	10	BEV overcharged when market price low; cost incurred		3	2	8	- As above - Track expectation vs. reality; sell excess charge at next peak time
Decision Engine	Battery charged at high market price, discharged at low	11	Financial loss	- Time arbitration opportunities only considered in "Investor" persona	3	3	4	- Capital at risk warnings - Frequent performance feedback - Regular prompting that they're happy to continue in this mode

6.2. Simulations

Supplier/ESO pricing and demand data for the past several years is available via sources such as BRMS. This can be used directly in a simulated environment to analyse how the system would perform.

Household energy utilisation and generation data, as well as BEV utilisation data, could be gathered from a range of target audience members over the course of several weeks/months using prototype sensors (thus also enabling field testing of these sensors too). Even in the initial days/months of data collection it would be possible to start creating simulated environments. Trends in the collected data could repeat over several weeks/months, or increase/decrease over time, etc. As more data is collected the simulations can be refined. The use of such simulated environments will allow investigation of many possible combinations of events and user/energy system behaviours, as well as the performance of sensitivity analyses. The decision engine can be exposed to many different simulations and combinations of user settings. The impact of the decisions it makes can be assessed immediately.

Models can be trained using varying periods of real/simulated data, and then assessed against the following weeks or months of data. While conducting field tests will still be vital for identifying additional sources of noise, simulations offer an efficient way to analyse performance against a highly diverse collection of potential user profiles within broad-ranging environmental settings in a highly cost-effective manner.

6.3. Usability Evaluation

Table 11 provides an evaluation of the V2E mobile app against Shneiderman's Eight Golden Rules [25]. This relatively cheap-and-cheerful evaluation was quick to conduct, and highlighted areas that had not yet been considered. For example, no shortcuts have been implemented thus far. The Calendar screen is a prime candidate for shortcuts: tapping on a day/event could open a screen where it can be edited. Having the ability to select what data and actions are shown on the home screen may be useful to advanced users.

6.4. In-Situ Validation

While the use of simulators will provide significant insights into the ability of the product to meet pre-defined requirements, it will be vital to get prototype units into the homes of real target audience members at the earliest opportunity to perform fields tests and validate that the product fulfils user expectations.

For example, the personas assume users can be clustered into the groups defined in Table 2, and the initial recommendation engine will make decisions based on both data and questions that have been predicted to be insightful for effective classification. Further, the choices made by the decision engine based on the user's assigned persona will initially be founded on assumptions regarding how the user would want the system to act. Information can be gathered from target audience members regarding their agreement with the system's reasoning and assessment. Users' assessment of the decisions and their performance will be insightful for refining how users are grouped into personas, and the impact the personas have on the choices made by the decision engine. Once users are in broad agreement with the persona they have been assigned to and the decisions being made, it will be possible to evaluate how happy the user is with the system's performance. That is: how well is it achieving their household energy priorities?

Table 10: VCRM

Req #	Requirement	Method	Allocation	Environment	Success Criteria
1	Device *should* have a motion-activated light and/or screen.	Demo	Prototype charging unit	Prototype unit mounted 1.5m above the ground in a real or mock garage of typical size.	When the tester moves towards the unit in a vehicle (simulating parking) the screen activates.
5	Charging unit *shall* deliver power to the BEV at 7 kW.	Test	Prototype charging unit	Prototype unit connected to BEV power unit capable of measuring power delivery.	Power delivery is 7 kW ± 5 %.
7-9	Device *shall* have access to supplier/ESO data and models.	Test	Prototype processing unit software	Computer	Integration test suite – ability to access data/model endpoints tested automatically with every merge to main branch.
11-13	Device *shall* be able to establish data connection to BEV and determine charge level/battery health.	Test	Prototype charging unit	Prototype unit connected to a selection of makes and models of BEV.	Data connection established and desired information accessed.
14-16	Device *shall* have sensors to determine electricity consumption and generation, and a data connection to these.	Test	Prototype processing unit and sensors	Initial tests in lab environment; ultimately a test in a real home (field tests) required.	Censors detect rate of power consumption/generation within ± 5 %, and transmit this data to the processing unit.
17	BEV utilisation model *shall* correctly predict vehicle use within 30-minute window, 70 % of the time.	Analysis	Prototype processing unit	A range of synthetic/simulated datasets modelling a variety of usage patterns and timescales.	Classification model achieves desired prediction accuracy; analyse poor performers.
19-20	Recommendation engine reasoning *shall* be provided and can be readily interpreted by 80 % of target audience members. 70 % of audience agree with recommendation.	Analysis	Prototype processing unit software	Selection of target audience members are asked to complete the initial system setup.	Required thresholds of target audience members agree with the personas they were assigned, and understand why they were aligned to them.
21	Device shall have a decision engine which makes decisions such that users have sufficient charge for this journey 95 % of the time.	Analysis	Prototype processing unit software	Simulated environments, and then field tests in real homes over the course of multiple months.	Required threshold is met; analysis of scenarios that result in near failure of requirement.

Table 11: V2E app evaluation against Shneiderman's Golden Rules.

Rule	Evaluation of the V2E App
Consistency	Consistent use of colour, font, and language, and standard icons throughout.
Shortcuts	None implemented so far, however the Calendar screen is a prime candidate.
Informative Feedback	Clear indication of where the user is in the setup process.
Closure	Descriptions given regarding why the user has been assigned to a persona. Home page explains what the system plans to do next and why.
Error Handling	Not yet considered. Key here will be to avoid jargon; errors must be explained simply.
Action Reversal	Users can go backward and forward through the setup screen; made clear that they can repeat the process anytime.
Locus of Control	Ability to charge vehicle to 100 % prominently displayed on home page. Further options may help with adherence to this heuristic.
Short-Term Memory Load	Initial setup and settings screens have been kept as simple as possible by minimising the number of choices and using standard control elements.

7. SUMMARY

By following a structured and systematic approach, it has been possible to make significant progress in the initial developmental of a V2E system. Conducting user interviews, in accordance with section 2.2, would be the most crucial next stage. Many assumptions had to be made regarding the likely primary drivers of target users, culminating in the development of the personas in Table 2, which have pervaded throughout the remainder of the design process. Identifying whether these truly reflect the diversity of typical users, and what actions each group would expect the decision engine to take, will be invaluable for the detailed design of the system, and continuing to validate that the right product is being built. It will be necessary to complete the full requirements specification process, and appropriately update the conceptual and embodiment design stages. A FMEA assessment of the decision engine would be useful in further exploring the impact the failure of this component could have. Continued expansion of the VCRM will be critical, as will continuing to revisit validation as prototypes are developed. There is an exciting journey ahead for the product, whatever its final form may be.

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