Title: **Report for Deliverable 1.5 “Review of available data and techniques to model new loads and DER”**

Synopsis: This document presents a literature review on data and methodologies that can be used to produce time-series profiles (generation/consumption every minute/hour) of domestic-scale electric heat pumps, electric vehicles, and photovoltaic systems.

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Executive Summary

This report corresponds to Deliverable 1.5 “Review of available data and techniques to model new loads and DER” part of the Low Carbon Network Fund Tier 1 project “LV Network Solutions” run by Electricity North West Limited (ENWL).

The aim of the LV Network Solutions project is to provide ENWL with greater understanding of the characteristics, behaviour, and future needs of their low voltage networks. This will be based on the analysis of data gathered by appropriate monitoring schemes to be deployed on hundreds of LV feeders and substations, and the assessment of the corresponding computer-based network models in current and future scenarios.

Based on a thorough literature review, this report presents available methodologies and tools to model the corresponding consumption/generation profiles of electric heat pumps (EHPs), electric vehicles (EVs) and photovoltaic (PV) systems. These time-series models (with minute to hour resolutions) can then be used to assess the time-dependant behaviour of LV networks considering future penetration scenarios.

The main conclusions are:

- **EHP Modelling**. Although most reports found in the literature show understanding of the parameters to be considered, only two produced high-resolution EHP demand profiles that could be used for the LV Network Solutions project. These two reports were carried out recently at The University of Manchester and will create the basis for the production of more realistic high-resolution profiles to be used in the project.
- **EV Modelling**. Methodologies proposed in the literature will certainly create the basis for the production of profiles for the LV Network Solutions project. However, the available models (UK-based included) cannot directly be used. A much more detailed (or tailored) approach is required where regional and network-related characteristics (i.e., urban/rural area, availability of fast charging points, etc.) are considered.
- **PV Modelling**. A freely available tool developed by the Centre for Renewable Energy Systems Technology (CREST) can be used directly in the LV Network Solutions project given its sophistication and granularity (one minute). The corresponding parameters needed by the tool can be based on real locations of the monitored LV networks combined with suitable assumptions.

In general, while The University of Manchester is capable of creating high resolution profiles for EHPs, EVs and PV systems, it is ideal to validate and improve these models with actual monitored data in order to make them as realistic as possible. This data could be gathered from other UK projects but requires ENWL to engage with those organisations involved (e.g., Energy Saving Trust, Ofgem’s Smart Grids Forum WS3, TSB Ultra Low Carbon Vehicles Demonstrator Programme). Another solution, particularly for PV modelling, is that a very limited number (5 to 10) of the LV networks to be monitored in the project have also installed meters to provide local irradiance.

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1 Introduction

As part of the transition towards a low carbon economy, Electricity North West Limited (ENWL), the Distribution Network Operator of the North West of England, is involved in different projects funded by the Low Carbon Network Fund. The University of Manchester is part of the Tier 1 project “LV Network Solutions”.

The objective of this project is to provide ENWL with greater understanding of the characteristics, behaviour, and future needs of their LV networks. This will be based on the analysis of data gathered by appropriate monitoring schemes to be deployed on hundreds of LV feeders and substations, and the assessment of the corresponding computer-based network models in current and future scenarios.

1.1 Deliverable 1.5

In order to understand the corresponding impacts on LV networks, it is required to develop models of the circuits themselves (network models), demand (residential, commercial), special loads (EHPs, EVs) and generation (PV panels). Given the time dependencies among demand, special loads, and generation, it is not possible to simply assume a worst case scenario such as minimum load-maximum generation or maximum load-minimum generation. In order to adequately assess the impacts (e.g., voltage unbalance during a week, voltage rise occurrences, etc.) of different penetrations of such low carbon technologies, the corresponding generation/consumption models should reflect changes in time (every minute, every hour).

Producing generation/consumption profiles for these low carbon technologies is, however, a complex task as they depends on many factors:

- For an EHP it is necessary to know the corresponding rated capacity, its usage will depend on dwelling type, occupants’ behaviour, weather, etc.
- The profile of an EV will depend on its battery specifications and how it is used.
- Generation profiles of PV panels will depend on their rated capacity, tilt, location, solar irradiation, cloud effects, etc.

The following flow chart presents a generic process to model the corresponding profiles.

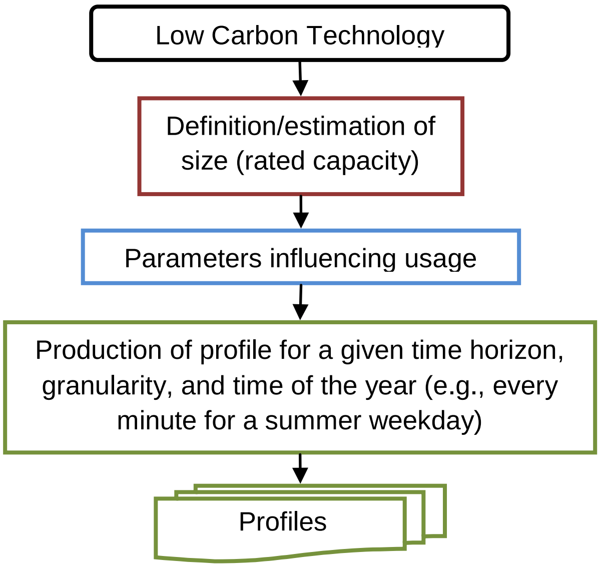


Figure 1 Generic profile modelling flowchart

To understand the behaviour of LV networks in future scenarios it is essential that EHPs, EVs and PV panels are modelled in a realistic manner. However, currently, there are a limited number of studies on the profiling of new technologies.

This report provides a through literature review in order to define available methodologies, tools and data in order to create the profiles for EHPs, EVs and PV panels. As such, the report is comprised by three sections:

- Electric Heat Pump Modelling;
- Electric Vehicle Modelling; and,
- Photovoltaic Modelling.

Each of the following sections has been structured in a similar way. First, a more specific modelling flowchart is presented, summarising different aspects to be considered for each technology. Then, the technology itself is briefly described, followed by the corresponding literature review. Finally, conclusions are drawn.

2 Electric Heat Pump Modelling

Electric heat pumps (EHPs) are expected to have a significant role in domestic heating systems. As a consequence, EHPs could cause a large increase in electricity demand. To analyse the impacts of this technology on LV networks, realistic modelling of EHP profiles is essential.

The demand profile of an EHP will depend on a number of factors:

- Type of EHP (air source, ground source);
- Efficiency of the EHP;
- Type of dwelling, age, size, insulation;
- Occupancy pattern, number of occupants, heating strategy;
- Weather (temperature, sunlight, etc.); and,
- Time (weekday, weekend, month, season).

Considering the above parameters a specific modelling flowchart is shown in Figure 2.

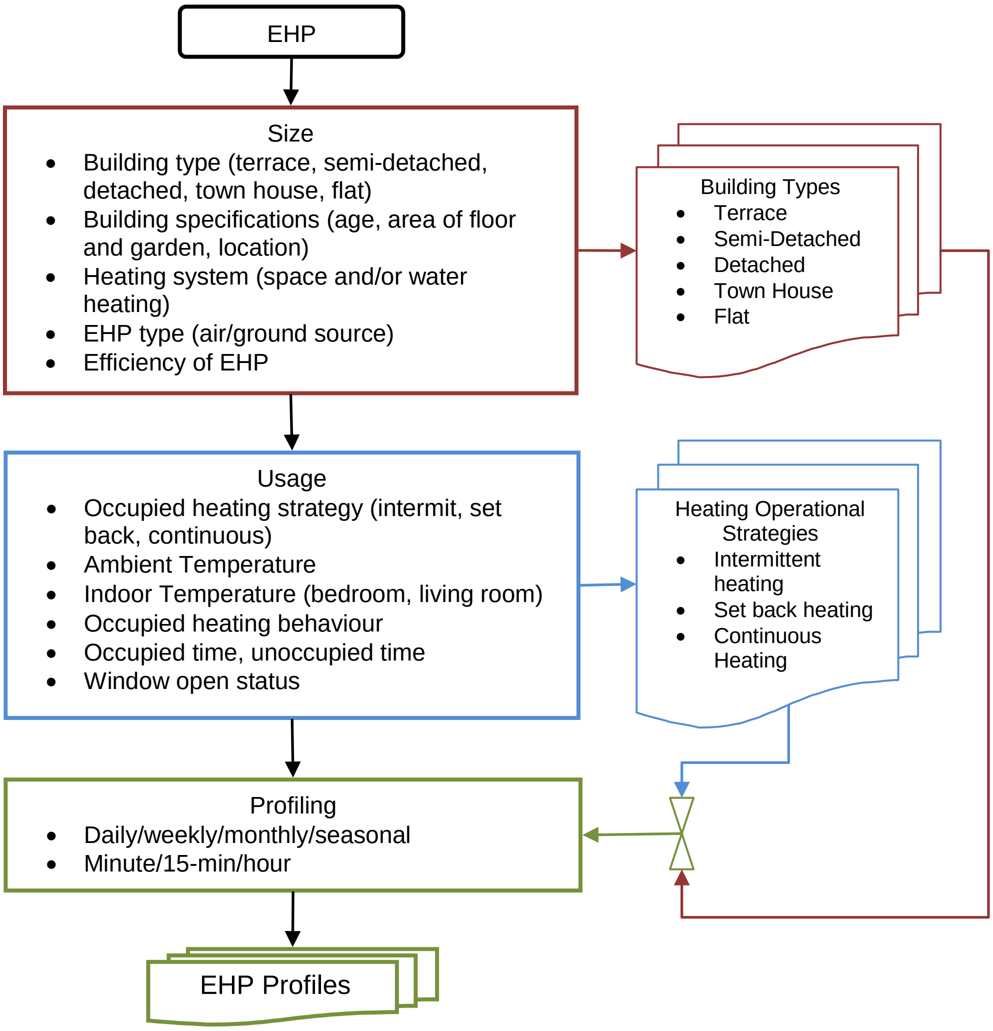


Figure 2 Electric Heat Pump Demand Profile Modelling

2.1 EHP Technology

EHPs are devices capable of reversing the natural flow of environmental heat from cold to hot using electrical energy. For domestic heating, most EHPs extract heat from the outside air, ground or water, to be then sent to a heat sink. From here, the heat is transferred to the central heating system (including domestic hot water store, Figure 3). EHPs are named as their sources such as: Ground Source Heat Pump (GSHP), Air Source Heat Pump (ASHP), Water Source Heat Pump (WSHP).

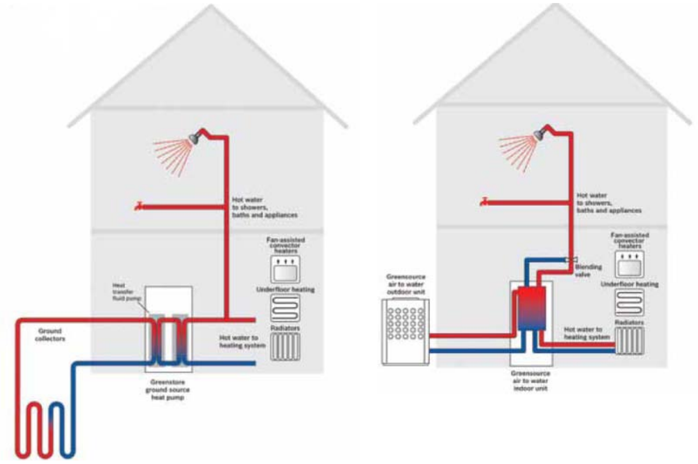


Figure 3 A typical ground sourced and air to water heat pump system layout [1]

EHPs use a thermodynamic cycle to transfer heat from a source to a sink at higher temperature by varying pressure and temperature (Figure 4). A heat source causes to evaporate a working fluid. The vapour from the fluid enters the compressor. When the compressor, driven by an electric motor, compresses the vapour, the compressor raises its pressure and increases the temperature. The high-pressure vapour enters the condenser where it condenses at a higher temperature. Heat flows naturally from the condenser to the heat sink. The high pressure fluid enters the expansion valve, which reduces the pressure to its original point, and the cycle is complete. EHP performance is measured with the ratio of useful heat output by the EHP to the amount of electric energy input for operation [1], [2]. It is usually expressed in terms of its Coefficient of Performance (COP), defined as:

$$COP = \frac{Q}{W}$$

where *Q* is heat output of the EHP and *W* is the corresponding power consumption. The COP is typically between 3 and 5 [3].

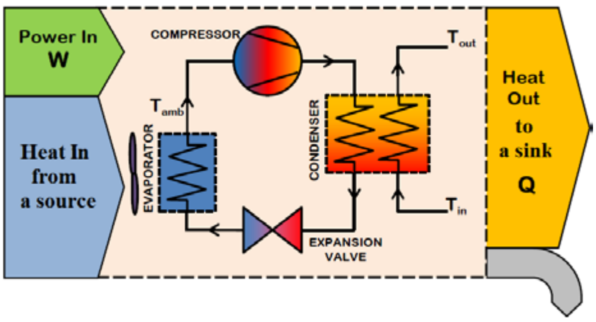


Figure 4 EHP Thermodynamic Cycle [2]

2.1.1 Ground Source Heat Pump (GSHP)

The two most common types of GSHP systems are horizontal ground loops and vertical borehole loops. Ground loops GSHP uses the solar energy found in the ground via a pipe. The pipe is coiled around the area at a depth of approximately one meter. A large ground area is required to lay the pipe network (Figure 5-a). A borehole loops heat pump uses the solar energy found within the earth. Pipes are lowered through one or more boreholes 15-100 meters deep (Figure 5-b) [1]. The main advantage of using the ground is that its temperature is much more stable than the ambient air temperatures. It is higher in the winter and lower in the summer (in the case of cooling mode usage of a reversible heat pump), which can make the COP higher than other systems, such as air source heat pump systems [4].

2.1.2 Air Source Heat Pump (ASHP)

ASHPs retrieve the energy from the surrounding air using an air handling unit. Most ASHPs are sited just outside the property (Figure 5-c). An electrically-driven fan draws air across the evaporator, cooling the air stream and supplying heat to the heat pump. ASHPs include a defrost cycle to melt the ice on the evaporator when the ambient temperature falls below about 7°C. In cold weathers, the frosting occurring on the evaporator reduces the COP of ASHP system [1].

a) Ground Loops GSHP **b) Borehole Loops GSHP** **c) ASHP**

Figure 5 Types of Heat Pumps

2.1.3 Sizing EHPs

The applicability of electric heat pumps to UK dwellings was presented in [3]. Single-tier ground loop GSHPs might be considered for implementation in either semi-detached or detached houses, which together comprised 44% of the housing stock in 2004 [5]. Due to the limited availability of space and difficult access to any available spaces, GSHPs with horizontal ground loop might not be feasible for application to terraced houses and flats, which comprised about 48% of the housing stock in 2004. For such dwellings, wherever accessibility was not an issue, installation of either the double-tier horizontal or vertical ground loop GSHP or an ASHP might be considered. In the case of terraced houses, which comprised over 28% of the total stock in 2004, the implementation of ASHPs might be viable.

Clearly, the size and type of an EHP vary according to the dwelling's features. The online EHP calculator from one manufacturer [6] can be used to assess the recommended technical specifications required for GSHPs and ASHPs according to different types of properties, as presented in Table 1, Table 2, Table 3 and Table 4.

As seen from the tables below, electricity driven heat pumps generally required high electric current on start up and this limits the size of the heat pump. In addition to this, in general, the nature of EHPs is such that the COP reduces significantly when they are operated to supply higher temperature heat outputs. This further increased the current requirements [3].

It is important to highlight the maximum power consumption of EHPs. In the examples from the tables, this ranges from 2.7 to 7.7kW. Depending on the extent to which these maximum power consumptions coincide (and how frequently), LV networks might see significant impacts in terms of voltage drops, unbalance, asset utilisation, etc.

Table 1 Recommended GSHP according to dwelling features

GSHP Calculator Recommended GSHP	Required pipe work	Floor area of property	Age of property	Emitter system	Heating system
Borehole loops GSHP 8kW	2 borehole of 100m depth	85m^2	1970-1995	radiators	an integral hot water cylinder
Borehole loops GSHP 6kW	1 borehole of 100m depth	85m2	2010	radiators	an integral hot water cylinder
Borehole loops GSHP 17kW	4 borehole of 100m depth	178m^2	1970-1995	radiators	a separate hot water cylinder
Ground loops GSHP 6kW	garden area 328m^2	178m^2	2010	underfloor heating system	an integral hot water cylinder

Table 2 Technical specifications of recommended GSHP

	Borehole loops GSHP 8kW	Borehole loops GSHP 6kW	Borehole loops GSHP 17kW
Heating output	8.1kW COP=4.2	6kW COP=4.2	17.3kW COP=4.3
Max power consumption	4kW	2.8kW	7.7kW
Voltage / Starting current	230V / <45A	230V / <45A	230V / <25A with soft starter

Table 3 Recommended ASHP according to dwelling features

Recommended ASHP	Location	Type of property	Age of property	Number of bedroom	People in property	Type of current heating
ASHP 7kW	North England	Flat	New Build	2	3	LPG
ASHP 7kW	North England	Terrace	2000-2010	3	4	Electricity
ASHP 12kW	North England	Terrace	1970-1990	3	4	LPG
ASHP 15kW	North England	Terrace	Pre 1950	3	4	LPG
ASHP 7kW	North England	Semi	New Build	3	4	Electricity
ASHP 15kW	North England	Semi	Pre 1950	3	4	LPG
ASHP 12kW	North England	Detached	2000- 2010	3	4	LPG
ASHP 15kW	North England	Detached	Pre 1950	3	4	LPG

Table 4 (Some) Technical specifications of recommended ASHP

	ASHP 7kW	ASHP 12kW	ASHP 15kW
Heat Output kW @ -4 C	4.38kW	7.3kW	8.05
Heat Output kW @ 7 C	6.71kW	11.04kW	13.7kW
Max power consumption	2.7kW	5.1kW	5.1kW
Voltage / Max current	230V / 14A	230V / 23A	230V / 20A

2.2 Literature Review

There is a limited number of studies/reports on electric heat pumps integrated with dwellings that could be used for modelling purposes within the LV Network Solutions project [7, 8, 9, 10]. In [7], ASHP systems were analysed by using energy modelling software. A retrofit ASHP performance was assessed in [8] by using both field trial data and simulated data. In [9], 83 field trials of electric heat pumps were examined. Finally, electric heat pump profiles were produced in [10] but using very limited heat pump field trial data.

In the study presented in [7], different unit sizes and different operational strategies were analysed to understand the impact of a residential energy system over an ASHP system installed in a refurbished dwelling. The building and the ASHP system were simulated using the TRNSYS software package as well as half-hourly London climate data over a year. The simulation results revealed the ASHP system’s cost and life span. Due to the lowest number of cycles per day, intermittent heating with 4-hour preheat time was found to be best operational strategy (out of three) in terms of life span.
The three operational strategies considered in this study were:

- Intermittent heating (when unoccupied shut down otherwise set to 20°C)
- Set back heating (when unoccupied set to 16°C otherwise set to 20°C)
- Continuous heating (set to 20°C through the entire day)

These operational strategies may be useful when producing end user heating behaviours for modelling purposes.

The study in [8] used a combination of simulations and field trial data to assess the annual performance of a domestic ASHP system retro-fitted into social housing in Westfield, Scotland. An ASHP model was developed on the ESP-r platform and integrated into a whole-building, dynamic simulation tool. The predictions of the whole-building model were compared to the Westfield field trial data, indicating that the model suitably replicated the trial’s ASHP operating conditions.

Simulations were undertaken to estimate the annual energy performance of the ASHP device and an equivalent gas condensing boiler system when retro-fitted into a typical Westfield dwelling. These indicated that: the provision of space heating using the ASHP resulted in approximately 12% CO_2 savings in comparison to a gas condensing boiler system; and 55% CO_2 savings compared to the all-electric system (using 2009 UK CO_2 emissions coefficients for electricity and gas).

In this study, data was collected from 8 houses. The houses were all of a similar size (Figure 6). The characteristics of a typical house are presented in Table 5. The retrofitted ASHP heating system served the space heating only. ASHP had a nominal coefficient of performance of 3.0 with a rated thermal capacity of 8 kW.

During the trial, the occupants were also free to select the set point temperature of the heating system, its operation time, select thermostatic radiator valve settings, open doors and windows, and to occupy the property as they normally would. The performance parameters’ data recorded were as follows:

- the electrical consumption of each heat pump was measured using a current transformer clamp on the supply to the heat pump. The current clamps transmitted data every 30 seconds;
- the total electrical consumption in each house was measured along with voltage;
- the heat output of the heat pump was measured using a heat meter;
- outside air temperature and relative humidity were recorded;
- monitoring started in February 2008 and stopped in July 2008.

The integrated ASHP/dwelling model was simulated with a time resolution of 1 minute; this fine temporal resolution was employed to adequately capture the action of control on the operation of the ASHP (e.g., on/off cycling). The heating system control regime was arranged with the heating system operating 07:00–09:00 and 17:00–22:00 during weekdays and 08:00–23:00 at weekends. The assumption was made that the system was switched off at night rather than reverting to a set back-temperature (common practice in the UK).

Table 5 Westfield house types [8]

Type	Date of construction	Bedrooms	Roof	Windows	Number of houses
Semi-detached	1969	1	Concrete tile	Double glazed	1
4-in-a-block flat	1938	3	Natural slate	Double glazed	2
End terrace	1938	3	Natural slate	Double glazed	1
End-terrace	1967	3	Concrete tile	Double glazed	2
Mid-terrace	1967-1969	3	Concrete tile	Double glazed	4

Figure 6 Dwellings at Westfield [8]

Some results of the annual ASHP detailed simulation such as the monthly actual COP, electrical consumption, and ON/OFF cycles are shown in Table 6. This table gives general information about the ASHP’s operating regime according the variation of seasonal temperature.

Table 6 ASHP detailed simulation results [8]

	Jan	Feb	Mar	Apr	May	Sept	Oct	Nov	Dec	Year
Actual COP	2.58	2.55	2.7	2.77	2.9	3.1	2.91	2.78	2.67	2.77
Electrical (kWh)	308	261	219	113	57	37	143	221	272	1631
ASHP heat out (kWh)	793	667	593	314	164	113	418	613	727	4403
System heat loss (kWh)	46	44	41	35	30	22	37	39	42	335
Total system heat out (kWh)	747	623	552	279	134	91	381	574	685	4067
ON/OFF cycles	459	456	477	301	166	116	388	478	470	3311

If this study’s monitored and simulated data could be made available to The University of Manchester, it would be possible to produce (to some extent) a number ASHP profiles. Region-related parameters can be adapted, for instance, ambient temperatures that reflect the North West climate. More simplistic profiles could also be produced by using certain information from this study such as monthly ON/OFF cycles and monthly electrical consumptions.

In [9], the Energy Saving Trust monitored 83 heat pumps in residential properties across Great Britain from April 2009 to April 2010, aimed (during its first phase) at examining a number of these heat pump installations, paying particular attention to the factors that influence system performance.

Monitored heat pumps distributed across the UK were installed in residential properties only and included the following installation types:

- ASHPs and GSHPs;
- EHPs installed in private and social housing properties;
- EHPs installed in new-build and retrofit properties;

- EHPs providing heating only;
- EHPs providing heating and hot water;
- EHPs installed with different heat delivery systems: under-floor heating and/or radiators.

Electric meters, heat meters and temperature transmitters were installed in each house to determine the efficiency of the entire heating system. The electricity consumed by the heat pump and any immersion heating elements, the heat delivered to the space heating, the heat delivered for domestic hot water and temperatures were collected every five minutes.

The results of analyses obtained from field data trials such as histograms of system efficiency for all heat pumps in the trial, examples of good performance, and examples of poor system design or installation were reported. Time-dependent GSHP operation was also given in the report.

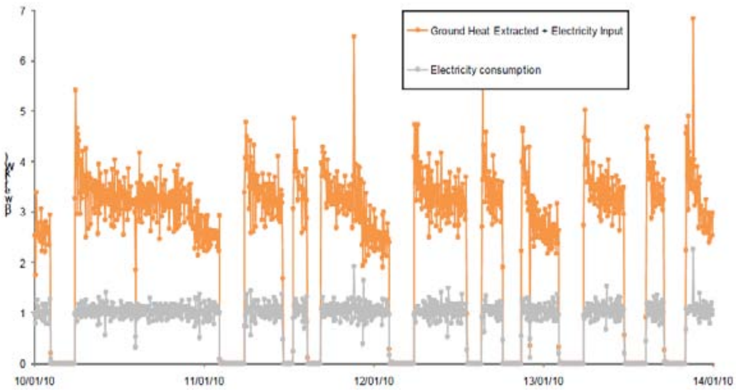


Figure 7 Electricity usage and ground heat extracted for a site with minimal cycling [1]

A 3.5kW GSHP for space and hot water heating integrated into a semi-detached bungalow located in Cornwall, with a SAP rating of 49 (band E). Figure 7 showed electricity demand, which was fairly steady at around 1kW, except during a short period at night when the system was off.

The report *“Assessing the Impact of Low Carbon Technologies on Great Britain’s Power Distribution Networks*” [10], prepared for the Ofgem’s Smart Grids Forum, provided an assessment of required network developments (in terms of smart grid options) to address the challenging network issues that lie ahead due to the low carbon transition. In this report, after-diversity electricity demand profiles were generated for each building type for three different electric heating systems (Figure 8): direct acting resistive heaters; storage heaters (Economy 7); and electric heat pumps.

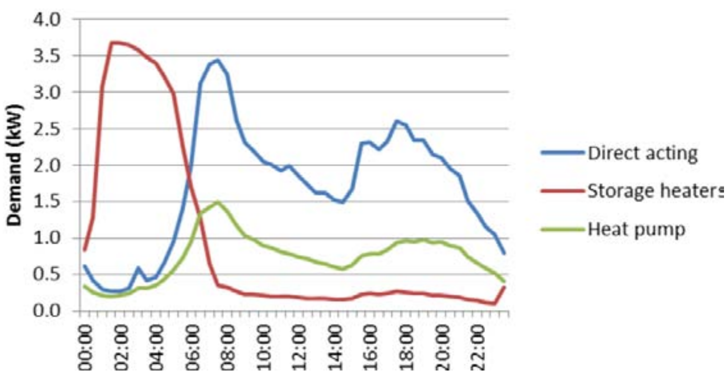


Figure 8 After-diversity heating system profiles [10]

It was assumed that there was no heating demand in the summer. In order to generate average and peak winter heating demands, simulations were run at external temperatures of -5°C and +5°C, with an average room set temperature of 18°C. This range of external temperatures was assumed to cover the range of peak and average winter temperatures which occur in different regions of the UK. The heating profiles were averaged across all domestic building types to produce average profiles.

During the modelling of heat pump demands, a number of important assumptions were made. First, the heat pumps were assumed to be air-to-water ASHP. It was also assumed that the heat pumps were supplemented by a small top-up electric resistive heater (with a COP of 1) which started to be used when the external temperature fell below 2°C. Moreover, heat pumps were assumed to be run intermittently as heating system operation was set to 14°C at unoccupied time.

2.2.1 Work Done at The University of Manchester

Two recent studies on heat pump modelling [11, 12] were carried out at The University of Manchester. Heat demand profiles were derived from the records of The Carbon Trust's Micro-CHP Accelerator Project [13]. The Carbon Trust's project involved a field trial of 87 micro-CHP units in both domestic and small commercial applications. Key parameters were monitored every 5 minutes during the continuous operation period. The parameters used to develop EHP models were the heat output data of the micro-CHPs and the outside ambient temperature, as well as the corresponding technical characteristics of the micro-CHP units. In [11], seven different EHP profiles were used to analyse the corresponding impacts on LV distribution networks. In [12], 50 EHP profiles were produced to evaluate the impacts on MV distribution networks.

In [11], a computational tool was developed to analyze a deep understanding of distribution network behaviour with seven different models of EHP. The corresponding (initial) 5-minute resolution profiles were derived from heat output profiles and ambient temperature recorded data from micro-CHPs (as mentioned previously). Figure 9 shows one of these (initial) EHP profiles.

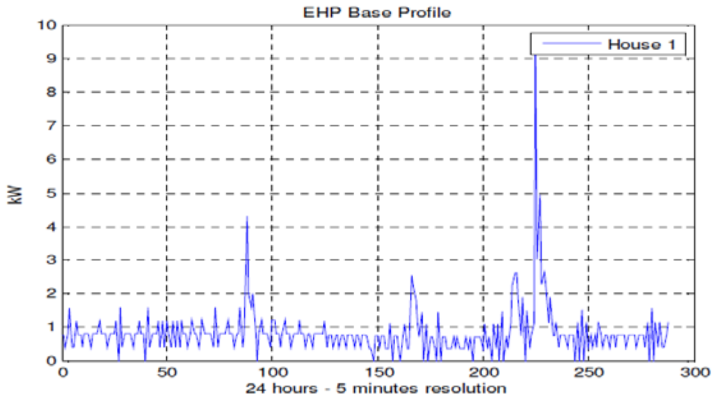


Figure 9 Seven different HP Profiles [11]

Given that these profiles were based on boiler data (most of the boilers were oversized, about 25 kW), the electricity peaks were unrealistic for EHPs. To avoid these peaks, the profiles were integrated over one hour as presented in Figure 10. These correspond to the final profiles used in the network studies.

In [12], EHP profiles were produced considering also the findings from the Carbon Trust's Micro-CHP Accelerator Project. However, here the data from those houses with similar characteristics to the MV network studied (in the North West) were chosen, leading to a more realistic approach. It was assumed that the demands from space and water heating were met from ASHP with suitable capacities. The EHP profiles were produced with the following assumptions:

- EHP systems were well installed and were able to achieve design performance;
- The output flow temperature of EHPs was set to 55ºC to heat up the buffer cylinders which had adequate capacity, then delivering heat for under floor, space and water heating;
- The only variable that affected the COP was outside ambient temperature;
- The heat output of micro-CHPs was equal to the heat demand of the household;
- One EHP per household.

By using different heat and temperature profiles as well as ASHP COP data, base profiles of EHPs were formed. An example is shown below (Figure 11).

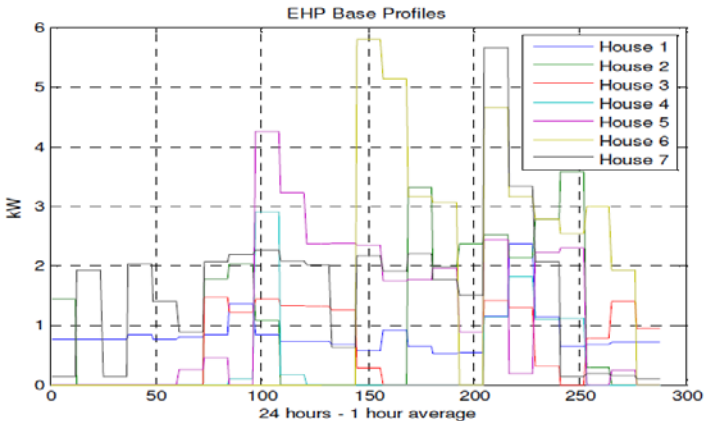


Figure 10 Electric Heat Pumps Average Profiles [11]

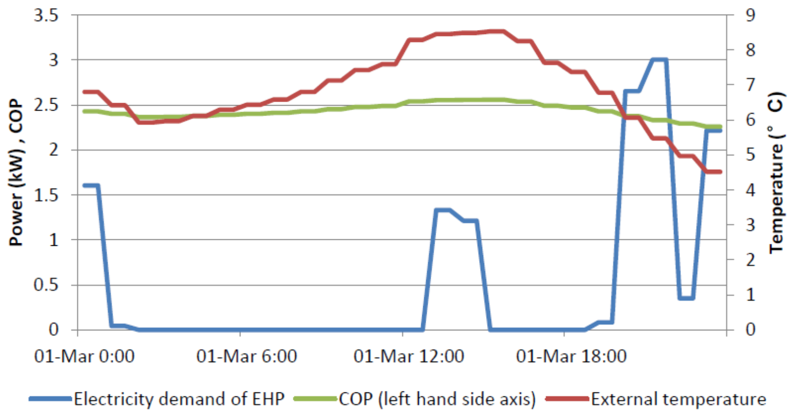


Figure 11 Electricity demand and COP of ASHP (rated heat output 9kW) [12]

2.3 Conclusions

In order to adequately model an EHP integrated into a dwelling many parameters have to be considered. This includes: the characteristics of the dwelling itself (e.g., size, age, etc.), the EHP technology (e.g., GSHP/ASHP, size, performance, control modes, etc.), the dwelling's heating demand behaviour, ambient temperature, etc. The dwelling's heating demand behaviour, perhaps the most complex element to model, is particularly affected by the settings used for the heating system to different indoor temperatures throughout the day, as well as air flows (i.e., windows open/shut), number of occupants, type of day (e.g., weekday/weekend), etc.

As the literature review shows, although most reports show understanding of the parameters to be considered, only two produced high-resolution EHP demand profiles that could be used for the LV Network Solutions project (or similar time-series based studies). These two reports, [11, 12], were carried out recently at The University of Manchester and create the basis for the production of more realistic high-resolution profiles to be used in the LV Network Solutions project.

It is important to highlight that the data from the reports [8] and [9] would be extremely useful in the production of EHP profiles. However, to date, The University has been unsuccessful in receiving a reply from the Energy Saving Trust.

3 Electric Vehicle Modelling

The adoption of (fully) electric vehicles (EVs) is encouraged by governments around the world. As a consequence, similarly to EHPs, EVs could cause a large increase in electricity demand. To analyse the impacts of this technology on LV networks, realistic modelling of EV profiles is essential.

The demand profile of an EV will depend on a number of factors, including:

- EV characteristics (electric range, size of battery, etc.);
- driving habits (or daily mileage) and consequently state of charge when 'returning home';
- timing of the charging;
- charging characteristics of the battery;
- type of day (e.g., weekday, weekend, etc.).

Considering the above parameters a specific modelling flowchart is shown in Figure 12.

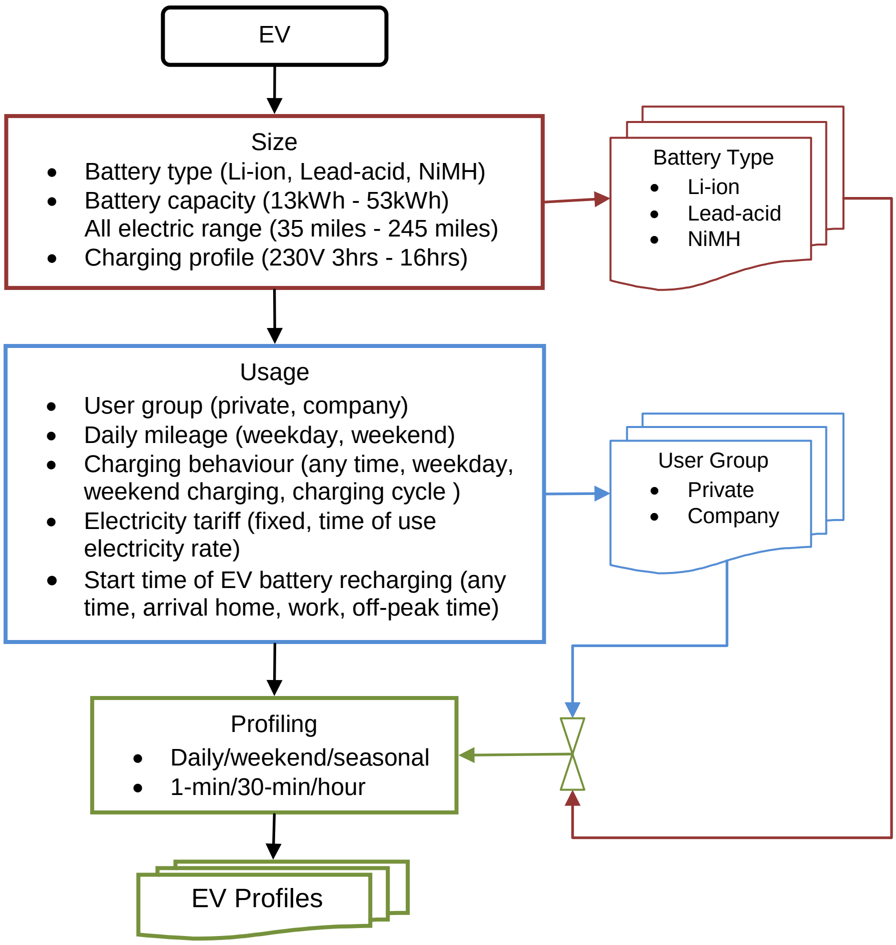


Figure 12 Electric Vehicle Demand Profile Modelling

3.1 EV Technology

EVs use an electric motor for propulsion with batteries for electricity storage. The energy in the batteries provides all motive and auxiliary power onboard the vehicle. Batteries are recharged from low voltage power outlets and/or charging points/stations. EVs offer the prospect of decreasing significantly transport emissions of greenhouse gas and air pollutants, as well as very low noise. An important advantage of EVs over conventional internal combustion engine (ICE) vehicles is the very high efficiency and relatively low cost of the electric motor [14].

Generally, EVs can be divided into two sections: Plug-in Electrical Vehicles and Plug-in Hybrid Electrical Vehicles. Hybrids retain the entire ICE system but this is used to turn a generator which supplies power to an electric motor. A battery provides capacity to enable the extended operation of the electric motor. EVs require much greater battery capacity than hybrids in order to have a minimum acceptable driving range and peak power. However, EVs provide a substantial energy efficiency advantage, with up to three times the engine and drive train efficiency of conventional ICE vehicles and over twice that of hybrids [14].

In the UK, the Plug-In Car Grant covers the following cars (mostly fully electric):

- Chevrolet Volt (EV)
- Citroen CZero (EV)
- Mia Electric, Mia (EV)
- Mitsubishi iMiEV (EV)
- Nissan Leaf (EV)
- Peugeot iON (EV)
- Renault Fluence Z.E. (EV)
- Smart Fortwo Electric Drive (EV)
- Toyota Prius Plug-in (Hybrid EV)
- Vauxhall Ampera (Hybrid EV)

3.2 Literature Review

This section will focus on the four main aspects to be considered when modelling EV demand: driving population, battery types and charging characteristics, charging start time, and, state of charge. Then, further considerations and some examples for the production of EV demand profiles will be presented.

3.2.1 Driving Population

The 2009 UK National Traffic Statistics [15] reported that from the 28.4 million registered cars during 1999 to 2008: around 61% were privately owned and used for commuting, 9% were company owned, and 30% were owned by people who are older than 60 (most of whom are retired from work/ unemployed).

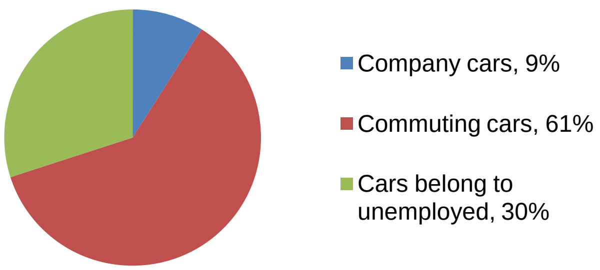


Figure 13 Cars divided by user groups [18]

3.2.2 EV Battery Types and Charging Characteristics

EV batteries are categorised as follows:

- Lead-acid;
- Nickel based (e.g., NiMH, NiCad);
- High temperature sodium-nickel-chloride (NaNiCl or Zebra);
- Lithium based (e.g., Li-ion, Li-poly);
- Metal air (e.g., Al-air, ZN-air).

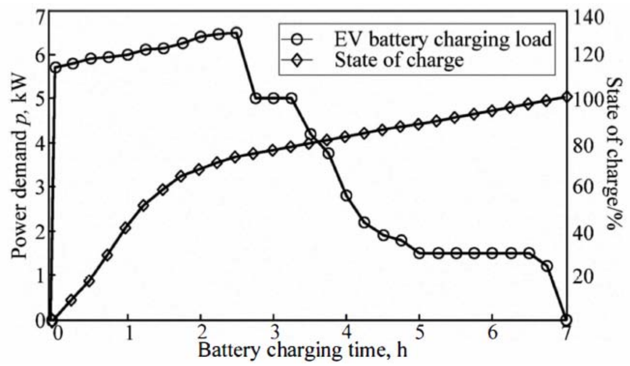
Lead-acid, Lithium-ion (Li-ion) and Nickel Metal Hydride (NiMH) have so far been the top three technologies for EV batteries due to a combination of factors such as performance, safety, life and cost. Lead-acid represented the most mature battery technology while Li-ion has recently seen rapid improvement in performance characteristics and an increase in popularity [16].

Charging level and charging duration mainly depend on the battery type. For illustration purposes, the battery specifications of some EVs presented in [17] are given with their maximum power, charging power and all electric range in Table 7.

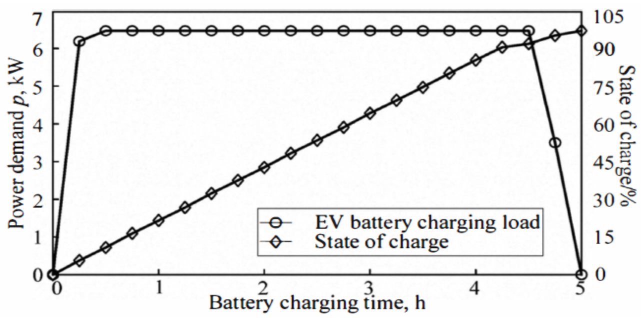
Table 7 Some EV Battery Specifications (all Li-ion)

Make, Model	Battery Capacity	Max Power (motor)	All Electric Range	Charging
GM Chevy Volt (Hybrid EV)	16 kWh	111 kW	35 miles	230V 16A (8 hrs) 230V 10A (12 hrs)
Nissan Leaf (EV)	24 kWh	90 kW	100 miles	230V (6-8 hrs)
Ford Focus Electric (EV)	23 kWh	100 kW	75 miles	230V (6 hrs)
Tesla Roadster (EV)	53 kWh	225 kW	245 miles	230V 70A (3.5 hrs) 230V 32A (6 hrs) 230V 13A (16 hrs)

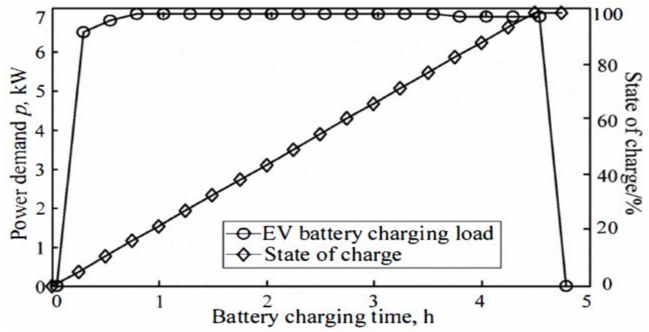
Other EV models such as the GM EV1 and the Toyota RAV 4 are based on lead-acid and NiMH batteries, respectively. The power demand and related battery state-of-charge profiles of the three main types of batteries are shown in Figure 14. The lead-acid based GM EV1 has a capacity of 27.19 kWh, the NiMH-based Toyota RAV4 has a capacity of 32 kWh, whilst the Li-ion-based Nissan Altra has 29.07 kWh, all when fully charged from a fully discharged state [18].



a) Lead-acid (GM EV1)



b) Li-ion (Nissan Altra)



c) NiMH (Toyota RAV4)

Figure 14 Charging profiles of three battery types [18]

3.2.3 EV Charging Start Time

The start time of battery charging depends on the EV user behaviour. The daily traffic to and from work by vehicles for both business and commuting purposes shown in percentage of daily traffic versus time of day in the UK is illustrated in Figure 15 [18]. Two peaks are observed for commuting and business use, the morning peak (07.00 am–09.00 am) and the evening peak (16.00–18.00) [19].

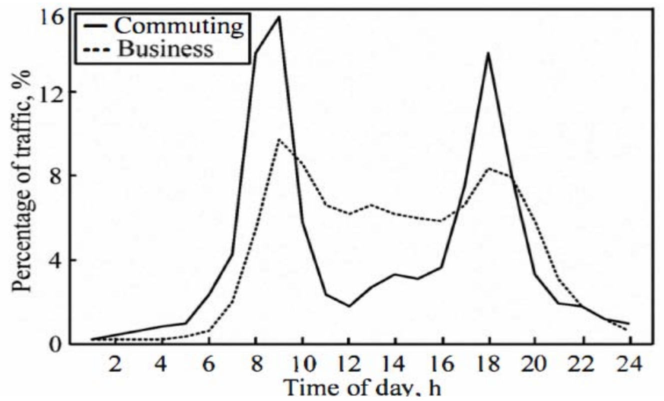


Figure 15 Percentage of traffic for both commuting and business EVs [18]

These traffic habits assist in specifying the start time of EVs' charging. In [16], it was assumed that company (i.e., business) vehicles would recharge at 5pm, 5.30pm and 6pm; and private vehicles would do so in three groups from 5.30pm, 6pm and 6.30pm.

Recent studies carried out at The University of Manchester [20] assumed EV charging starting times between 4pm and 10pm during weekdays for private cars and between 6pm and 8pm for company cars. The start charging time of EV could be anytime in weekends.

3.2.4 EV State of Charge

The initial state of charge (SOC) of the battery depends on a number of factors such as daily mileage of the EV, all electric range, and time interval of the charging. The annual mileage band for private cars and company cars from the National Traffic Statistics database can be used for EVs. In [18], it was assumed that the average daily miles for private cars and company cars are approximately 25 and 50 miles, respectively, and that private cars can be recharged every two days during weekdays. Company cars can be recharged every day. Due to long trips during the weekends, EVs can be recharged all day. The SOC before charging can be estimated considering the maximum EV range (d_t), daily distance since fully charged (d_d), and the depth of discharge (DOD).

$$SOC = 1 - \frac{d_d}{d_t \times (1 - DOD\%)}$$

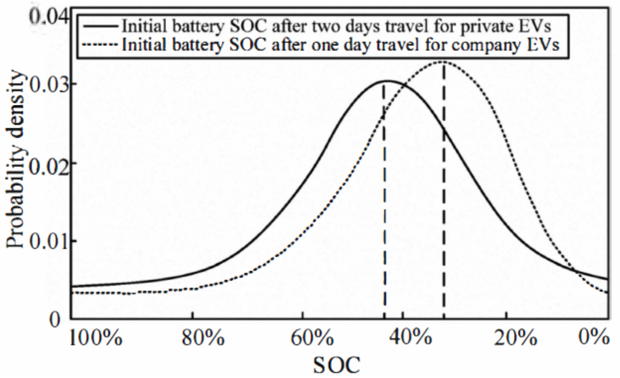


Figure 16 PDF of initial battery SOC for lead-acid battery based GM EV1 [18]

For instance, the probability density function (PDF) of the initial battery SOC using the lead-acid battery based GM EV1 is shown Figure 16. Its SOC distribution was obtained considering likely traffic habits of private EV owners and using the equation above (d_t equal to 80 miles).

3.2.5 EV Charging Profiles

Charging (or demand) profiles and corresponding assumptions used in four studies are presented in this subsection. First, EV charging profiles based on trial data from the report for the Ofgem's Smart Grids Form [10] are presented, followed by models produced at The University of Manchester [20] as well as those proposed in [16] and [18].

EV charging profiles used in [10] were generated using the trial data from the TSB Ultra Low Carbon Vehicles Demonstrator Programme. This trial considered (and resulted in):

- 8 consortia running EV-related projects;
- 19 vehicle manufacturers; and,
- 340 vehicles (electric, pure hybrid and fuel cell vehicles).
- 110,389 individual journeys (from December 2009 to June 2011);
- 677,209 miles travelled (1,089,862 km);
- 19,782 charging events; and,
- 143.2 MWh of electricity consumed.

The corresponding diversified 24-hour EV profiles are shown in Figure 17.

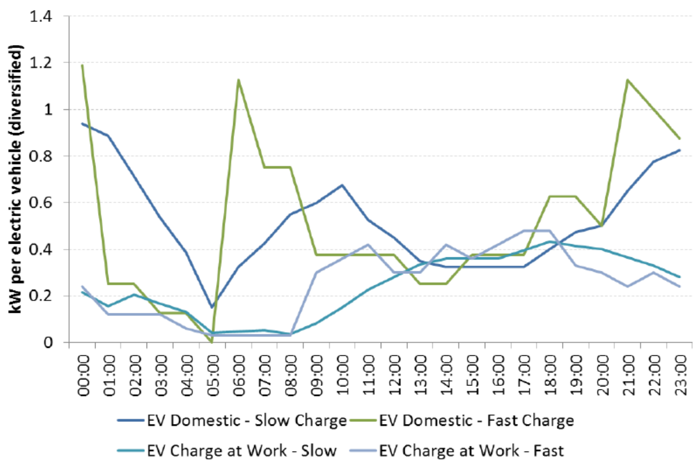


Figure 17 Diversified EV charging profiles with slow, fast charging at home and work [10]

In order to model the impact of EVs on LV networks, the modelling exercise from [10] included a number of assumptions such as:

- two charging types: 10A @ 240V and 32A @ 240V;
- 2hrs for full charge (flat battery) of a single vehicle, 10A charging (Figure 18);
- 5hrs for full charge of a single vehicle, 32A charging (Figure 18).
- realistic charging profiles for EVs charging at home or in other locations (MWh per hour over a typical weekday);
- average mileage per day taken from “Distribution of daily mileage by ownership” as being 25 miles for both private and fleet users;
- time of charge taken from TSB report;
- energy, by way of the time taken to charge (not the peak current) had been apportioned according to
  - the time required for a full EV charge,
  - the energy required for that daily distance,
  - the proportion of users who charge at different times of the day;
- every car drove the average daily distance, every day, and were charged on a daily basis.

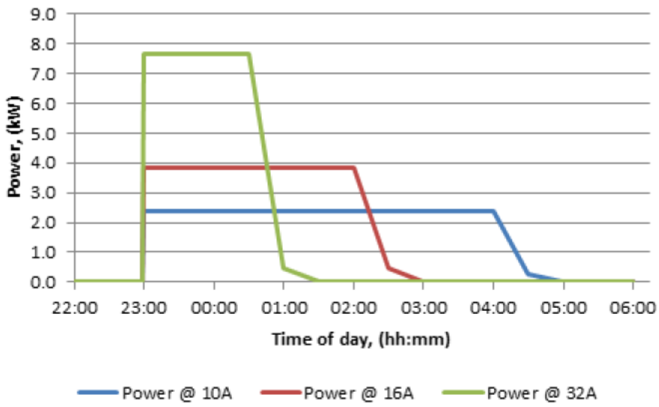


Figure 18 Individual EV (continuous) charging profiles from flat battery [10]

With these assumptions, the demand profile for a single EV charging at home was produced (as shown in Figure 19).

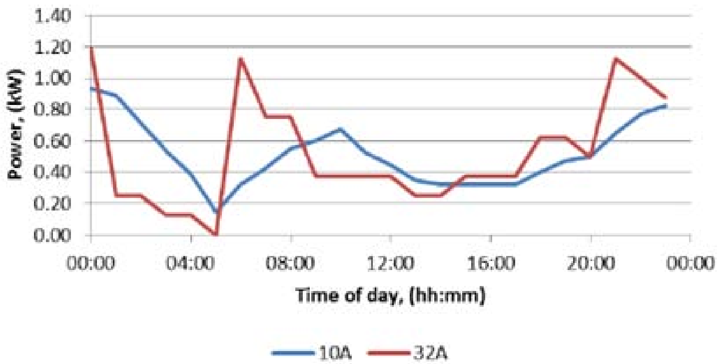


Figure 19 Single EV demand profile charging at home [10]

In the other three studies ([20], [16] and [18]) the production of single EV demand profiles was carried out in a similar manner, although making the calculations to obtain the state of charge of the EV batteries (when arriving at the charging point) more explicit. Daily mileage was randomly generated adopting transport statistics. In [18] and [16], the value of depth of charge (DOD) was taken as 100%. Some made by these studies to define the charging start time and frequency are listed in Table 8. In addition to this, further scenarios were also considered by taken account of different charging modes (i.e., slow and fast charging).

Table 8 Assumptions of Charging Start Time and Frequency

Ref.	User Group	Share of all EVs	Frequency	Start Time
[20]	Private	92%	Every 2 days, weekdays	4:00pm, 10:00pm
			Every day, weekends	Any time
	Company	8%	Every day, weekdays	5:00pm, 5:30pm, 6:00pm
[18, 16]	Private	92%	Every day, every 2 days	5:30pm, 6:00pm, 6:30pm
	Company	8%	Every day	5:00pm, 5:30pm, 6:00pm

3.3 Conclusions

The literature review showed that it is possible, based on national statistics, to produce sensible profiles that resemble potential driving patters of EV users. This, combined with the technical characteristics of EVs (i.e., size, battery charging characteristics, and charging modes), can then be translated into electricity demand profiles to be seen at homes.

While the presented methodologies will certainly create the basis for the production of profiles for the LV Network Solutions project, the available models cannot directly be used. A much more detailed approach is required where regional and network-related characteristics (i.e., urban/rural area, availability of fast charging points, etc.) are considered.

4 Photovoltaic Modelling

Thanks to the UK feed-in tariff, the number of small-scale photovoltaic (PV) systems (≤4kW) has increased significantly in the last two years. Given that these PV installations are connected to LV networks, small penetrations can result in reverse power flows as high solar irradiance coincides (in certain areas) with relatively low demand. Consequently, in order to assess the impact of future penetrations it is important to model the generation behaviour of such devices.

Different from electric heat pumps and electric vehicles, the electricity production from small-scale PV systems is not affected by the occupants of the dwelling. Consequently, its modelling largely depends on the technicalities of the PV system itself (e.g., nominal capacity, roof slope), as well as resource availability (e.g., weather conditions, cloud transients). Figure 20 shows the corresponding modelling flowchart.

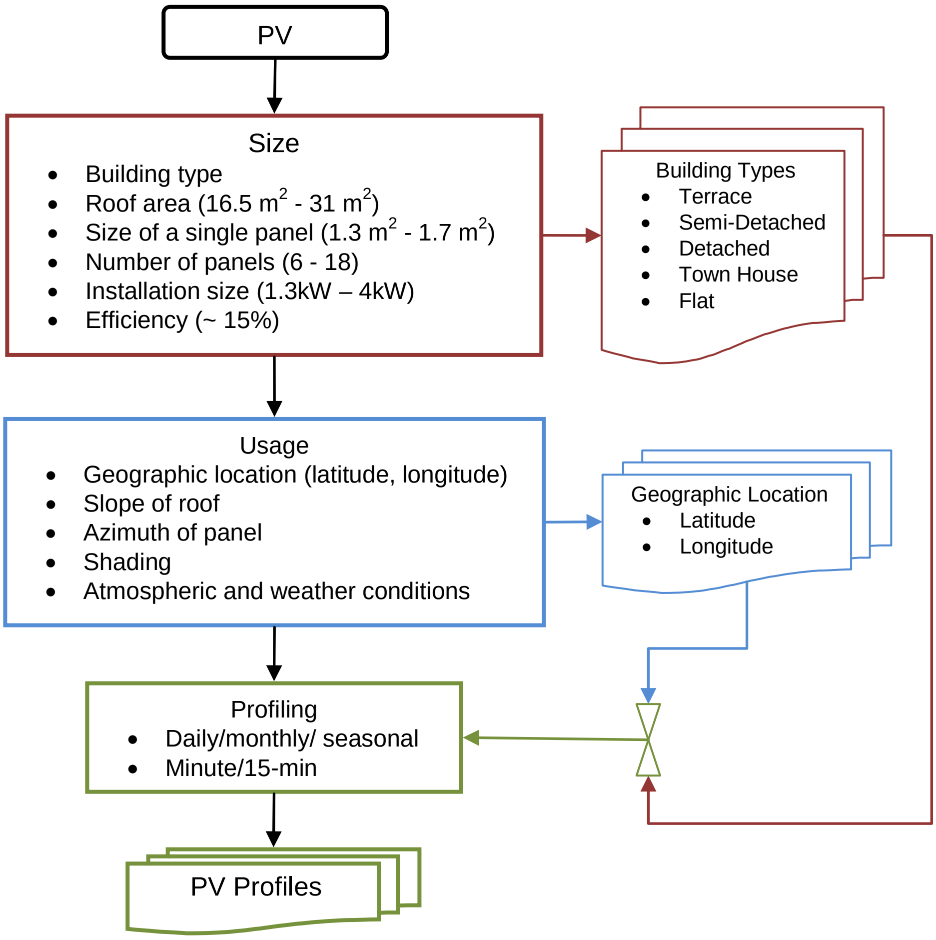


Figure 20 PV Generation Profile Modelling

4.1 PV Technology

Small-scale photovoltaic systems (≤4kW) capture the sun's energy using photovoltaic cells and an AC/DC inverter. The cells convert the sunlight into DC electricity which is then converted into AC by the inverter. PV cells are made from layers of semi-conducting material, usually silicon. When light shines on the cell it creates an electric field across the layers. The rated power of a PV cell is measured in kilowatts peak (kWp). This is the rate at which it generates electricity at peak performance (in full direct sunlight).

4.2 Literature Review

In this section, first typical sizes of PV systems to be found in the UK are presented. Then two main freely available tools are discussed.

4.2.1 PV Size

The typical size (area) of a single solar panel in the UK is 1.6m^2 (1.6m x 1m). Other sizes are also available, ranging between 1.3m^2 and 1.7m^2 [21]. The rated capacity (kWp) of a domestic PV system will vary depending on cost and the roof area available to accommodate the panels. Typically system sizes are between 1-4kWp. The roof area requirements for typical residential solar PV installations (1.6m^2 panel rated at 220W) are listed in Table 9. PV installation sizes are given for typical UK dwelling types in Table 10 [21].

Table 9 Typical roof area requirements for PV installation size [21]

Solar installation size	Small		Medium		Large		X-large	
Number of panels	6	8	9	10	12	15	16	18
Installation size/rating (kWp)	1.3	1.8	2	2.2	2.6	3.3	3.5	4
Typical roof area needed (m^2)	9.6	12.8	14.4	16	19.2	24	25.6	28.8

Table 10 PV installation size for typical UK building types [21]

Solar installation size	Building types	Typical suitable roof area (m^2)
Small and Medium	Period Mid-Terrace or End Terrace	16.5
	Small Semi-Detached House	17
	Modern Mid-Terrace or End Terrace	18
	Modern 3 Storey Town House	18
Large	Average Semi-Detached House	20
	Small Detached House	21.5
	Old 3 Storey Town House	23
X-large	Semi-Detached Bungalow	27
	Two Bedroom Flat (Top Flat)	28
	Average Detached House	29.5
	Detached Bungalow	31

4.2.2 PV Generation Profile

Every roof is exposed to different amounts of sun. This depends on its location, the slope of its roof, shading and the direction its roof faces. The optimum angle for solar power collection in the UK is 35°. The default angle for a typical UK roof is 40°. The best direction for solar power collection in the UK is south facing (i.e., 180°). The typical roof slope for the average UK home is about 40° [21].

A domestic PV system generates electricity that partially offsets electricity demand consumption at the dwelling. The PV output relates closely to outdoor irradiance. Maximum generation typically occurs at solar noon, subject to atmospheric and weather conditions. The size and efficiency of a PV installation are the basis for estimating its maximum electrical output. However, irradiance is a critical input to actually model the corresponding generation profile. Passing clouds (or cloud transients) can also cause rapid variations in PV output.

The Photovoltaic Geographical Information System (PVGIS) [22], a freely available online tool, is capable of estimating daily and monthly radiation, as well as PV generation, by entering geographical information (location) as well as PV specifications (Figure 21).

The freely available MS Excel VBA-based tool developed by Centre for Renewable Energy Systems Technology (CREST) [23], [24] is capable of modelling small-scale PV systems with realistic time steps (every minute) for areas in the UK. In this model, synthetic irradiance data for any given geographic location is generated at one minute resolution. Then, PV electricity generation is modelled considering the corresponding irradiance as well as panel areas, size and orientation.

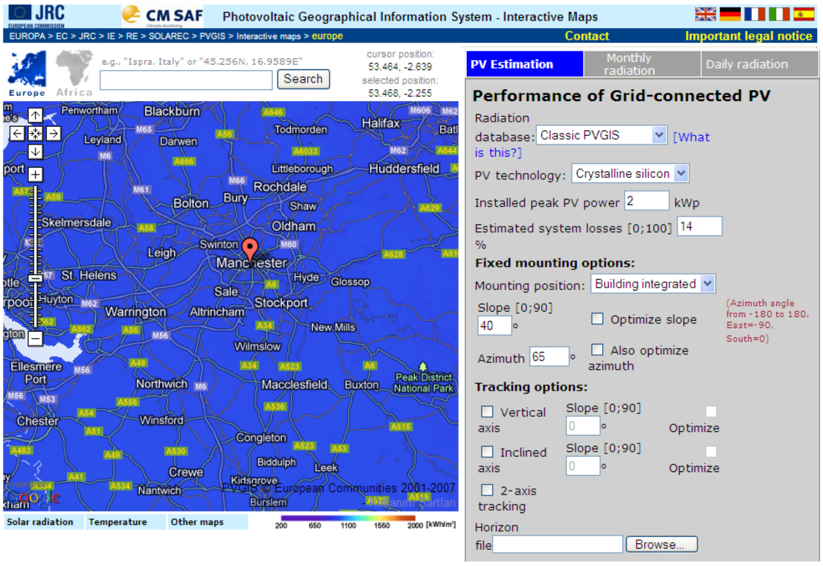


Figure 21 PVGIS User Interface

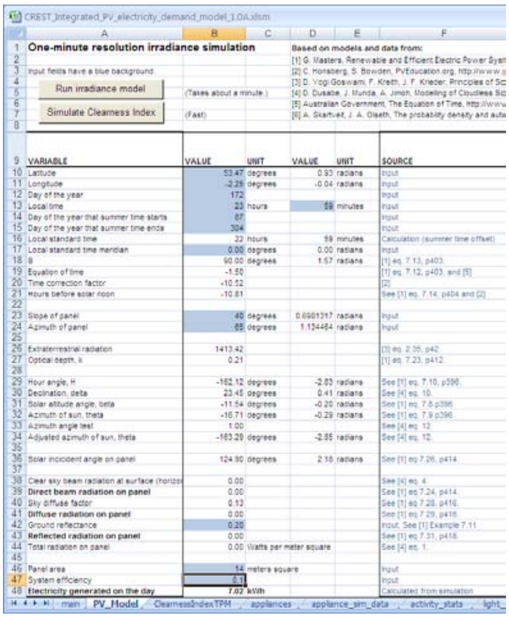


Figure 22 CREST Integrated PV electricity demand model [24]

To illustrate the use of the above tools, a randomly chosen semi-detached house on Mallow Street, Manchester will be used. Its latitude and longitude (obtained from Google Maps, Figure 23) can be used to calculate the corresponding azimuth. The slope of the roof is assumed to be 40°. The roof area and PV system size are chosen from Table 9 and Table 10, and presented in Table 11.

Figure 23 A semi-detached house on Mallow Street, Manchester

Table 11 Parameters of PV modelling for a semi-detached house

Day of the year	July 21st/ Jan 7th
Latitude	53.46928°
Longitude	-2.254855°
Slope of panel	40°
Azimuth of panel	65°
Panel area	14m^2
Number of Panels	9
Installation Size	2kWp
Typical roof area needed	17m^2

The estimated PV generation across the year and daily radiation for January calculated by PVGIS are shown in Figure 24. It can be noticed that the irradiance provided is very smooth, i.e., does not cater for the effects of passing clouds.

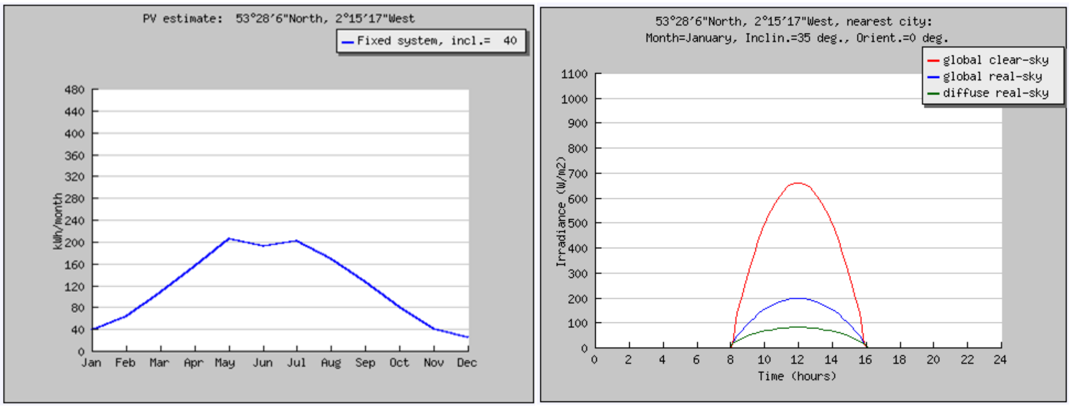
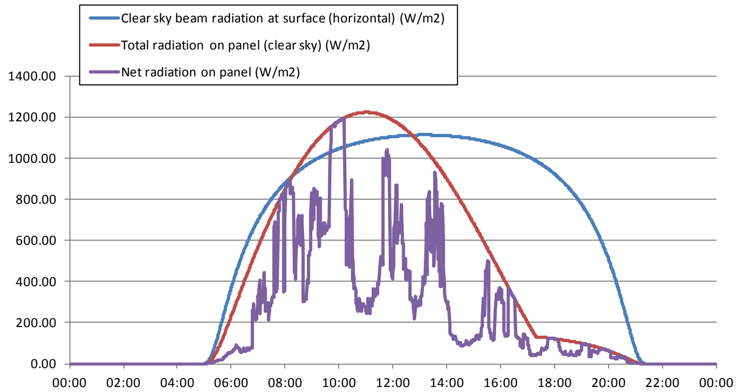


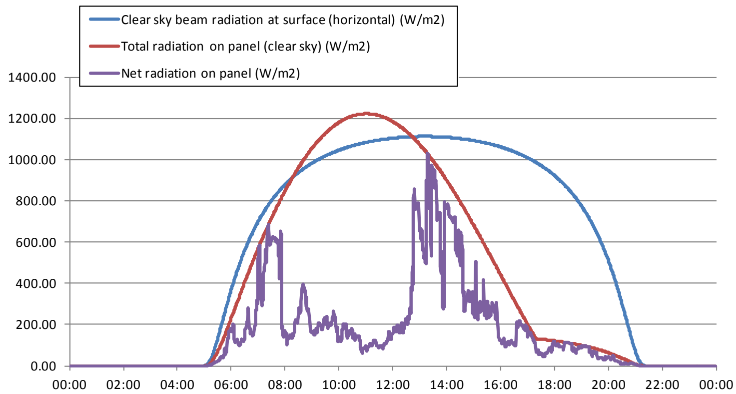
Figure 24 Monthly PV Generation and Daily Radiation for January

Using the CREST tool [24], generation profiles can also be produced for the illustrative PV system. Figure 25 and Figure 26 show two PV generation profiles considering different ‘clearness’ indexes for 21st July and 7th January, respectively.

The higher ‘clearness’ index (case a in Figure 25 and Figure 26) led higher overall generation. In addition, it can be observed that this more complex model also considers the effects of passing clouds.

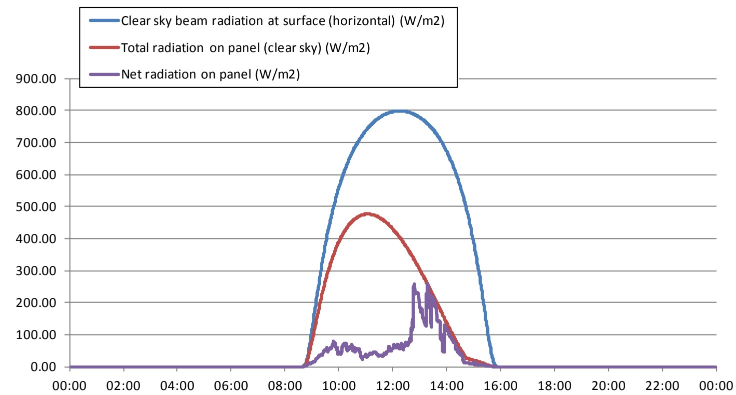


a) Daily PV profile resulting in 7.2 kWh

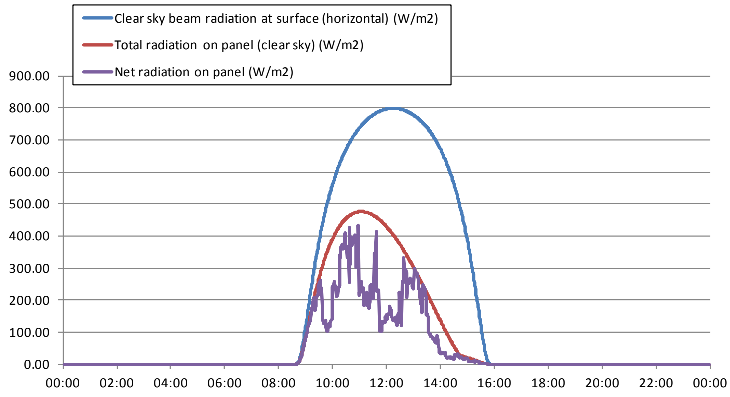


b) Daily PV profile resulting in 5.09 kWh

Figure 25 PV generation profile for 21st July, one minute resolution



a) Daily PV profile resulting in 0.64 kWh



b) Daily PV profile resulting in 1.54 kWh

Figure 26 PV generation profile for 7th January, one minute resolution

4.3 Conclusions

The electricity production from small-scale PV systems is not affected by the occupants of the dwelling. Consequently, its modelling largely depends on the technicalities of the PV system itself (e.g., nominal capacity, roof slope), as well as resource availability (e.g., weather conditions, cloud transients).

From the two models presented in the literature review, the one produced by CREST can certainly be used directly in the LV Network Solutions project. The corresponding parameters needed by the tool can be based on real locations of the monitored LV networks combined with suitable assumptions (such as roof angle).

However, it is important to highlight that while this tool is able to create high resolution (one minute), high quality profiles for specific locations in the UK, it is ideal to validate (or even improve) such models with actual monitored irradiance or PV generation at or close to the monitored LV networks.

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