Harvesting Green Miles from my Roof:
An Investigation into Self-Sufficient Mobility with Electric Vehicles

Jacky Bourgeois, Stefan Foell, Gerd Kortuem, Blaine A. Price,
Janet van der Linden and Eiman Y. Elbanhawy
The Open University
Walton Hall, Milton Keynes, MK6 7AA, UK
{jacky.bourgeois; stefan.foell; g.kortuem; b.a.price;
janet.vanderlinden; eiman.elbanhawy}@open.ac.uk

Christopher Rimmer
E.ON UK, Technology Centre
Nottingham, NG11 OEE, UK
christopher.rimmer@eon-uk.com

ABSTRACT

Electric vehicles are an increasingly attractive option for households to reduce carbon emissions, especially when they are powered by renewable energy. In this paper we report the results of an 18-month field trial investigating the desirability and feasibility of powering electric vehicles (EVs) with domestic solar electricity. Based on extensive collection of data from 7 households including over 75,000 miles of daily EV use, home electricity consumption and generation, and in-depth interviews with householders we develop a detailed understanding of what drives EV decisions in households, quantify to what extent our participating households currently power their EVs with solar electricity, and investigate how feasible the vision of "self-sustaining electric mobility" is. We use this understanding to draw implications for future research into supporting emerging practices of EV drivers.

Author Keywords

Electric vehicle; sustainability; microgeneration; solar electricity; domestic charging; user study; data mining

ACM Classification Keywords

H.5.m Information interfaces and presentation (e.g., HCI): Miscellaneous

INTRODUCTION

Electric vehicles are an increasingly attractive option for households to reduce carbon emissions, especially when they are powered by renewable energy. Studies show that pro-environmental orientation is one of the key factors for the purchase of EVs [39,7,17]. This is similar to the adoption of domestic solar Photovoltaics (PV) installations, which enable homeowners to generate a portion of their own energy, thus leading to the 'harvesting' or self-consumption of PV electricity [4,3,22]. The combination of EVs and solar PV installations raises the intriguing vision of "self-sufficient electric mobility", where EV/solar households power their EVs exclusively with self-generated electricity. Self-sufficient electric mobility represents a radical departure from the current situation where car owners are wholly dependent on energy companies for the purchase of energy. Instead the concept of self-sufficient electric mobility raises the possibility of a sustainable energy economy supporting free local mobility (ignoring installation and maintenance costs).

In this paper we investigate the desirability and feasibility of this vision by combining qualitative and quantitative insights from a field trial spanning 18 months and comprising 7 EV households using their EVs for a total of 75,926 miles and generating 7036 kWh of solar PV electricity in their homes.

Up to now the research literature has treated home energy and EVs as separate topics. There is an increasing literature on HCI issues related to EVs [8,16,28,25,36,38] dealing for example with issues such as range anxiety [32,24,26,23] or EV route planning [27]. On the other hand, there is a plethora of work on home energy issues [1,10,5,4,31,11,34,30,22,18] with an emerging literature on HCI issues around solar generation [21,19,35] and self-consumption [4,3,22]. In this paper we view EVs as an extension of the home, and investigate EV usage as an extension of home and work life to understand the desirability and feasibility of powering electric vehicles with domestic solar electricity. With this paper we make the following empirical and theoretical contributions: 1) we create a detailed understanding of what drives EV decisions in households and how EV owners appropriate the public/private EV infrastructure. 2) We examine how EV/solar households currently use solar energy to power their EVs and how they might do so in the future. 3) We identify directions for future ubiquitous computing research related to the home/EV/solar nexus.

The paper is organized as follows: the next section outlines existing research and clarifies the research problem. We then describe the trial set-up and study methodology. Subsequent sections then present and discuss findings of quantitative and qualitative studies. We conclude by identifying future research directions.

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BACKGROUND AND RESEARCH PROBLEM

Sustainability as Motivation to Adopt EVs

EVs are widely promoted as a green mobility solution and the literature indicates that pro-environmental orientation is a major factor for adoption of EVs. In a before/after study conducted as part of an EV trial [7] 39% of participants stated CO2 emissions as an important purchase factor before the start of the trial but this figure rose significantly to 92% after the trial. EV Drivers understood the potential for EVs to reduce carbon emissions, but realized that this can only be achieved by the use of electricity from sustainable, renewable sources. Similar studies [39,17] indicate that drivers have a strong desire to power their EVs with energy generated from renewable sources and are uncomfortable about the current green credentials of EVs.

The actual environmental benefit of driving an EV when using grid energy depends on grid carbon intensity which varies with hourly demand and geographic region. For instance, the French grid takes 77% of its energy from nuclear power plants [37], which results in a stable low grid carbon intensity (ignoring other drawbacks related to the technology). In contrast, the German and British grids have a higher proportion of wind and solar energy sources supplemented by fossil fuel sources. As a result, the carbon intensity can be higher (about 7 times) and varies significantly over the day and seasons [6]. We observe the same variations in the US, between states and within states over the day [2].

Domestic Energy Generation as Driver of Attitude and Behavior Change

Solar photovoltaic systems (solar PV) enable households to produce their own electricity, as alternatives or supplements to traditional centralized grid-connected power. Evidence is beginning to emerge that households with solar PV develop saving behaviors intended to maximize the use of local energy and to minimize the use of imported grid energy [19]. Similarly, recent work has shown the potential for energy interventions that promote or support solar self-consumption [4,35,3,22]. These studies suggest that solar PV householders appear to be willing to change behavior and make significant investments (time, money, cognitive effort) to do so. Since EV drivers also appear to have a high environmental motivation, we can speculate that EV households and especially EV/solar households are a rich field for studying intrinsic behavior change and emerging practices (originating from people's own desires, practices and local context).

HCI Research on Electric Vehicles

There is an increasing literature on HCI issues related to EVs [8,16,25,28,36,38] dealing for example with issues such as drivers worrying about whether their battery will last long enough to cover the distance they need to travel, referred to as range anxiety [15,16,32,24,26,23] or how to plan their route so that there are sufficient charging points [27]. Most of this research views the EV as a car that is hampered by limited range and the need for frequent recharging. Thus, most of this work is primarily focused on remedying perceived shortcomings and helping EV drivers deal with their cars' limitations on an emotional and/or cognitive level (range anxiety, range prediction, route planning).

Research Gap

Up to now research has treated home energy and EVs as separate topics. In EV research in particular the home and the household have been virtually invisible, despite the fact that home- and work-life fundamentally shape the demand for mobility. The relationships between household members, as well as those between them and outside organizations (school, employer), other people (friends, boss) and locations of significance (home, school, workplace, shopping center) need to be explored to understand to what extent a sustainable lifestyle is desirable/feasible – or why not. The existing EV research literature does not deliver these insights, nor has the existing HCI and UbiComp research literature developed a proper understanding of EV issues.

In this paper we view EVs as extension of the home, and investigate EV usage as an extension of home and work life to understand the desirability and feasibility of powering electric vehicles with domestic solar electricity. We do this by exploring the following research questions:

- What role do family, home and work play in shaping EV usage?
- How do EV owners appropriate the public/private EV charging infrastructure to accommodate their mobility and energy needs?
- To what extent do EV/solar households currently power their EVs with solar electricity and to what extent might they be able to do so in the future?
- What role does home life play in enabling or preventing self-sufficient electric mobility?
- Which implications do prevalent mobility and energy practices of EV households have for future Ubicomp research?

METHODOLOGY

We performed an 18-month field trial with EV households in the UK to investigate the complex interplay between electric mobility and home energy using a combination of quantitative and qualitative data analysis.

To prepare our study, we conducted explorative interviews with 16 EV drivers from England, which provided us with an understanding of the current state and perceived limitation of urban EV systems from the perspective of EV drivers. The main study was conducted with 7 of these 16 households who consented to comprehensive data collection and analysis of their home energy and EV use. These 7 households were recruited from among the participants in the Thinking Energy project [12], a 75-household smart home trial in Milton Keynes, UK, led by

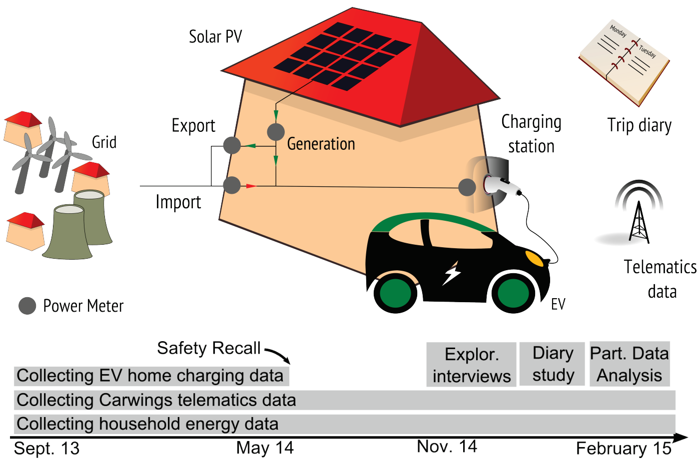

Figure 1: Study Overview

the energy company E.ON. As part of the trial, households had the opportunity to lease a Nissan Leaf (the most popular EV model in the UK). Out of the 7 households, 4 had solar PV installations on their roofs. For an overview of the households' attributes see Table 1. We use P1, P2 etc. when referring to each household, and explicitly detail when a single person is mentioned (e.g. husband, wife).

Energy and Mobility Data Collection

In order to collect household energy data we used several means. Each house was equipped with smart meters to monitor electricity imported from the grid (the typical fiscal meter), and, in case of solar PV households, generated solar energy and excess energy exported to the grid. Moreover, a dedicated smart meter was fitted to the domestic EV charging point in the garage of each house. Unfortunately, these smart meters were recalled midway through our study in May 2014 due to safety reasons. Fig. 1 gives an overview of the timeline of our data collection which lasted from September 2013 to February 2015.

To source information on households' EV mobility behaviors, we accessed data from Nissan's telematics service known as 'Carwings'. The Carwings data provided us with daily trip information, including mileage and energy consumed for single trips but excluding any location information such as trip origin and destination. For technical reasons and to protect users' privacy, we were unable to add automatic GPS logging to the vehicles so we conducted a paper-based diary study to enrich the automatically monitored vehicle data with insights about contextual trip information and charging activities including the purpose of the trip, accompanying passengers, as well as trip start and end location (e.g. home or work). We asked EV drivers to record this information on a paper-based form located in each EV. The diary study started at the end of January 2015 and lasted four weeks

	Household	Work distance	EV user	Solar PV
P1	2 adults, 2 children	Retired	shared	-
P2	2 adults, 2 children	Long commute	single	3.2kWp
P3	2 adults, 2 children	Work Locally	shared	-
P4	2 adults, 2 children	Work Locally	shared	7kWp
P5	2 adults	Long commute	shared	3.2kWp
P6	2 adults	Retired	single	1.9kWp
P7	2 adults, 2 children	Work Locally	single	-

Table 1: Household participants

Quantitative Energy and Mobility Data Analysis

The collected data was analyzed using data mining techniques to create an understanding of the household energy, EV energy and EV mobility aspects of each of the 7 households. Home energy data was combined with Carwings trip statistics to answer questions which required broader insights into the relationship between households' home energy and mobility practices such as: What is the daily mobility demand and EV electricity consumption and how does it relate to home electricity consumption? How much of solar electricity is currently used for charging EVs and how much could be used? Do households generate enough electricity from solar PV to meet electricity demand of their EVs?

Participatory Data Analysis

To enrich the quantitative insights we performed contextualized interviews with individual households using an approach which we call Participatory Data Analysis (PDA) [5]. PDA aims to understand human behavior and practices by conducting interviews in which participants interpret and reflect on their own behavior using high-level visualizations of their own data. To this end, we created what we call 'mobility clocks', visualizations that represent 24-hours of mobility and charging behavior for each household (Fig. 6). By discussing and analyzing these visualizations together with EV drivers, we were able to expand the quantitative findings with insights on the influence of household life on decisions about daily EV use and how these may aid or prevent solar exploitation.

THE URBAN EV SYSTEM

We conducted our study in Milton Keynes, a fast growing city in the UK where significant investments into the development of EV infrastructure have been made. To understand what it means for our participants to use an EV in this environment, we provide an overview of the urban EV system in Milton Keynes with a focus on public and private charging. In this context, we also look at domestic solar PV systems and the implications of energy generation tariffs for EV households in the UK.

Private and Public Charging Infrastructure

In contrast to fossil fuel cars, a wide variety of re-fuelling (charging) options exist for EVs, especially as they can be charged at domestic and/or public charging points.

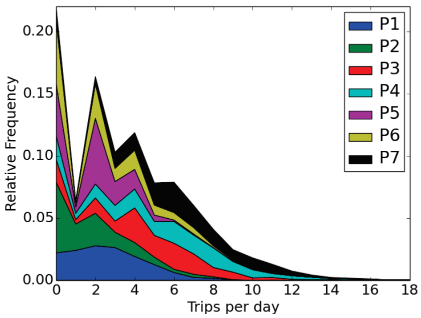

Figure 2: Distribution of number of EV trips per day

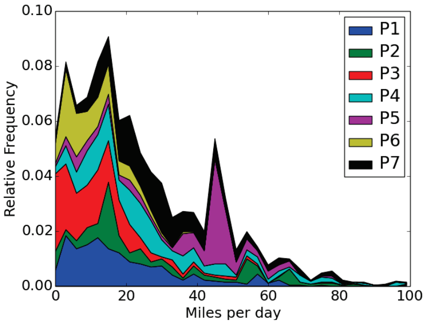

Figure 3: Distribution of EV mileage per driving day

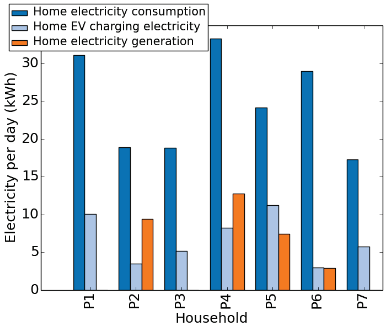

Figure 4: Daily home electricity generate and consumption

While it is feasible to plug an EV into a standard household power supply at home, most households have a dedicated charging point which eliminates power safety issues and can provide slightly faster charging than a conventional household plug. Nevertheless, domestic charging points are limited in power supply (mostly 3.3 kW, some 6.6 kW) which results in slow charging times depending on the amount of electricity charged. For instance, the Nissan Leaf 2012/2013 model that is used by our study participants has a battery capacity of 24 kWh which gives about 75 miles of urban driving range. Consequently, a full charge of the car's battery may take up to 7 hours when plugged in at home. The costs of home charging are GBP 0.12 per kWh given current UK daytime electricity prices, hence EVs imply lower per mile fuel costs compared to fossil fuel cars. Households may also decide to use a dual electricity tariff, known as Economy 7, where electricity is cheaper at night at GBP 0.06 per kWh but more expensive during the day at GBP 0.18 per kWh.

Away from the home, drivers can rely on a workplace or public charging infrastructure where they can also find more powerful rapid charging opportunities [29]. Rapid charging is the quickest charging option available by which it is possible to reach 80% charge within only 30 minutes. However, using non-domestic charging infrastructure poses challenges in terms of costs, convenience and reliability. First, drivers need to carry separate RFID membership cards for each system they might wish to use, as there is no integration of public charging systems managed by different providers. Second, public charging often incurs higher costs - with an hourly rate of GBP 1.00-1.70 at 3-9 times the cost of home charging. In terms of rapid charging, companies charge GBP 7.50 for 30 minutes use (3-6x the cost of slow home charging) while at the time of writing, one provider offered unlimited free (with membership card) use of its rapid charger network at IKEA stores and major motorway service stations. Workplaces may also offer slow charging with a paid-for membership card. Some EV owners desire to charge their EVs while at work in addition to domestic charging [20]. However, studies show that the vast majority of current users rely on domestic charging [9,33].

Domestic Solar PV Systems

As domestic solar PV systems have become more widespread in the UK, charging EVs at home also appears in a new light. The combination of EVs and solar PV installations further increases the value of domestic charging as free and green electricity is generated by the households that can be used for self-consumption and support mobility electricity demand.

The introduction of a Feed-in Tariff (FITs) scheme in the UK in 2011 has made the deployment of solar PV installation very attractive [14]. Under this scheme, home owners receive rewards for electricity generated on-site and unused generated electricity exported to the grid. The original scheme in 2011 paid GBP 0.43 per kWh of generated electricity plus GBP 0.03 per kWh of exported electricity. Consequently, the financial incentives for making use of self-generated electricity are high, since the payment for export is very small while electricity import is expensive. Meanwhile, the subsidies on solar PV FIT have been cut by more than 50% [13], so that effective self-consumption of solar energy is becoming even more important. By providing battery storage, EVs reduce the need for solar PV households to export energy to the grid and thus improve the ability of solar PV household to productively exploit the free and green electricity they generate, thereby helping to make households more autonomous and energy-independent despite the fact that EVs increase overall electricity consumption.

QUANTITATIVE ENERGY AND MOBILITY ANALYSIS

Powering EVs implies a wide range of energy decisions, in particular in homes with solar PV installations. However, existing research is scarce about insights into the relationship between EV mobility behaviors, the electricity demand resulting from EV mobility and opportunities of home electricity generation. Below we investigate this relationship with a detailed mobility and energy analysis based on 12,434 EV trips covering 75,926 miles, and 4.95 million instant power consumption readings sourced from the 7 households participating in our study (4 of which with solar PV installations).

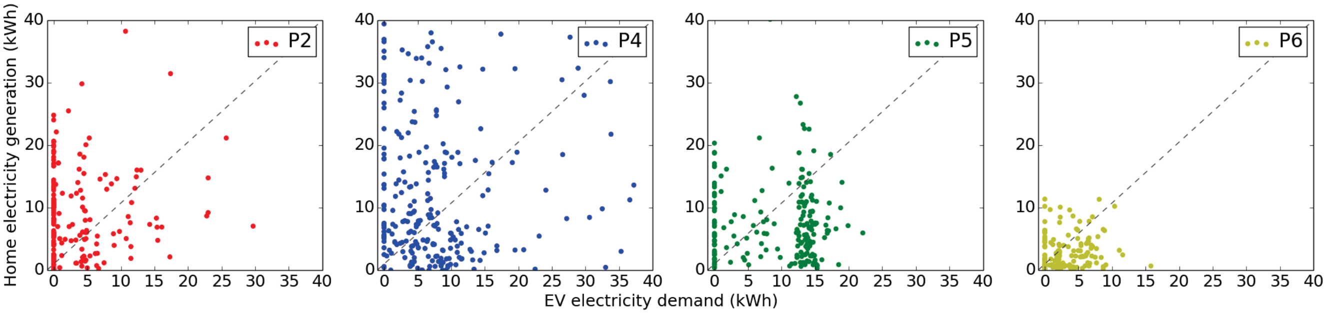

Figure 5: Scatter plots comparing daily EV electricity demand and solar PV electricity generation per household

EV Mobility

From the trip information recorded by the cars' telematics systems, we can characterize and differentiate daily EV usage of the seven participating households. Fig. 2 shows the distribution of number of trips per day for each household. Overall, since EVs are often used for short and opportunistic trips around the city, we can see that EV usage sums up to many trips on single days. Especially, P3, P4 and P7 that represent employed households with children have a wide distribution of daily trip activity and frequently use their EV for 4 or more trips per day. While P2 and P5 are also households with regular employment, they have to perform longer daily commutes and use their EVs often for 2 trips per day only. P1 and P6 are retired households with a restricted mobility demand in the range of 2-4 trips per day. Moreover, there is also a high fraction of days (22%) combined for all households with no trips at all where the cars were parked and stayed still.

Fig. 3 depicts the distribution of total EV mileage per driving day. The median of daily driving distances is 20.8 miles while on 75% of all days driving distance was below 40 miles (out of a 75 mile capacity). P5 stands out by a high concentration of longer-distance trips caused by daily commutes of the two household members to workplaces outside of Milton Keynes. Other households' mobility radius is smaller and most often restricted to intra-city distances, given a high density of daily trip distances of no more than 7 miles (P3 and P6) or maximum 17 miles (P1 and P2). P4 and P7 have a wider distribution of daily mileages which is characteristic of their need for being flexible about their mobility behaviors due to changing roles and responsibilities in their jobs and lives. Sometimes, the households used their cars for journeys to remote destinations at greater distances, e.g., to travel to the airport (P2 and P4) or visit relatives and friends in other towns (P1).

Home Electricity

We have performed further analysis of smart meter data to understand the implications of households' EV usage for the home energy ecosystem. Fig. 4 displays overall household electricity consumption against electricity expended for home EV charging. EV charging introduces a significant overhead to home electricity consumption. Combined for all households, the median of household electricity spent on EV home charging is 28%, with some households reaching 46%. Moreover, Fig. 4 depicts the amount of generated daily electricity of the four households with solar panels. Over the period from September 2013 to May 2014, we could observe a median electricity generation of 8.44 kWh per day. With the Nissan Leaf's expected driving efficiency of 24kWh/75 miles, this translates to about 26.4 miles of free green driving range per day. It is important to note that the availability of solar electricity is strongly affected by seasonal variations. While during the winter months electricity production was at its lowest with 3.94 kWh per day, households produced significantly larger amounts of solar electricity during the spring period with 13.73 kWh per day.

At the same time, solar electricity generation also varies among the individual households depending on the size of installed solar panels and further contextual factors associated with the houses (orientation of roof, shade effects, etc.) Both P2 and P5 equipped their homes with standard PV installations of 3.2 kilowatt-peak (kWp) capacity, hence similar amounts of solar were generated among them. In March 2014 P4 put additional solar panels on the roof of his house to double peak capacity to 7 kWp which enhanced the potential for high levels of electricity production all year-round (i.e., spring generation increased to 22 kWh per day). Due to a smaller investment into panels with 1.9 kWp capacity, P6 produced the lowest amount of solar electricity among the different households.

Overall this analysis shows that EV electricity consumption significantly increases overall electricity consumption and that for our 4 solar/EV households electricity generation and EV electricity consumption are of similar magnitudes.

EV Charging with Self-Generated Electricity

While the data demonstrates a high potential of powering EVs with self-generated electricity, the analysis ignores the asynchronicity of home generation and EV demand. Unless the homes have a battery for storage of solar electricity (which currently they do not), the solar electricity cannot be directly used for EV driving. We found that currently only a fraction of the electricity for EV home charging comes from solar and that the fraction varies considerable between households from 3% to 27%.

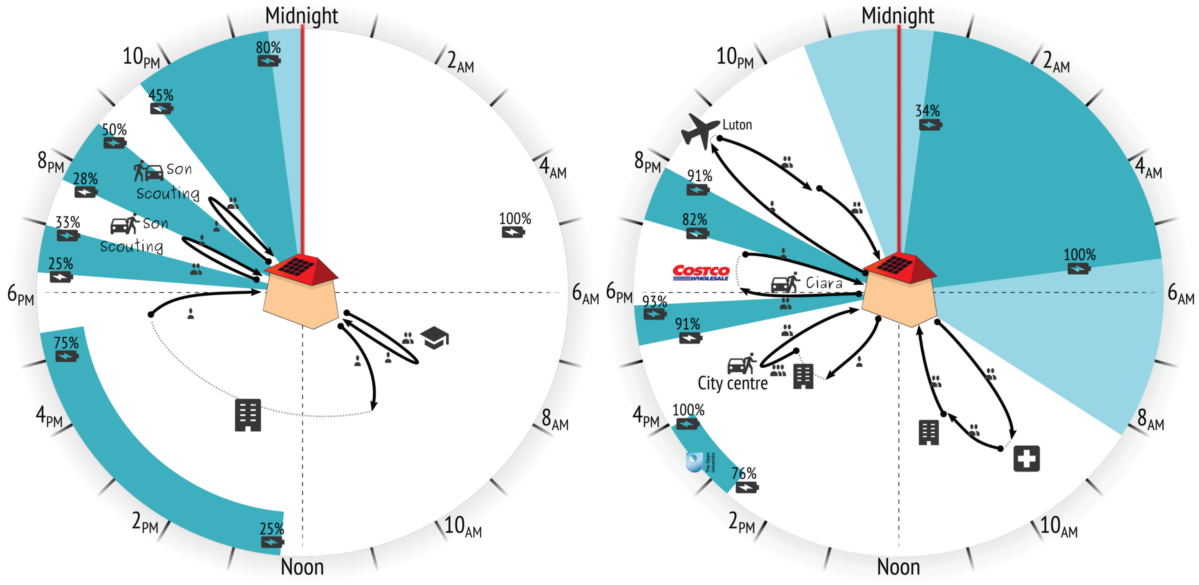

Figure 6: EV mobility of P2 on Feb. 23rd (left) and P4 on Feb. 12th (right)

To explore this issue in depth, Fig. 5 compares daily household electricity generation with daily EV electricity consumption, with each scatter plot depicting one of the 4 EV/solar household and each dot representing a single day. Dots on the diagonal indicate days where electricity demand from EV driving exactly matched home electricity generation, dots above the diagonal represent days when electricity generation exceeded EV electricity use (we call this an ‘energy-positive day’), and dots below the diagonal represent days when electricity generation was less than EV electricity use (i.e. ‘energy-negative day’)

All households exhibit energy-positive and energy-negative days. The percentage of energy-positive days is 77% for P2, 59% for P4, 42% for P5 and 46% for P6. P2 and P5 show similar generation patters (they have identically sized solar PVs) but because of P2’s more moderate mobility demand P2 has many more energy-positive days. P4 and P6 show diverging patterns: P4 has a large mobility energy demand but also generates a lot of energy, while P6 has a small mobility energy demand and also generates comparatively little energy. This is both a result of the relative size of the solar PV installation (P4 = 7 kWp; P6 = 1.9 kWp) as well the family characteristic and the resulting mobility demand (P4 is a four person household and P6 is a retired couple).

Of note is that the 4 participating households are typical homes located in a country (the UK) that is traditionally not seen as an ideal place for solar generation (compared to let’s say California). Yet despite the less than ideal weather and the typical solar PV installation all homes generate enough electricity to sustain the EV mobility demand on at least 42% of days.

PARTICIPATORY DATA ANALYSIS

In order to understand the behavioral opportunities to close the self-sufficient mobility gap we needed to explore the reasons why EV drivers exhibit the observed mobility behavior and how flexible mobility behavior is. In order to achieve this goal we conducted a Participatory Data Analysis (PDA) study [5], a method which we developed to create a deeper understanding of human behavior and practices through a participatory data interpretation process of researchers and participants using high-level behavior visualizations generated from detailed behavior data. We first created behavior visualization and then conducted interviews with participants where we asked participants to reflect on their own behavior.

Visualizations: the Mobility Clock

We created behavior visualizations that use a 24-hour clock metaphor, which we call a mobility clock (Fig. 6). The mobility clock represents the spatio-temporal mobility behavior of a household. The home is located at the center of the clock (indicated by a house icon). EV journeys are represented by arrows, with the distance between the home and end points indicating the relative driving distance. A point located at the outer edge of the clock indicates a journey end-point furthest away from home. The start and end times of trips are indicated by their position with respect to the clock times. For example the mobility clock on the right side of Fig 6 shows one trip between 8pm and 9pm from home to the airport and back, with three trip segments. Destination icons indicate the purpose of a trip, e.g. school run, commute, pick up and drop of children, etc. Moreover, the names of accompanying passengers are indicated next to the arrows. This trip information was derived from trip diaries recorded by the participants.

Automatically recorded data from the home charging systems and Carwings EV information system was used to augment the visualization: home charging and time periods when the EV was plugged in at home but not charging are

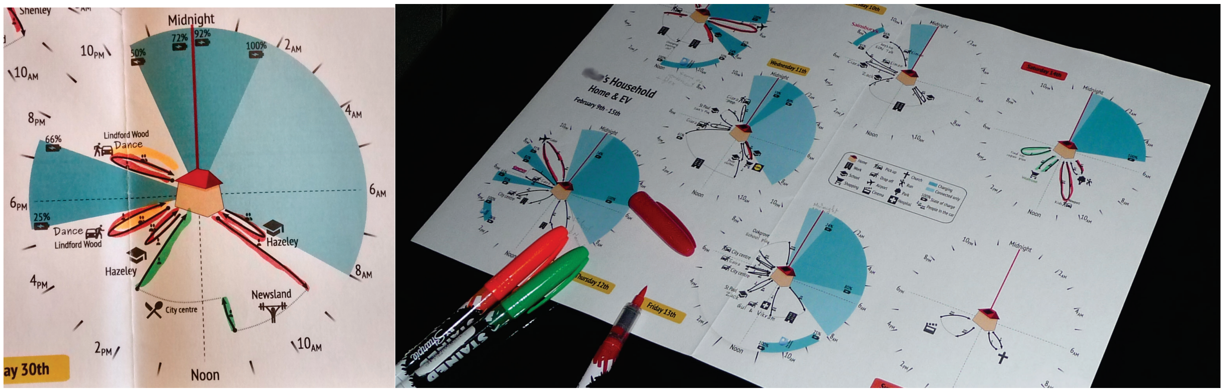

Figure 7: Interviews pictures: P1's highlighted trips on Feb. 30th (left) and P4's full week visualization (right)

represented by shaded circular areas with a dark shade indicating charging and a light shade indicating plugged in but not charging (see for example Fig. 6 on the right, around 4 am), Charging events away from home are represented by shaded areas on the edge of the clock (see Fig. 6 on the left, around 2 pm). The battery's state of charge is displayed at the beginning and the end of each charging period and after longish journeys.

Interviews

We conducted interviews with each participating household, in which we used the visualizations to help participants reflect on what they did during each day, how and why they used their EV, when, where and why they charged it, and issues going on in their lives at home or at work that might affect their mobility needs. Each interview lasted about 45 minutes and took place at the participants' home or workplace, with one or two household members. Each session was voice recorded and transcribed. We briefly introduced the visualization to the participants through an enlarged and generic mobility clock. The actual interviews were conducted using an A3 paper sheet with 7 mobility clocks representing the last week of driving and charging behavior from before the interview date.

We initiated the discussion by asking them to talk us through their patterns of EV usage as shown in the mobility clocks. During the interviews we asked open questions such as "*How did you plan this trip?*" and "*Why did you decide to undertake this journey*?", as well as closed questions such as "*Was this charging event planned or opportunistic?*". We also invited participants to use different colored pens to indicate flexibility of trips – red indicating inflexible trips that had to take place at the time when they took place (for example a school run) and green indicating flexible trips which the participants could have undertaken earlier or later than they actually took place (Fig. 7). In other words a flexible trip is one that could be time-shifted (started earlier or later), while an inflexible trip has to start at or near the time when it did.

The participants had no difficulty interpreting the mobility clocks and describing their daily routines. The only difficulty was changing from one day to the next as it required a mental exercise to visualize the end of the day on one mobility clock and the start of the next day on the following mobility clock. In our experience the use of behavior visualizations led to deeper insights and more engagement than traditional unmediated interviews. Participants uncovered their own routines, made new discoveries about their own behavior, explained their behaviors or reasoning at the time with anecdotes triggered by events or situations recorded in the visualizations and occasionally checked their dairies to add vital information that was missing from the visualizations.

FINDINGS

Daily Usage

For all participating households, the EV is the primary car and is used for any local trip and daily commute. Many had either a second car or a bicycle as backup. P4 and P7 used the EV for all trips, even those that stretch beyond the nominal range, while P1 and P6 used a fossil fuel car for out-of-town trips. P4, P5 and P7 had jobs and used their cars for daily commutes to and from work. These trips were obligatory and not flexible. However P1, a retired couple with children, indicated similar constraints as they engage in many activities (e.g. visits to the yoga class, doctor's appointments) as well as school runs and children activities.

We asked participants to highlight their '*flexible*' trips in green and others less flexible in red. Figure 7 illustrates this exercise, showing on the left P1 with non-flexible a school run and a yoga class in Newsland in the morning marked in red. The rest of the sport session did not have a time constraint, marking in green the way back and lunch break in the city center as more flexible activities. Overall participants marked between 25% and 40% of all trips as flexible and 50% as non-flexible (not all trips were marked by the participants). Most of the non-flexible EV activities were connected with appointments, classes or meetings.

Several participants remarked that during actual driving there is also some flexibility as they are able to adjust their driving behavior when noticing that electricity consumption deviates from what they had planned for. On such occasions they are able to adjust to consuming less power by driving at lower speed, switching off heating, etc.

A different point was made by P3 who drives mostly for very short trips, and never risks pushing the available mileage (as indicated on the EV mileage prediction indicator) to its limits. They noticed a perverse effect of driving only short trips: the range – computed on past driving habits – becomes shorter and shorter and their willingness to drive for longer distances also decreases. Improving the range prediction with a forward view of the household's upcoming trips appears to be an important step toward an easier trip planning.

Planning

Family life in most of the households requires coordination and management of mobility needs of both parents and children. Most trips are regular and fixed, e.g., school runs of the children, and are incorporated into planning of weekly schedules to make sure that the car is charged with sufficient energy for these trips. Planning is essential for the participants to anticipate the use of their cars.

Participants mention a continuous awareness of the state of charge of the car's battery and how this determines the remaining range. We observed two forms of planning, either in a weak or strong form depending on how much routine behavior is involved in a trip. For instance, daily mobility routines require no explicit form of planning; the participants have learned the driving implications from previous trips. P4 has distance and energy demands memorized for all routine trips. Yet even for routine trips participants estimate the electricity demand beforehand.

P1: "It's easy to do in your head (daily trip planning), because there are only 3 or 4 distances."

In contrast, exceptions to daily routines require more planning effort. P3 makes use of a calendar in the kitchen to indicate unusual events for the whole family. This helps him to anticipate any need for special EV trips. P4 has a similar calendar on his smartphone of which he makes use to plan the coming EV usage. He would appreciate if the car could be aware of upcoming events automatically.

On top of household's activities, the season and weather impacts on the way people use their EV. In the summer there are more opportunities for alternative modes of non-motorized mobility such as walking or cycling. When there is good weather P4 and his family often do not use their car as part of a conscious decision to increase their level of physical activity. Looking at P7's data we were surprised by the radical changes in the charging pattern from one week to another. During the interview we understood that while P7 normally relies on free public charging, cold winter nights alter the charging pattern. To defrost the car's windscreens, they decided to have the car at home as they can then use a smartphone app to start the heating while the car is charging in the driveway. This highlights that even regular routines can be altered to satisfy a different objective, for instance from cost saving to comfort.

Roles of EV Users

The management of EV charging is mostly done by one person in the household - usually the person with the interest in energy and car technology and often the one who has driven the EV purchase decision. However, the usage of the EV is more evenly spread across all the drivers in the household. In household P1, the husband is doing all the planning of charging management while his wife uses the EV as a normal car without looking at its state of charge.

> *P1: "My wife is not aware of it (state of charge), she just drives it."*

Similarly in household P7 the EV is mostly used by the husband. Occasionally his wife drives the EV, particularly if she is late for work as there is reserved parking for EVs near her workplace. Occasionally their daughter wants to be picked up with her friends and show off the EV but other than that the husband is the household's main EV user.

Plug-in and Charging Activities

For many households plugging in the EV and starting a charge has become a routine activity which is executed at a particular time of the day and in a particular way. P1 plugs in the EV every evening before going to bed. This has been integrated into P1's evening routine which includes locking the door, turning off the lights, and connecting the car to domestic charge point in order to start the charge.

While P7 connects his EV in the evening, charging is scheduled not to start until night. P7 had originally planned to adopt the Economy 7 tariff – but this plan never went ahead and he now still works through a routine for charging which is not applicable at his house. P4 is on Economy7 and has configured charging to start after midnight. This only works if the EV is connected, but sometimes P4 forgets to plug in his EV car after coming home. As a result, the EV has not been charged overnight.

We observed that the more participants used their EV, the more they plugged it in all the time, either at home or at work. This correlation seems obvious as there is a higher need for energy. As a result, households P2 and P4 (Fig. 6) connect their EV almost each time they are not driving, creating opportunities for controlling when precisely to start the charging process. In contrast, household P6 only plugs in their car when it is needed and hence there is reduced opportunity to fine-tune the timings for charging. In the case of P6 it is hard to establish a link between PV and EV.

The confidence of users in EV technology has implications for their charging preferences and behaviors. While driving an EV does not create any problems, charging EVs is a big issue for the participants. Most participants see the home as a more predictable and reliable charging facility in contrast to public charging points. Although P7 usually prefers free public charging networks to save money, he often resorts to charging his car at home on Saturdays. This is because public charging stations such as the ones at IKEA or at the Nissan dealer are likely to be busy on weekends. P4 charges mostly at home as he can cover all of his daily trips with one full charge. Sometimes he charges at work but there the problem is that there is not always a parking bay available if all spaces are occupied by other EV drivers.

> *P4: "It's wasn't crucial (charging at home) [...] I knew I'll be running around here (driving later on in the day) [...] but I didn't know if I will get a charging position at work."*

In contrast, P5 shows high confidence in her workplace charging station. Charging only the minimum required amount to get to work, she arrives almost empty at work to take advantage of the free charging. Even though it can appear as an audacious behavior, this confidence came from daily commutes and the insurance of being able to charge. This does not apply to P5's other trips which are rare and within a comfortable range.

Free Public Charging as Replacement of Home Charging

While home charging is seen as the most reliable option, public charging points can replace home chargers if certain conditions are met. Participant P7 mostly charges at IKEA which is free.

> *P7: "I charged at IKEA [...] that is within walking distance from home"*

While P7's daily routines are driven by the desire to save money and fast top up from the free rapid chargers, it is only the close distance from home that makes it a real alternative. The IKEA public charger has effectively become the (alternative) home charger as it is only a few hundred meters away from P7's house which causes the boundaries between private and public charging to blur in this specific case. The household of P7 also changed its shopping preferences to fit with this new routine, using a supermarket that is close to the free public charging point in order to charge and shop at the same time.

While some participants like P7 exhibit clear choices about where to charge and their mental reasoning behind it, others appeared to become aware of some potential choices during our interviews. For instance, P3 charges only at home, not bothering with calculations about charging at a nearby rapid station which might be cheaper than charging at home. However, while describing his daily routines based on our visualizations, he outlined the need for a tool that would compare the potential charging points in the neighborhood (including charging at home) in terms of tariffs and other benefits or constraints.

EV and Solar PV Connection

The combination of solar PV and EV is of great interest to all participants. Even those participants who have an EV but no solar PV installation have considered investing in solar. They are hesitating to invest into solar PV mainly because of the change of UK policies in reduced subsidies for solar PV installations and the cut in feed-in-tariff which has a negative impact on the expected payback period.

P6 is skeptical about the notion of self-sufficient electric mobility, maintaining that there is no direct link between PV and EV. However, he does admit being interested in real time information about how much power from the PV would go into the car *'if such a link had existed'*.

As the most active of the participants, P5 is away at work during weekdays. However, she looks at the weather on Friday evening to see if it makes sense to wait and charge from the sun on Saturday or Sunday, of course provided it fits in with their plans for the weekend. At first motivated by the money, she explains how she realized the potential for other benefits.

> *P5: "so the incentive of the money is a good incentive to start with and then you think about all the other implications and obviously understand how it's beneficial for energy as well as for your wallet."*

EV is potentially in conflict with other household appliances which can also take advantage of solar energy. For instance, P6 does not really care whether the local generation powers his car or his dishwasher. However, the participants point to barriers which make the exploitation of solar energy for EV charging appear difficult. P1 has observed that the car charger requires a constant high power which exceeds the peak capacity of his solar PV installations so that always less than 50% of the charging energy can be provided through solar even on sunny days.

Our four participating households with solar PV installed their panels before getting the EV. All but P6 were keen to try out the EV in combination with their solar PV while P6 sees his solar PV as a 'separate' system. For the others, solar PV created an awareness of energy savings which has strengthened their motivation to purchase an EV. The idea of driving an EV through solar energy is an effective use of locally generated surplus energy. If in addition the Economy 7 tariff (UK night & day tariff) is available, some participants argue that this guarantees constant cheap or free energy supply around the clock with maximum flexibility about when to start a charge. However, for others this creates a complex decision space and they struggle to calculate whether it is better to use cheap night-time energy or green energy during the day. To support their decision making they identify the need for information currently not available; primarily real-time information about the grid's energy mix and the flow of solar energy into the car batteries.

DISCUSSION

Through our EV study we have revealed numerous issues which impact on the feasibility of achieving self-reliant mobility. On the one hand, quantitative data analysis has revealed a great potential for using solar PV to power EVs with sufficient energy to cover a large fraction of the daily mobility and energy demand. On the other hand, our diary study and participatory data analysis has shown barriers but also opportunities for effective EV solar charging practices.

Viability of Powering Electric Vehicles with Domestic Solar Electricity

In the introduction we described our vision of self-sufficient electric mobility as a household's ability to exclusively power EVs with domestic solar electricity. The EV/solar households in our study currently use only a limited fraction of solar electricity for EV charging (ranging from 3% to 27%), but on a significant number of days households do indeed generate enough electricity to cover their EV electricity demand. For some households the number of energy-positive days makes up even for the majority of all days and is as high as 77%. An increase of solar PV capacity in combination with installation of a home battery solution to bridge the time difference between generation and demand could make self-sufficient electric mobility a reality, albeit at a significant investment cost of several thousands of UK pounds. Alternatively, households could adjust their mobility and charging behavior to more effectively use self-generated electricity, for example by time-shifting non-essential journeys. An obvious drawback of powering the EV with solar electricity is the electricity cannot be used in the home (as it currently is). However the emotional benefits of being able to completely power their EV with free, green, self-generated energy could be a big driver for households to adopt this option and a motivator for behavior change.

Flexibility of Mobility Demand in Time and Space

In the home, energy related behavior change is connected with the use of appliances and devices. With respect to EVs, energy related behavior change is connected to mobility. Not using the lights to save energy might be inconvenient, not being able to drive feels like a much more difficult limitation. The desire to use a car is not just a matter of utility (e.g. having to go to work) but is closely connected to notions of autonomy and freedom (perhaps more so in the US than in Europe and Asia). Cars and mobility are powerful emotional triggers and thus the proposition to curtail or shift mobility is a difficult one. It was therefore surprising to see that participants seemed open to the suggestion to change their behavior. While mobility curtailing seems difficult the option to time-shift trips to an energetically more optimal time seems doable – except that currently EV drivers do not have access to the information that would allow them to make effective decisions.

Implications for Future Research

At the outset of the paper we asked which technological interventions might make sense in the context of EV/solar households. We argue that ubiquitous computing technology can play a major role in dissolving the tensions between potentials and barriers for self-sufficient mobility. EV drivers lack tools that are informed by and address the needs of the rich social patchwork of EV/solar households. Current technological interventions are narrowly focused on the driver's experience and rooted in the perceived limitations of EVs. Our research opens a wide range of opportunities for novel digital interventions and tools to help EV households make decisions about mobility and energy. We outline the following topics for future research:

1. Increasing Visibility of Green Electricity

Issue: EV drivers currently have no understanding or awareness of the energy mix in their cars' batteries. How much electricity came from green sources and how much came from dirty sources?

Opportunity: Introduce the concept of a virtual battery fuel mix and design information interfaces that indicate how much green and dirty electricity is 'stored' in the EV battery (obviously, once stored in a battery electricity is neither green nor dirty). A more elaborate version could differentiate between free/cheap/expensive energy.

Impact: A virtual fuel mix indicator could become a powerful tool to stir behavior change and help EV households stay within their green electricity limit.

2. Personalized Energy Management

Issue: Current information interfaces are vehicle centric – but have no understanding of the user's and household's context or past and future behaviors.

Opportunity: There is an opportunity to build predictive tools for EV drivers that can anticipate future mobility demand, provide charging mechanisms that understand contextual EV usage patterns and recommend energy management strategies.

Impact: A predictive tool could reduce cognitive load and mental stress incurred by EV drivers to achieve their personal energy goals while providing smarter charging decisions.

3. Supporting Household EV Routines

Issue: EVs are shared within a family and serve multiple purposes involving various stakeholders.

Opportunity: Support household decision-making and collaborative planning by family members.

Impact: Improved utility resulting from better planning will reduce coordination overhead and might accelerate adoption of EVs.

CONCLUSION

EVs are not just cars that happen to be powered by electricity; EVs create space for radical innovation in the mobility space. In this paper we define the radical vision of self-sufficient electric mobility and identify important avenues for its realization. Viewing EVs as extension of the home, and EV usage as an extension of home and work life, we are able to identify how daily life patterns shape mobility demand and the use of EVs. The insights presented herein define important directions for future ubiquitous computing research that will help reshape mobility.

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