Accepted for publication – Applied Energy 2014

Probabilistic modelling and assessment of the impact of electric heat pumps on low voltage distribution networks

Alejandro Navarro-Espinosa and Pierluigi Mancarella*
School of Electrical and Electronic Engineering, University of Manchester,
Ferranti Building, M13 9PL, Manchester, UK

* *Corresponding author*: Tel: +44 (0)1613064654; Fax +44 (0)1613064820.

E-mail addresses:
alejandro.navarroespinosa@manchester.ac.uk (A. Navarro Espinosa)
p.mancarella@manchester.ac.uk (P. Mancarella)

HIGHLIGHTS

- High-resolution calculation of power requirements for different types of air source heat pump (ASHP) and ground source heat pump (GSHP)
- 5 minute-time series simulations by using three phase unbalanced power flow based on OpenDSS
- Modelling of consumption diversity and uncertainties through a Monte Carlo approach
- Probabilistic assessment of thermal and voltage impacts of ASHP and GSHP in a suburban LV network
- Sensitivity analysis for house insulation level, external temperature, EHP sizing, auxiliary heating type, reactive power consumption, etc.

ABSTRACT

Electrification of heating by making use of the Electric Heat Pump (EHP) technology powered by increasing shares of electricity renewable sources is seen as a potential key approach to decarbonise the energy sector in many countries, and especially in the UK. However, the widespread use of EHPs in substitution of fuel boilers might cause significant issues in terms of electrical distribution network impact, particularly at the low voltage (LV) level. This has not been addressed properly in the studies carried out so far also due to lack of available data and suitable models. In this light, this paper introduces a novel and comprehensive probabilistic methodology based on Monte Carlo simulations and a relevant tool to assess the impact of EHPs on LV distribution networks. Real electricity and heat profiles are taken as a starting point of the studies. Both Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP) types are modelled as black boxes with performance and heat capacity characteristics changing with operating conditions according to manufacturers' curves, addressing in particular the need for and impact of different types of Auxiliary Heating (AH) systems. A specific LV network analysis tool has been built that integrates the three-phase unbalanced power flow solution engine OpenDSS with the developed EHP models and is capable of properly addressing single-phase connections, adequately modelling the unbalanced nature of LV networks. Different metrics are used to quantify the impact of the considered technologies, with emphasis on thermal and voltage limits, according to current engineering standards. To cope with the many relevant uncertainties (EHP size, location in the network, operation pattern, reactive power consumption, network headroom, etc.), various case studies and sensitivity analyses have been carried out for representative suburban areas in the UK and for different scenarios in order to exemplify the developed methodology and illustrate the main drivers for impact and trends in the different cases. The tool can be adapted to perform studies for different situations and scenarios and can be used as decision making support by network operators, energy planners, policy makers, and so on, to better quantify the potential implications of large scale electrification of heating.

Keywords – air source heat pump, auxiliary heater, decarbonisation, electric heat pump, ground source heat pump, low voltage distribution networks, OpenDSS, unbalanced power flow.

Nomenclature

Acronyms

ADMD	After Diversity Maximum Demand
AH	Auxiliary Heating
ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DNO	Distribution Network Operator
EHP	Electric Heat Pump
GSHP	Ground Source Heat Pump

1. Introduction

In order to meet the challenging environmental targets that have been set out by Governments worldwide in the attempt to fight climate change, there are clear paths towards decarbonising the electricity sector by means of renewable sources such as wind. However, in order to drastically reduce the environmental impact of the *entire* energy sector, decarbonisation of the heat sector represents an even more strategic and challenging point, particularly in the UK and for the domestic sector. Various "heat strategies" documents have therefore been issued (see for instance [1]) in the attempt of steering the most cost effective evolution towards low carbon domestic heating. In the envisioned energy futures, there is a widespread utilization of the Electric Heat Pump (EHP) technology, with an extreme scenario, an *electric-only future*, where EHPs supplied by renewable electricity, and in case supported by thermal storage [2] and/or possibly coupled to heat networks [3], allow supply of virtually zero carbon heating. However, an open key point to address is the impact that widespread adoption of EHPs would have on the electrical distribution network, particularly at the low voltage (LV) level in the case of domestic systems. In fact, the additional electrical load at households could be substantial [4] and trigger significant technical issues, eventually either calling for network reinforcements or impeding further EHP connections beyond a certain level.

The use of smart strategies to decrease network impact has also been advocated in [5] and [6], but practical implementations are still far or might not bring expected benefits [4] while EHPs are already becoming a reality today thanks to technology improvements and financial incentives that are allowing overcoming early stage economic limitations [7]. In this respect, there is lack of suitable tools and relevant studies to actually quantify the impact at a LV level for different scenarios, technologies and types of networks, including a detailed modeling of the LV network. Studies in this direction have been performed for instance in [8] by assuming three-phase balanced connections and based on average profiles only**.** In addition, those studies and other "classical" studies use hourly profiles, while [9] has indicated that much finer resolution, in the order of 5-10 minutes, is needed to properly account for the impact at a household level and particularly for individual peaks that might arise. An attempt to consider load diversity has been performed in [10], where the correlation between electricity and heat profiles is modeled through a heuristic approach; no network impact is however analysed. The paper [11] has considered the impact of EHPs on distribution networks based on experimental data available. However, there is no attempt to model the EHP performance characteristics in dependence of operating (and particularly external) conditions and to take into account the need for back-up heating under harsh conditions. Similarly, reference [6] has considered a number of worst-case situations, but without detailing the impact on LV networks**.** In addition, the impact might change significantly with different types of EHP such as Ground Source Heat Pumps (GSHPs) or Air Source Heat Pumps (ASHPs) and different types of buildings and operating conditions. An interesting analysis of the different types of EHP and their main characteristics for applications in the UK can for instance be found in [12]. No such studies allowing for detailed network impact analysis from different EHP types in different buildings are available in the literature.

On these premises, this paper introduces a comprehensive probabilistic methodology and an associated modeling tool that are capable to understand and quantify in a systematic way the impact on LV distribution networks of different types of EHPs, namely, GSHP and ASHP (but the model could also be extended to other types such as water-source heat pumps, for instance), with and without back-up

Auxiliary Heater (AH) of different types (for instance, fuel-based or electricity-based), different conditions (outdoor or ground temperatures, etc), different types of buildings (for instance, with different insulation levels), and different consumption of reactive power (different power factors). The analysis is carried out starting from real high resolution electricity and heat consumption profiles taken from field trials on micro-generation [13]. An input-output black box approach, such as in [14], [15] and [16], is then used to model the EHP for different types and operating characteristics, which "transforms" heat profiles into electricity ones taking into account real-time varying performance of the EHP (from manufacturers' curves) and the relevant AH operation. The electricity profiles obtained by combination of the base consumption profiles and the ones from the EHP are then input into an LV network analysis tool specifically developed. The tool is implemented in Microsoft Excel-VBA and integrates the OpenDSS software tool [17] (which is able to solve three-phase unbalanced power flows, intrinsic characteristic of LV networks) as a load flow engine. A number of numerical studies are performed in a Monte Carlo fashion to test the model developed and identify implications of electrification of heating under different conditions and for different applications and scenarios, with particular reference to the UK situation. This Monte Carlo approach is crucial to cope with the uncertainties that Distribution Network Operators (DNOs) could face with respect to EHP location, size, operation pattern, and so forth. Thus, the impact results are given in terms of expected values and relevant uncertainty (measured through the standard deviation indicator) rather than in a deterministic fashion as in most studies.

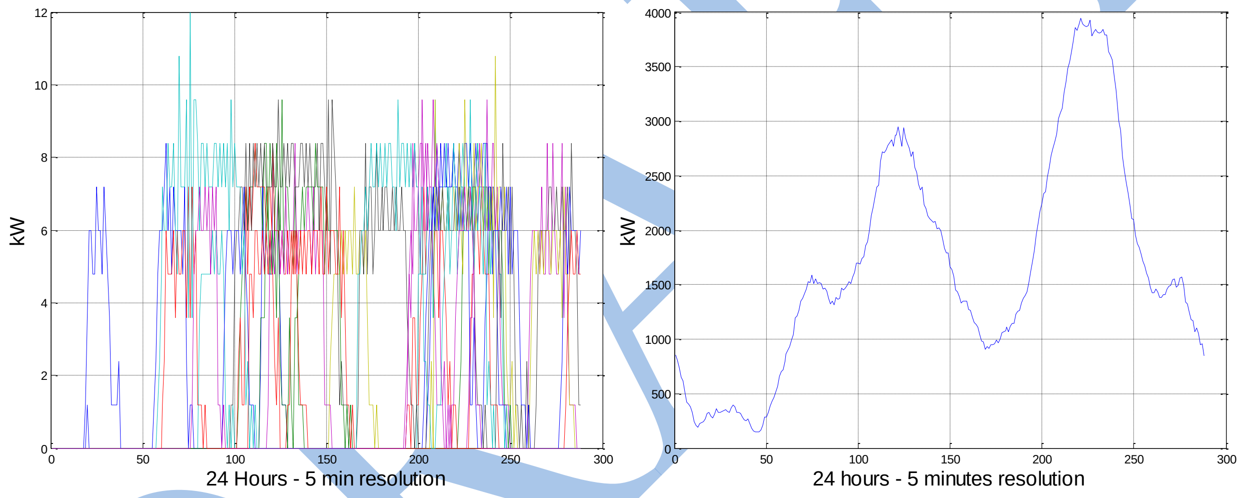
The paper is organized as follows. Section 2 describes the approach followed to derive electricity, heat and EHP electric load profiles for network studies. Section 3 discusses the methodology developed for LV network impact analysis and the relevant tool that has been built. Section 4 presents and discusses different numerical applications to test the methodology and quantify the impact of different EHP types in different scenarios. Section 5 contains the final remarks and bridges to future work.

2. Electro-thermal load modelling

2.1. Electricity and heat load profiles

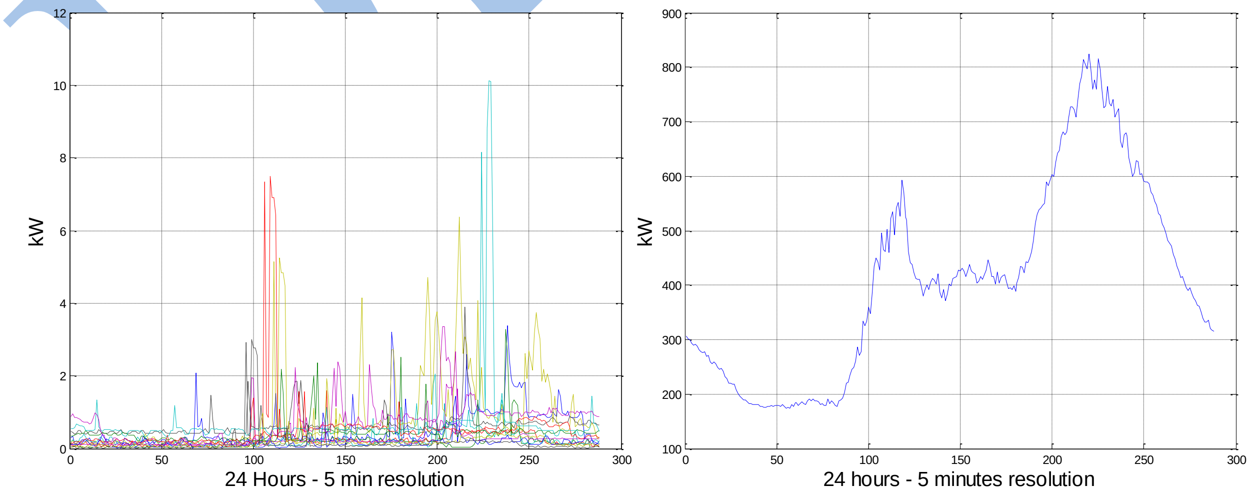
A critical aspect to get detailed network impact analysis is to have a proper temporal precision in the electrical load input data, particularly relevant to quantifying voltage quality issues based on equivalent 10-minutes resolution [18]. However, in most cases DNOs do not have any information at all available for individual residential customers, and in the best case only aggregated profiles at the MV level are available. Likewise, there are currently no detailed data available for EHPs, and it is likely that the statistical value of data available from initial trials would be limited. For instance, recent trials that took place in the UK have been analysed in [19], [20], where unexpected operational profiles and smaller coefficient of performance have been pointed out primarily due to down-rating of the EHP. In fact, in [21] a series of improvement for some of the houses in the original trial are carried out in order to increase the system efficiency, but again this is done for a small number of houses (38 from the original trial). Therefore, real load data for both electricity and heat consumption taken from a recent campaign conducted for micro-cogeneration systems [13] and which have already robustly used in several studies (see for instance [9]) have been considered in this work, which provide the consumption for different types of houses with 5-minute resolution. The micro-generators used in the trial are of smaller size (typically from 8 kW_t to 15 kW_t) relative to traditional boilers (that can be of 20 kW_t or higher), are equipped with an auxiliary heater, and are buffered by a hot water tank. Because of these characteristics that resemble very closely typical EHP installations, the heat production patterns from the trial represent a very good approximation of what the likely patterns of an EHP that is compatible with UK radiators would exhibit. However, it is important to remark that in some locations the size or the number of radiators per home should be increased in order to have the same heat exchange power than in the micro-cogeneration case (this type of upgrading is recommended in the Heat Emitter Guide for Domestic Heat Pump [22]). In fact, in the modelling studies presented in this paper a delivery temperature of 55˚C is assumed for EHPs, while from the trial the average delivery temperature was 67˚C.

Out of the complete set of data, specific information has been selected for “cold” (and “very cold”) winter days and sixteen houses in central England areas so as to properly take into account the coincidence factor and therefore diversity of the thermal load in a given area under harsh conditions. In order to create further diversity, a larger set of electricity and heat profiles has been generated by randomly shifting the original profiles by 5 to 30 minutes backward and forward. Hence, while the correlation with outdoor temperatures is still maintained (no significant temperature variations are observed in these short intervals), this shift allows to increase to certain extent the effect of diversity that would be observed in realistic consumption patterns for few hundreds of users (expected at the LV feeder level) in different houses. Examples of individual heating profiles and after diversity heating profiles for 1000 customers are shown in Figure 1.a) and Figure 1.b), respectively, while examples of individual electricity profiles and after diversity electricity profiles for 1000 customers are shown in Figure 2.a) and Figure 2.b) respectively. The after diversity electricity profiles obtained with this approach is consistent with typical electricity profiles [23], and the after diversity heat profiles are consistent with the ones available from other studies [24].



a) **b)**

Figure 1: Individual (a) and aggregated (b) thermal load profiles



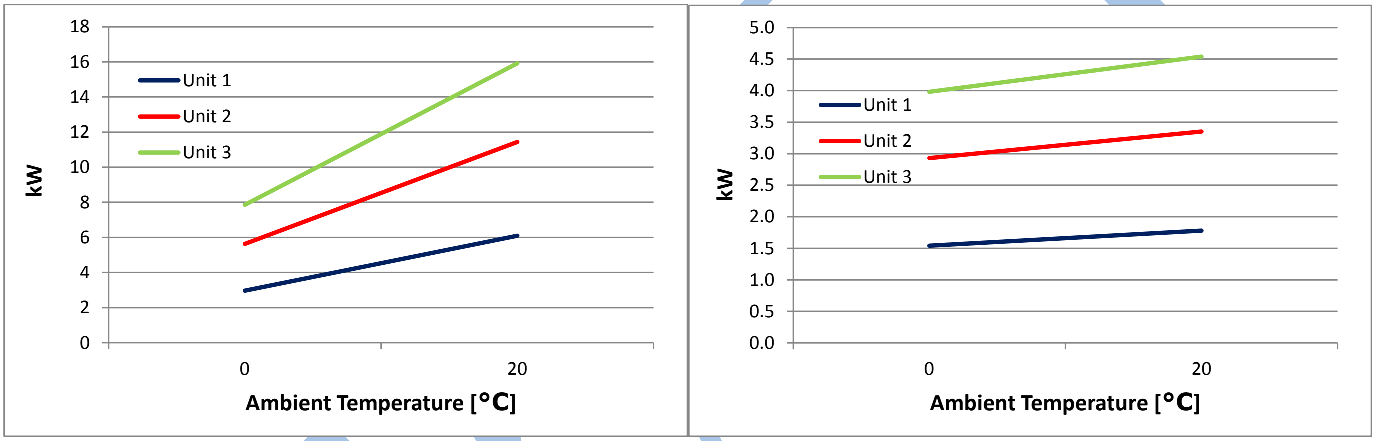
a) **b)**

Figure 2: Individual (a) and aggregated (b) electrical load profiles

2.2. EHP/AH system modelling

2.2.1. EHP performance maps

Starting from the heat consumption profiles discussed above, an input-output black box model approach is used to “transform” the household thermal demand into EHP electrical demand to be added to the “base” electrical demand. More specifically, the heat capacity and the relevant electricity consumption curves are taken from manufacturers’ catalogues (see for instance [25] and [26]) and fitted through linear models to represent their dependence on the air outdoor or ground/brine temperature (depending if ASHP or GSHP, respectively) and of the delivery temperature (typically air or water at different temperatures, depending on the house distribution system). Examples of heat capacity and electricity input characteristics in dependence of the external source’s temperature and for delivery temperature of 55 ˚C are provided in Figure 3 for three different ASHP units [25] (for which outputs at 7˚C outdoor temperature are 4.07, 7.66, and 10.68 kW_t, respectively). Similar characteristics could be drawn for GSHP having the ground/brine temperature as the independent variable and for different delivery temperatures (for instance for low-temperature under-floor heating distribution systems).



a) **b)**

Figure 3: Heating capacity (a) and corresponding electricity consumption (b) for an ASHP family

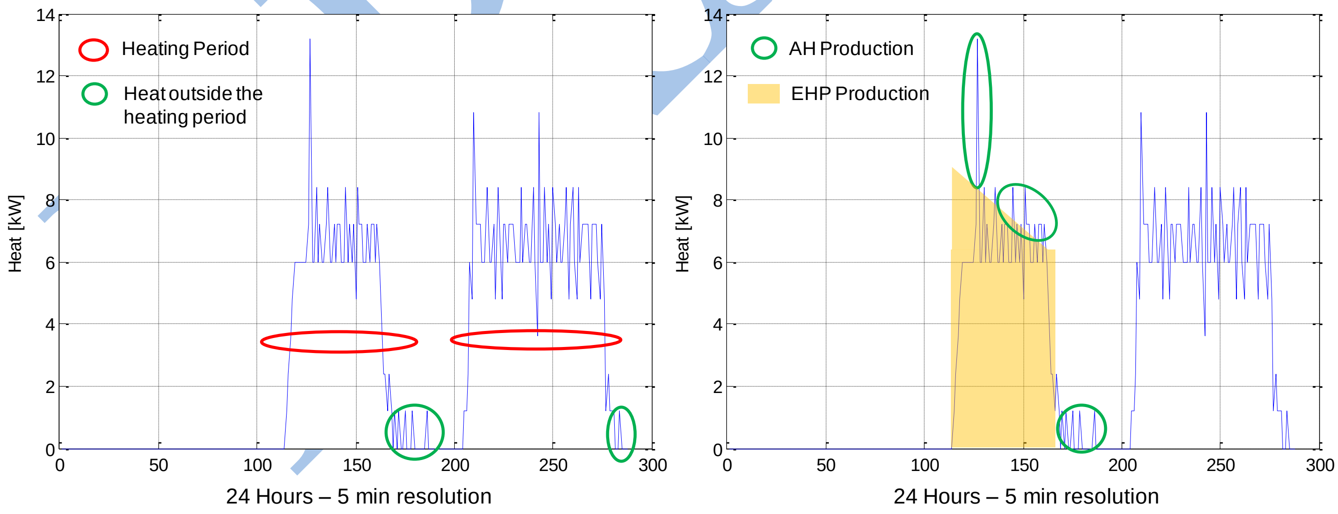
2.2.2. EHP-AH sizing

An AH is assumed to be available with the EHP (this also corresponds to common manufacturers’ offers). In fact, in order to properly capture the network impact from EHPs, it is crucial to properly model the EHP-AH interaction and particularly the need for AH operation when the thermal capacity of the EHP under harsh conditions is not sufficient to supply the heat demand. In order to size EHP and AH for different houses, the EHP has been designed so as to cover 80% of the peak thermal load on the coldest day, as indicated by manufacturers’ recommendations [26]. This peak thermal load is calculated from the aggregation of the real data over periods of 30 minutes rather than the original 5 minutes, in order to avoid oversizing of the EHP due to the short term peaks present in the real data (associated with typical “peakier” operation of boilers). After sizing the EHP device, the remaining capacity for space heating and DHW is covered by the AH if this is needed. A further study is conducted in Section 4.3.4 to assess the sensitivity to a different AH sizing approach (e.g., consistently with the model presented in [27], where a GSHP is sized to cover 60% of the peak heat demand).

2.2.3. EHP-AH operation and electricity consumption

The traditional operation of EHP is an on-off process, where the length of each period depends on the heat requirements (for space heating and/or domestic hot water) and the temperature conditions (outside and inside). In [28], a minimum “ON” cycling period of 6 minutes per hour is recommended. In the same report, different cycling periods are observed for different ambient temperatures. For instance, a cycling period of 11 minutes (4 cycles in 71 minutes) is observed at 5˚C and a cycling period of 42 minutes (4 cycles in 165 minutes) is measured at -4˚C [28]. To be consistent with the real EHP operation, the on-off operation is simulated in this paper by introducing different cycling period according to different heat requirements. The relevant heat production and electricity consumption and therefore the corresponding Coefficient Of Performance (*COP*) – EHP heat to electricity ratio – are then calculated for each time step (5 minutes interval) of operation in dependence of the external conditions (assuming fixed output delivery temperature of 55 ˚C). In order to calculate both the EHP and AH electricity requirements, the following procedure has therefore been implemented for each house's heat profile.

1. *Identification of the heating periods*: the number of periods, the length of each of them, and the relevant energy are identified. For instance, in Figure 4, it is possible to observe two well defined heating periods.
2. *Identification of the auxiliary heater operation (AH):*
    a. *Coverage of small heat requirement outside the main heating periods*: these relatively small energy requirements will be supplied by the auxiliary heater since they represent a sporadic and small amount of energy consumption (likely related to maintain the required temperature for the domestic water supply). This type of consumption is highlighted in Figure 4a and 4b.
    b. *AH operation inside the main heating periods*: to capture the operation of auxiliary heater either for harsh ambient conditions or for large unexpected heat consumption (e.g., large domestic hot water drawn-off) the auxiliary heater production should be extracted before modelling the EHP cycling operation (step 3). In this way, it is possible to avoid the elimination of the unexpected AH operation by increasing the EHP cycling period. Hence, for each time step (5 minutes) the plausible EHP production (e.g., yellow region in Figure 4b) is compared with the thermal demand (e.g., blue line in Figure 4b), and if the EHP production is lower, the AH makes up for the remaining heat requirement. Therefore, the heat to be supplied by the EHP cycling operation in each heating period is the difference between the heat demand and the AH production.



a) **b)**

Figure 4: Example of Heating periods (a) and auxiliary heater operation for heating period 1 (b)

3. *EHP cycling for each heating period*: for each heating period (dotted thick line in Figure 5), the total amount of heat is determined. Starting with a minimum EHP cycling period (i.e., time when the EHP is "ON") of 10 minutes per hour (consistent with the suggested minimum cycle duration of 6 minutes and considering the 5 minutes resolution data) and taking into account the outside

temperature (changing every 5 minutes), the EHP heat production and consumption is determined for each EHP cycle. If the heat production is lower than the energy requirement in the heating period the EHP cycling period is increasing by 5 minutes. This process is repeated until the EHP production is matched with the heat requirement for each particular heating period. For instance, if the heat requirement during a certain heating period is relatively low, the "OFF" time between two "ON" operations in the overall heating period will be longer than the time between two "ON" operations in the same period if the heat requirement were higher (in the limit case, if the heat requirement is extremely high, the EHP will be "ON" during the whole heating period). This approach is also consistent with the results suggested in [29].

While further research would be needed to characterize in detail the real operation of different EHP systems in given conditions, this approach can be considered a good first approximation for network studies that take into account on-off cycling and AH operation and which are consistent with real heat consumption data. Further model refinements are planned for the future when comprehensive information from field data on EHP operation and different compressors will be available. In any case, by visual inspection the results obtained with this approach match well the profiles that are for instance available in [28].

An example of the operational load patterns for an EHP/AH obtained by the above procedure is shown in Figure 5 for two different houses, while the diversified aggregated load pattern for 1000 houses equipped with EHP/AH is shown in Figure 6. The variation on the heat production output levels in Figure 5 is determined by the dependence of the heat output on the ambient temperature as from manufacturers' performance maps. Hence, it is possible to see how the EHP production increases as the temperature increases. Also, it is possible to observe that EHP on-period is longer for the lower temperatures.

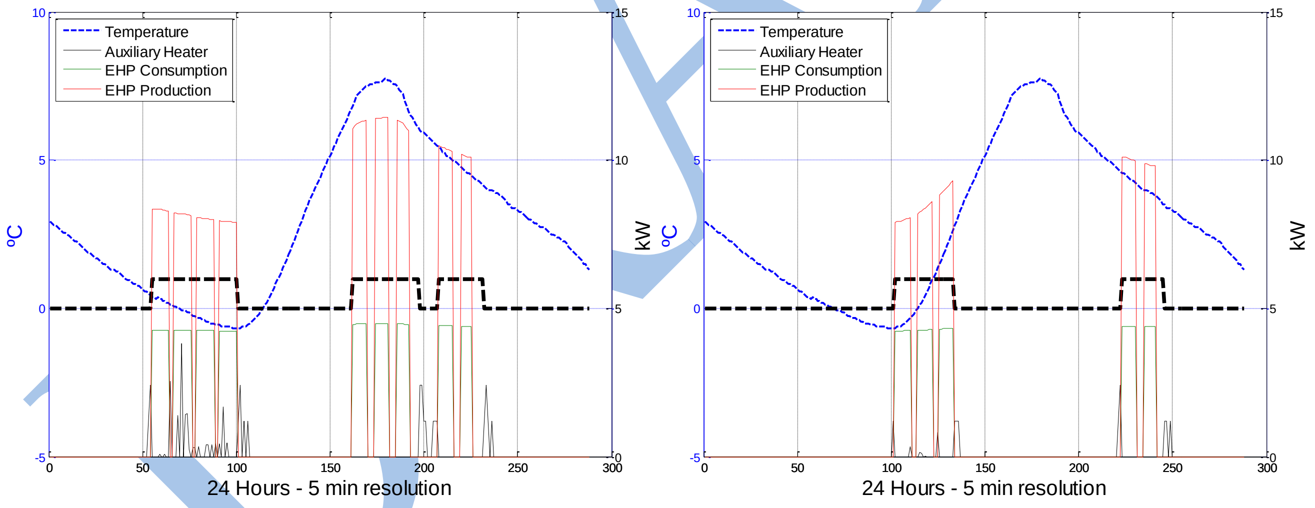


Figure 5: Example of EHP/AH heat production and EHP/AH electricity consumption for two different houses

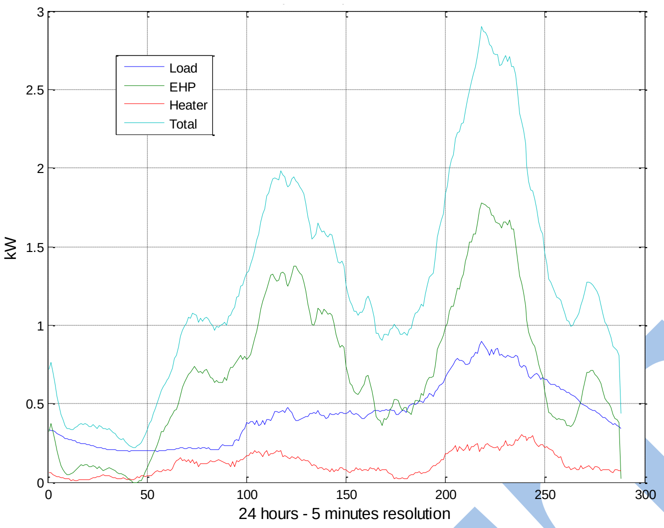


Figure 6: Example of diversified aggregated electricity profile for 1000 houses with Air Source Heat Pump (ASHP)

3. LV network impact analysis: methodology and tool

3.1. Generalities about the methodology and OpenDSS

As aforementioned, from the network side it is critical that the methodology to assess EHP impact can model the single-phase connections of individual houses and is then capable to solve unbalanced load flows, properly taking into account temporal and spatial resolutions in order to capture diversity effects for different conditions. In addition, the model needs to be fast and flexible enough to run a number of time-series based scenario studies, possibly based on probabilistic or Monte Carlo approaches that allow modelling the wide range of cases that could occur. However, in most power system simulation tools it is not possible to readily model three-phase-four-wire unbalanced distribution networks. In addition, while in commercial tools the user interface is usually very advanced, this inevitably limits the flexibility of implementing new models. Therefore, a methodology and relevant tool have been specifically developed to assess the impact of EHP on LV networks based on software commonly accessible and by deploying the OpenDSS software. More specifically, the user interface input (electrical and thermal load data, EHP and AH characteristics and control strategy, network data) has been developed in Excel, and VBA macros support the elaboration of electro-thermal profiles as from above and random allocation of profiles over the network and over the phases. In order to solve the network equations, the relevant data is input into the OpenDSS tool, which is used as the network time series unbalanced load flow engine. Finally, outputs from OpenDSS are sent back through VBA to and elaborated via Excel in order to quantify the network impact according to predefined criteria.

An overview of the process for impact assessment for penetration levels from 0% to 100% in shown in Figure 7, while more details are given in the following sections. This procedure is performed on a Monte Carlo basis (1000 simulations for the studies performed here) in order to obtain more robust solutions suitable for strategic information to be provided to DNOs and other actors involved in the decision making process.

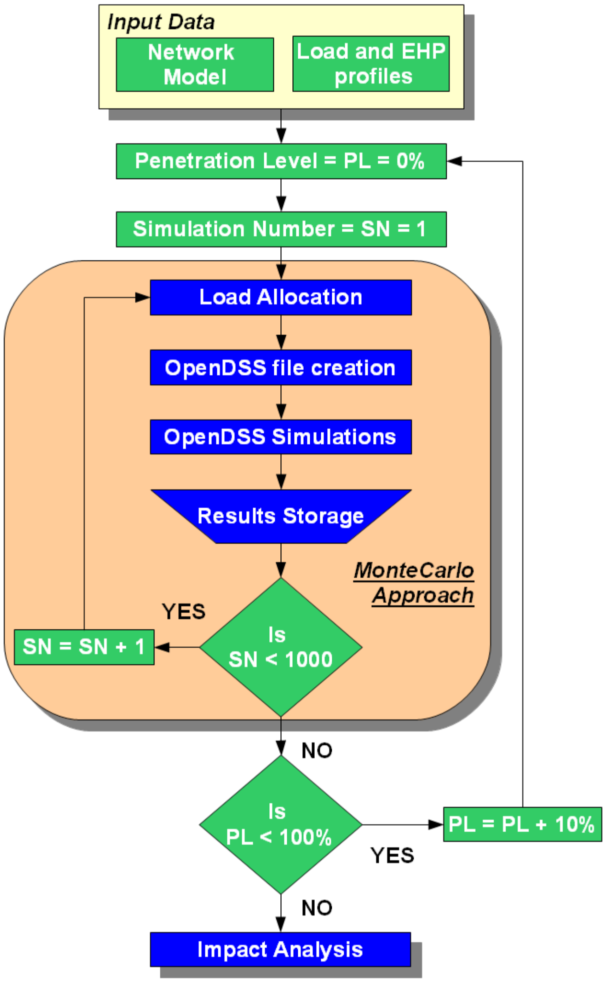


Figure 7: Overview of the process embedded in the tool for network assessment

3.2. Interaction with OpenDSS in the network assessment tool

OpenDSS is an open and free software developed by EPRI [17] and exhibits a number of features that make it very suitable for the studies discussed in this paper. In fact, it can be easily interfaced with other software (i.e., Excel), can efficiently solve multi-phase unbalanced networks, and is very flexible in solving problems with daily and yearly load/generation profiles with different time resolutions. In this respect, a unique feature of OpenDSS is that it is optimized to perform time-series studies, by considering the previous time step solution as the starting point for the iteration seeking the solution at the current time step. As mentioned above, time series studies are critical to capture diversity effect in electricity consumption and EHP operation as well as to check performance against standards. OpenDSS uses its own programming language and each element must be modeled one by one without graphic interface, following certain instructions and codes.

3.3. Criteria for network impact assessment

A number of criteria could be used for network impact assessment. The following metrics are considered here:

- Utilization Index (ratio of maximum hourly circulating power to nominal capacity) of relevant circuits (feeders, laterals, transformers);

- Number of customers with voltage problems, where a voltage problem event arises any time the 10-minute averaged values at the customer premises are outside the statutory range with respect to the nominal value of 230V in more than 5% of the measurements, consistently with the European Standards [18]. According to the EN 50160 [18], the statutory limits is +/-10%. However, in UK, the legislation requires a range between 10% and -6% with respect to the 230V [30]; this more restrictive range is the one used in this work.

Although the engineering recommendations and standards may indicate certain relaxation margins of the above limits (for instance, component overloading is allowed for certain durations, or voltage constraints can be breached with a certain frequency of occurrence), these margins will not be considered in the studies performed here which aim to perform comparative evaluations of EHP impact and evaluate the capability of the assessment tool developed. The results that are obtained should indeed be seen in the light of providing strategic indications on the likely impact of different types of EHPs, based on which DNOs can then formulate their remedial actions or reinforcement strategies. Further impact metrics such as possible harmonic content or short term voltage quality for instance due to starting currents are outside the scope of this work.

3.4. Network impact assessment methodology

The whole methodology for impact assessment of EHP on LV networks has been automatically implemented in the developed Excel/OpenDSS tool. The following steps compose the methodology.

a) *Excel input data and load allocation*

The electrical and thermal load profiles and the network characteristics are input in the Excel interface. More specifically, the “base” electrical load and thermal load (Section 2.1) are input to Excel, while the EHP-AH additional electrical load is generated through the model of Section 2.2. VBA is used to automatically generate randomly shifted load profiles and allocate them to different customer points in the network. Thus, the load profile is different in each house in order to properly capture diversity effect and localized network impact.

b) *Input data to OpenDSS*

The input data to the Excel interface are transformed into different “.txt” files that can be read by OpenDSS in the specific OpenDSS format. These files contain information about technical specifications of the system, such as types of lines, topological connection among lines, load profiles, data to be recorded (“monitors”), and so on.

c) *Time-series power flow solution*

Once all network and load profile data are passed to OpenDSS, time-series power flows are run with five minutes resolution. All voltages and currents are recorded for each time step with the purpose of checking voltage and thermal constraints. In order to do so, every monitor is “interrogated” and the information is stored and passed to Excel. Monitors are fundamental when the power simulation takes into account time series, as they need to store sequentially the electrical information (currents and voltages) for each network element after each power flow simulation in order to check *ex post* the thermal and voltage limits throughout the simulation window.

d) *Monte Carlo simulations and impact analysis*

The above procedure is repeated for 1000 runs of Monte Carlo simulations for all the assessment scenarios described below, with the aim to give a probabilistic representation of the likely impacts by considering possible diversity of operation in the different houses as well as random allocation of EHP across the network and across different phases. The impact results are given in the form of expected value for each of the indicators considered in Section 3.3 as well as by providing error bars corresponding to one standard deviation. For the utilization index, breakdown by circuit is analysed in order to identify what the “bottlenecks” (components where the first issues are likely to arise) could be.

4. Numerical application

4.1. Description of the study cases

4.1.1. Test network

A number of case studies have been run to test and exemplify the capabilities of the tool developed and to provide strategic insights on the implications of different EHP scenarios in terms of network impact. More specifically, a network based on a LV test network, already used for previous assessment of distributed energy technologies [31], has been implemented to represent suburban areas of the UK, which is the most widespread situation. The main features of the test network (schematically represented in Figure 8) are shown in Table 1, while further details can be found in [31]. All customers are assumed with a unitary power factor.

Table 1: Main characteristics of the case study test network

Electricity load density [MW/km^2]	2
Transformer size [kVA]	500-800
Number of feeders	4
Number of customers per feeder	100
Main conductors’ size [mm^2]	185
Lateral conductors’ size [mm^2]	95
Service cables’ size [mm^2]	25

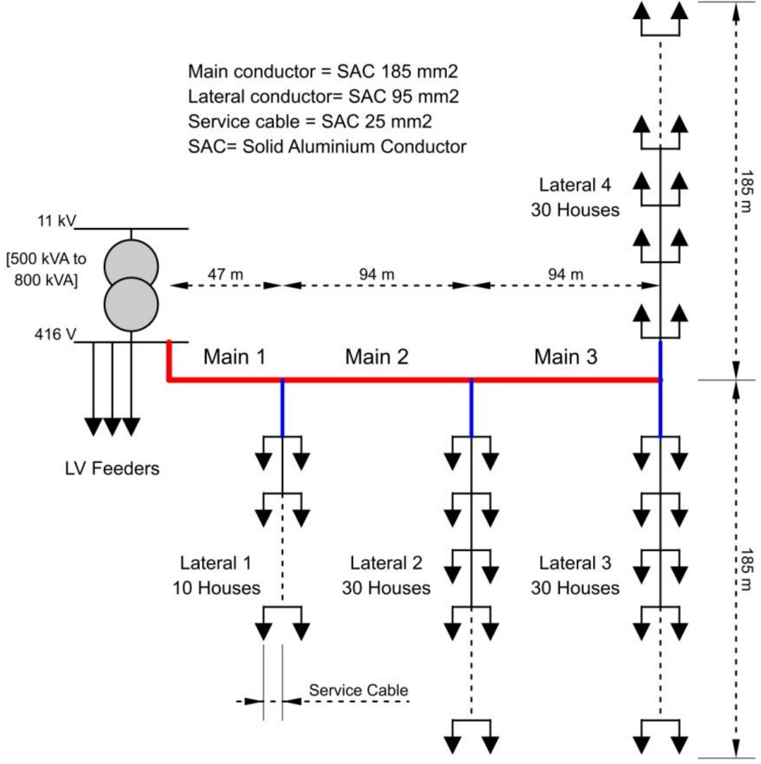


Figure 8: Schematics of the test network diagram

4.1.2. Base case load profile characteristics

A winter day (02/03/2007) was selected from the available data set. The day represents typical “cold” (although not extreme) conditions, with minimum temperature of -0.5˚C, maximum temperature of 7˚C, and average temperature of 3˚C. This temperature profile can be observed in Figure 5 (dotted line). Twelve terraced houses and four semi-detached houses with three bedrooms, an average floor area of 87 m^2, and a building age from 2006 were selected. Again, these are typical situations of UK dwellings and it is likely that EHPs will be applied in relatively new buildings.

As mentioned above, hundreds of profiles for the heat and electricity consumption were then generated by shifting the original data randomly between 5 and 30 minutes and used as inputs for network analysis.

4.1.3. EHP-AH systems

Both ASHPs and GSHPs (both with water distribution at 55 ˚C, compatible with modern radiators and in any case consistent with delivery temperature actually measured in the trial even for older distribution systems, as mentioned above) have been considered in the study. Heat-to-electricity “transformation” of the heat profiles (which also takes into account domestic hot water requirements) has been carried out according to the procedure of Section 2.2, with EHPs sized to supply 80% of the maximum heat requirement (estimated for -3 ˚C, as from design temperature [32]), while the rest of the power is supplied by the AH. Nominal data of the selected systems are shown in Table 2, and off-design models such as the ones in Section 2.2.3 have been applied in all cases. For the GSHP, an average ground temperature of 7.1 ˚C has been used**.** This temperature corresponds to the real ground temperature measured at one-meter depth for the same region and winter day under analysis (information taken from Woodford Meteorological Station located in Stockport [33]). As the performance of the GSHP was mapped with reference to the brine temperature, 6˚C difference between brine and ground temperature has been assumed at first approximation, as from [27].

Table 2: Main characteristics of the EHP/AH used in the base case studies

	ASHP			GSHP			
Nominal capacity[1] at 55 ˚C output [kW$_t$]	2.97	5.63	7.86	3.41	6.19	8.1	12.00
Nominal *COP* at 55 ˚C output	1.92	1.92	1.97	2.87	2.83	3.12	3.08
AH capacity [kW$_t$]	2x3			2x3			

[1] For ASHP and GSHP the reference outdoor air temperature and reference ground temperature (brine temperature), respectively, are 0 ˚C

An example of the operational load patterns for a GSHP/AH obtained from the procedure discussed in Section 2.2 is presented in Figure 9 for two different houses, where it is possible to observe that the *COP* is constant along the day because the ground temperature (7.1 ˚C) does not change at first approximation. In fact, the figure shows how both the EHP heat production and EHP electricity consumption levels are constant along the day, and therefore the ratio between them (i.e., the *COP*) also remains constant. The diversified aggregated load pattern for 1000 houses equipped with GSHP/AH is shown in Figure 10. In this case the ADMD is about 2.5 kW in comparison with 3.0 kW for the ASHP/AH.

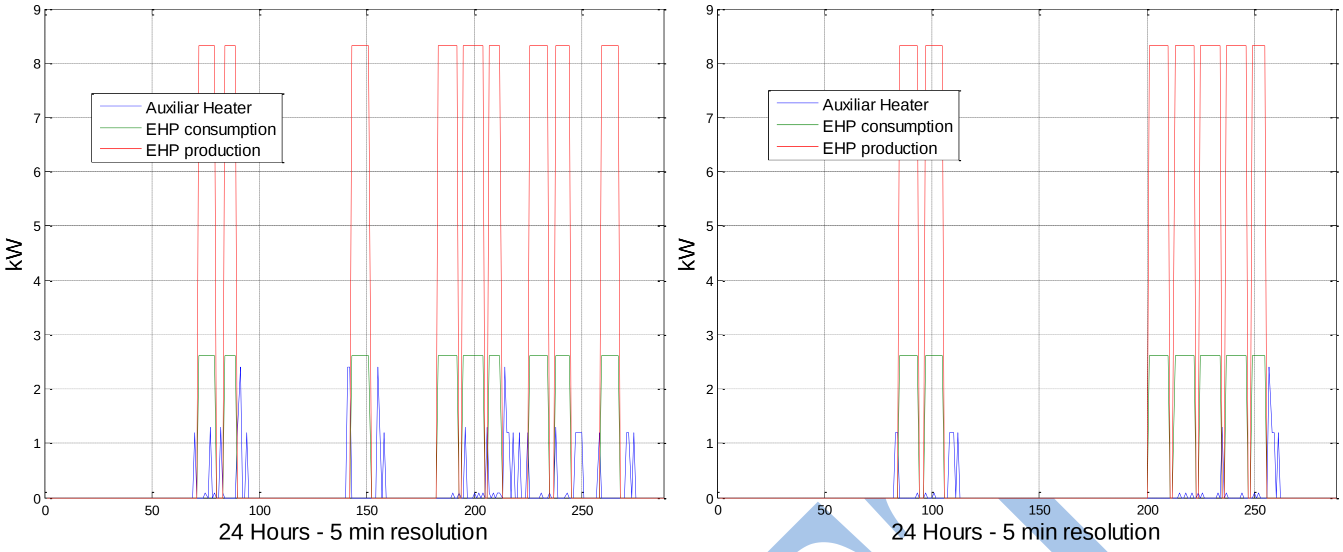


Figure 9: Examples of GSHP/AH heat production and electricity consumption for two different houses

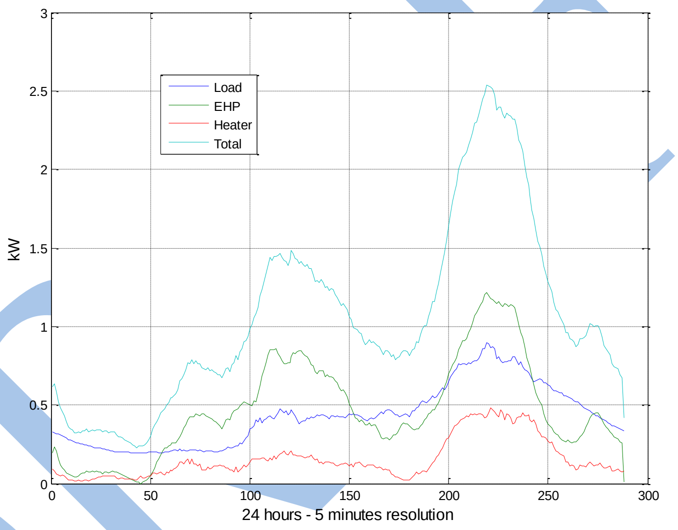
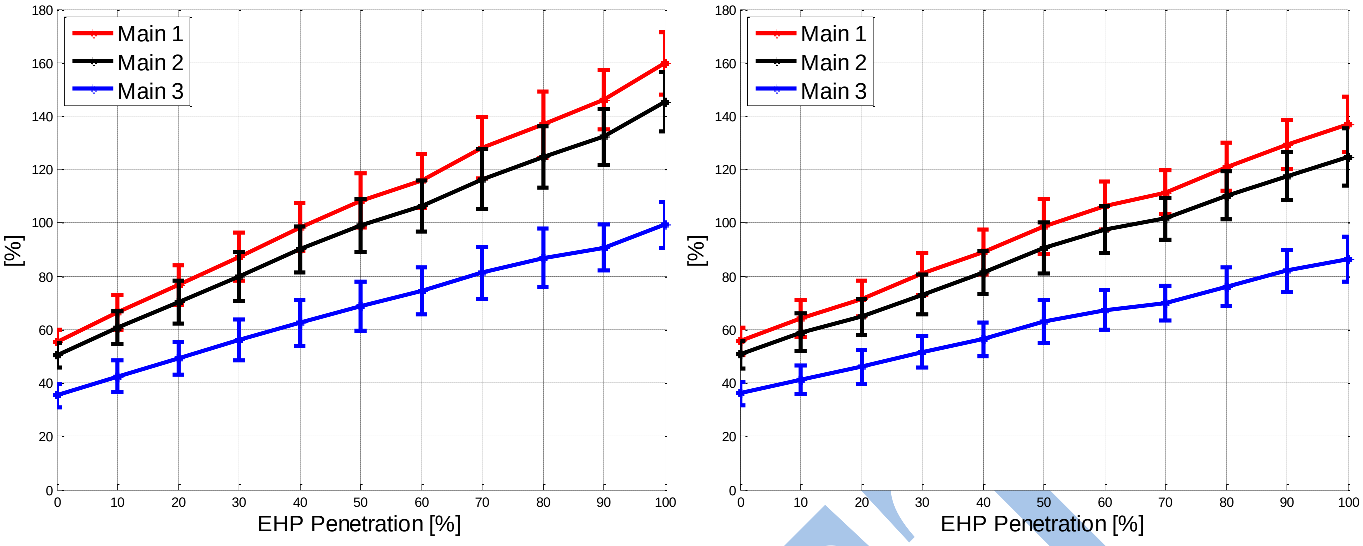


Figure 10: Example of diversified aggregated electricity profile for 1000 houses with Ground Source Heat Pump (GSHP)

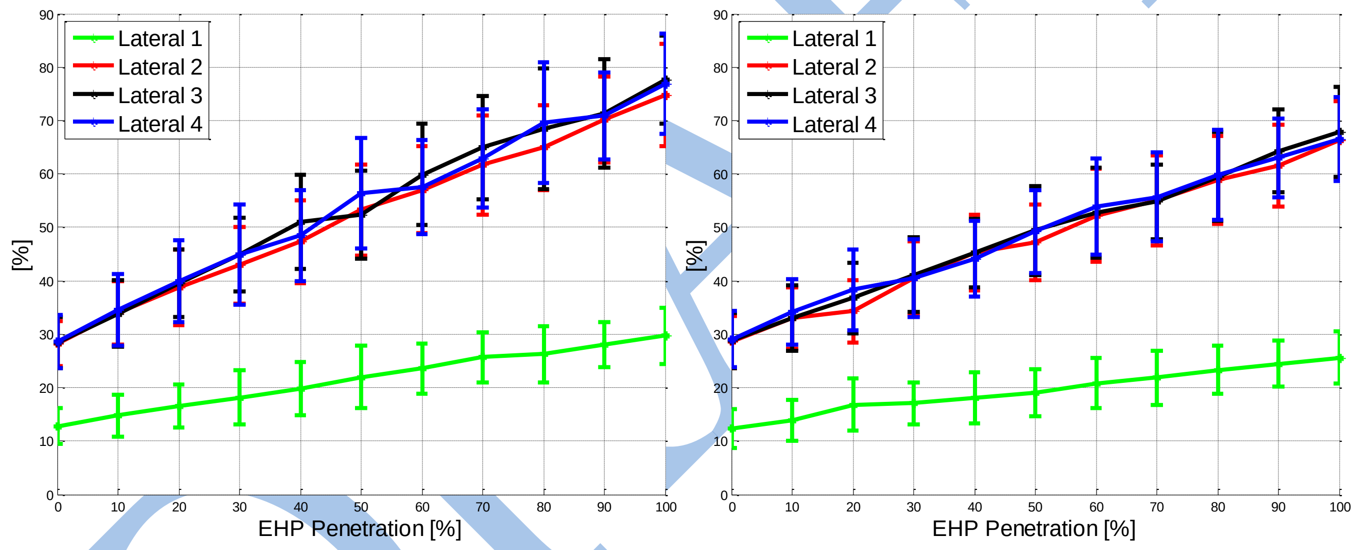
4.2. Simulations and analysis of the results

For all EHP types described above, the typical cold day has been simulated considering different penetration levels from 0% (reference case with no EHP, to set the base network conditions) to 100% (all customers equipped with EHP) with increment of 10%. For each case, random allocations of the EHP throughout the network and throughout phases as well as random load profiles have been simulated 1000 times in a Monte Carlo fashion in order to get a more robust output. For both ASHP and GSHP, the utilization indices and one standard deviation range for the main segments of the feeder and for the first segment of the different laterals are reported in Figure 11 and Figure 12 respectively, while the percentage of customers with voltage issues is shown in Figure 13 (in the study, the reference voltage is set at 240V at the transformer secondary). Additionally, in order to further assess potential impacts (not directly related to reinforcement needs) and check the results obtained from the developed tool, feeder energy losses have been calculated as well for both cases and are presented in Figure 14.



a) b)

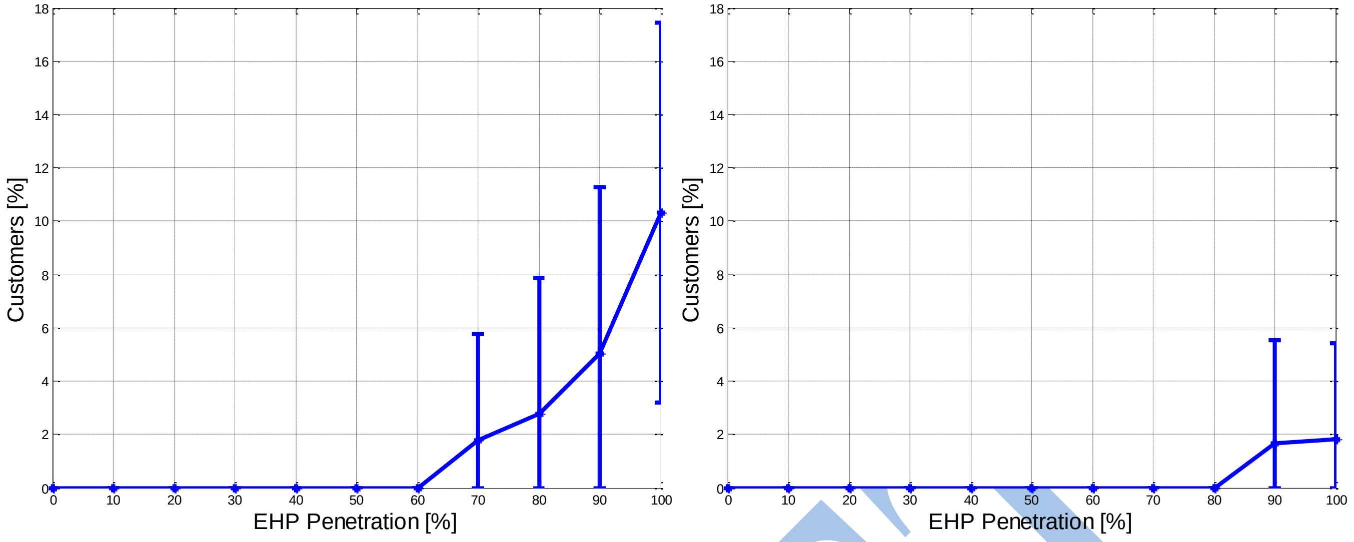
Figure 11: Average utilization index with one-standard deviation range for the main feeders for ASHP (a) and GSHP (b)



a) b)

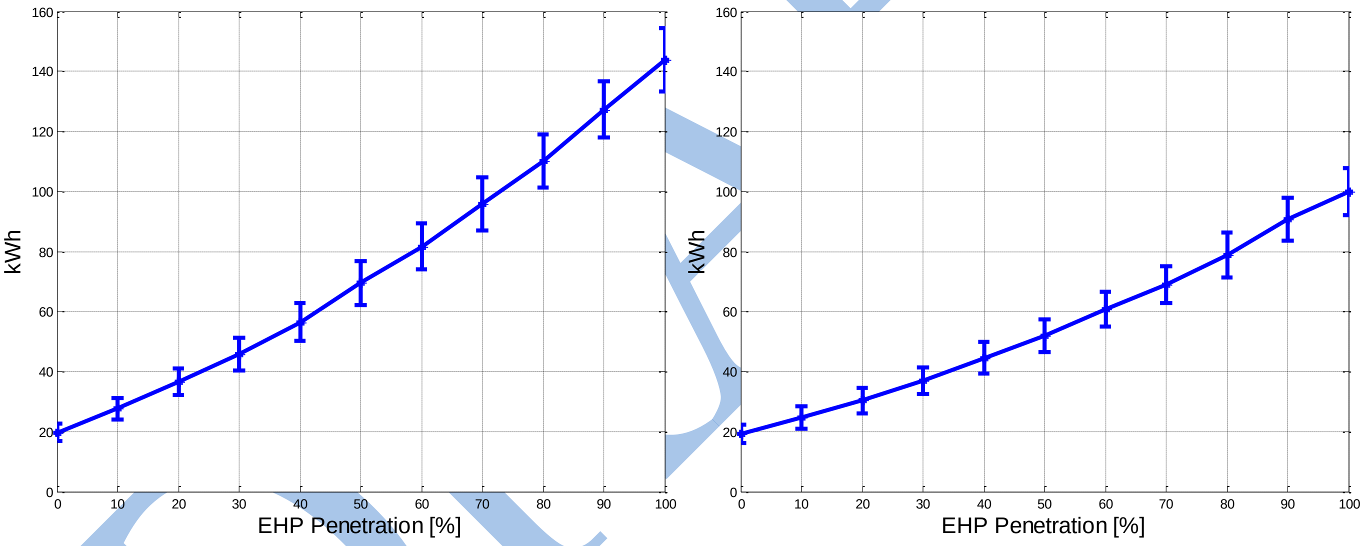
Figure 12: Average utilization indices with one standard deviation range for the lateral first segments for ASHP (a) and GSHP (b)

As a strategic indication, thermal problems are the main issue (always arising "before" voltage problems with respect to penetration levels) and the bottlenecks are arising for the upstream parts of feeders followed by downstream part, and finally by the initial parts of the laterals. This is consistent with noticing that heat consumption exhibit a much less diversity than (conventional) electricity consumption and thus problems first occur in the network components that have been designed by taking into account the higher level of diversity, namely, proceeding from transformers (highest level of diversity, with aggregation of all feeders) to downstream parts of feeders and then laterals. This is also confirmed by the standard deviation range of impact which is much less, due to the loss of diversity, in upstream circuits such as transformers and feeders than in laterals. It is worth highlighting that the initial utilization index (at 0% penetration level) of the test network is 56%, 52% and 36% for Main 1, Main 2 and Main 3, respectively.



a) **b)**

Figure 13: Percentage (with one standard deviation range) of customers with voltage issues for ASHP (a) and GSHP (b)



a) **b)**

Figure 14: Average daily energy losses (with one standard deviation range) for ASHP (a) and GSHP (b)

The voltage issues are not a significant problem unless for very high penetration levels (although in practice at that level reinforcement might already have taken place due to thermal issues so that voltages would not be a problem any longer). Indeed, the percentage of customers with voltages problems is just below 2% on average at 70% of penetration level in the ASHP case. This confirms the general idea that urban (and suburban) network design is mostly driven by capacity requirements rather than voltage requirements, so that they are relatively robust from a voltage profile point of view. Daily energy losses increase in a quadratic form with the penetration level, confirming that the simulation tool is performing as expected. In terms of percentage, the initial energy losses are 1.5% of the total energy consumption, rising to 4.3% and 3.5% for the ASHP and GSHP, respectively, at 100% penetration level.

In terms of comparison between ASHP and GSHP, arising of thermal problems for GSHP is “delayed” with respect to EHP penetration levels. Thus, the network can host some 50% of penetration level with

GSHP instead of 40% (ASHP case) before achieving any thermal limits. Also in the GSHP case, the voltage problems almost disappear for every penetration level and the daily energy losses are significantly less than in the ASHP case, particularly for higher penetration levels (as losses are quadratic with respect to the load). As a summary, it is possible to observe that the problems in the GSHP case are less pronounced or "delayed" because of the lower coincident peak demand. In fact, by comparing Figure 6 and Figure 10 for 1000 houses with 100% of penetration level, the ADMD is around 2.9 kW in the ASHP and 2.5 kW in the GSHP case.

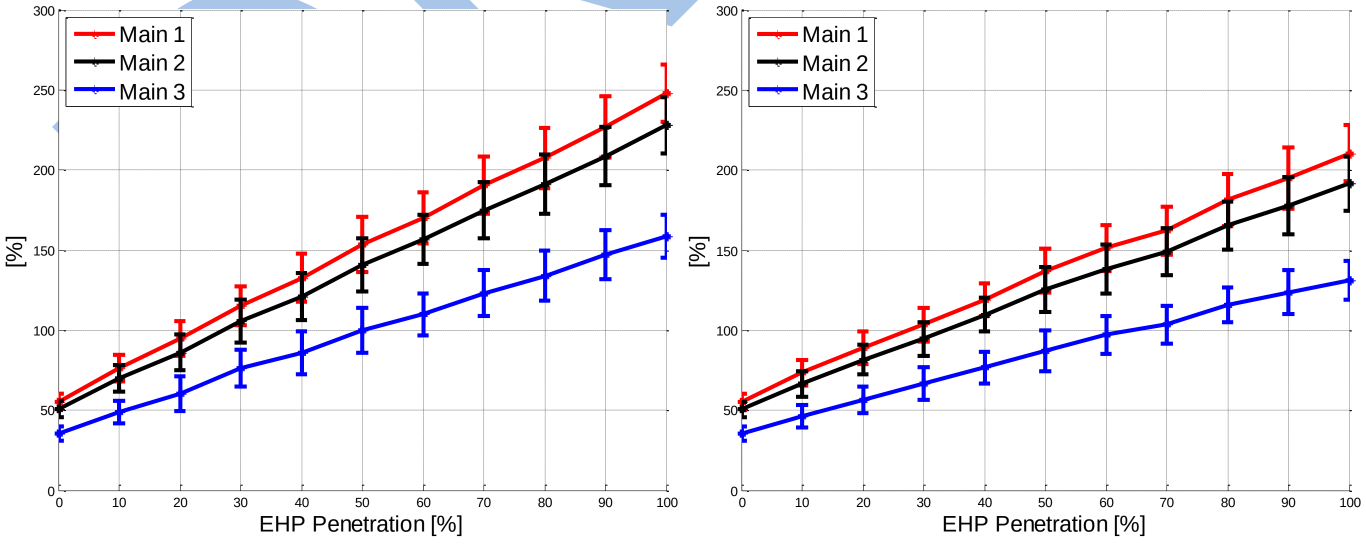
4.3. Sensitivity studies

4.3.1. Sensitivity studies to insulation level

The houses used in the above base case analysis are "modern" and therefore they are well insulated, with relatively low heat losses compared to "typical" houses. In order to assess the potential impact of adoption of heat pumps in older houses, the heat profiles for the original houses have therefore been scaled up according to the age classification and as from the average heat losses figures reported in [34]. Although in different houses the consumption profiles would slightly change, for the strategic assessment performed in this paper, this approach can yield relevant information, particularly for comparison purposes. New heat load profiles for "old" houses and "very old" houses have thus been simulated and the relevant network impact assessed as done above. The results for both ASHP and GSHP are shown in Figure 15 and Figure 16 for "old" and "very old" houses, respectively, with focus on the utilization index of main feeders which have been identified as the main bottlenecks.

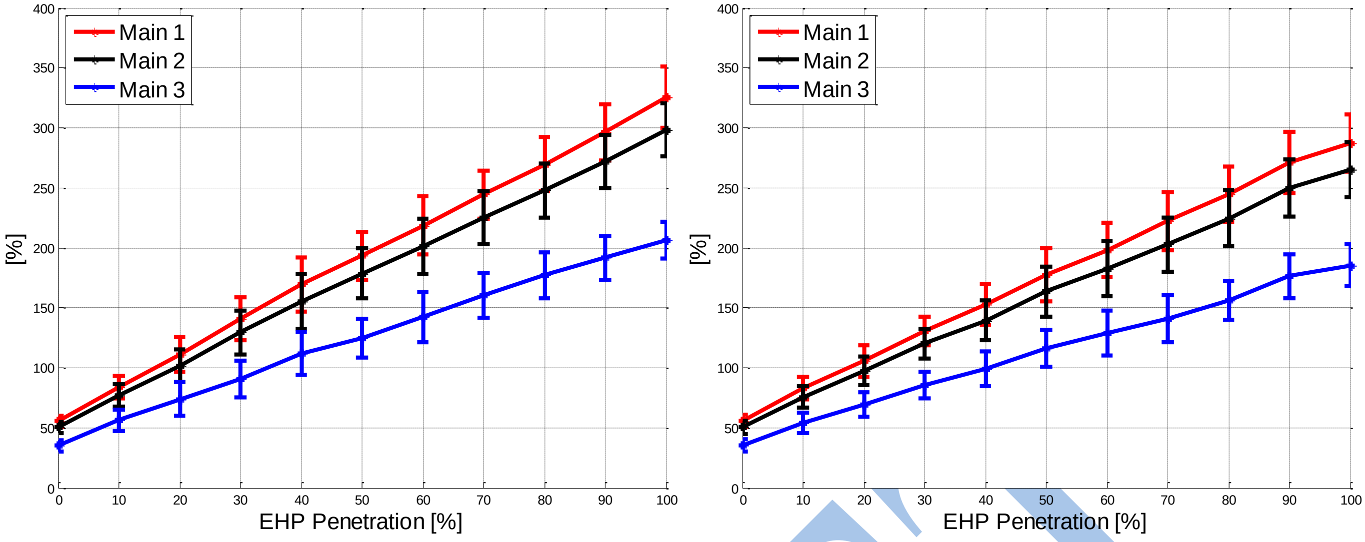
The thermal issues start much "earlier" when the house insulation level decreases for both cases under analysis (ASHP and GSHP). For example in the ASHP case, the thermal limit is reached in average for 20% of penetration level for "old houses" and at 15% of penetration level for "very old houses". In contrast the same limit is achieved at 40% of penetration level in the case of "modern houses". It is therefore very likely that significant network problems might have to be faced relatively soon in the case EHPs were to be used in poorly insulated houses (as the majority in the UK).

As a general comment, policy makers should encourage the installation of GSHP in new houses to avoid severe network problems from early penetration levels. However, in most cases the only suitable retrofit technology is the ASHP, which should be encouraged to be installed in well insulated homes only.



a) **b)**

Figure 15: Average utilization indices with one-standard deviation range for "old" houses for ASHP (a) and GSHP (b)

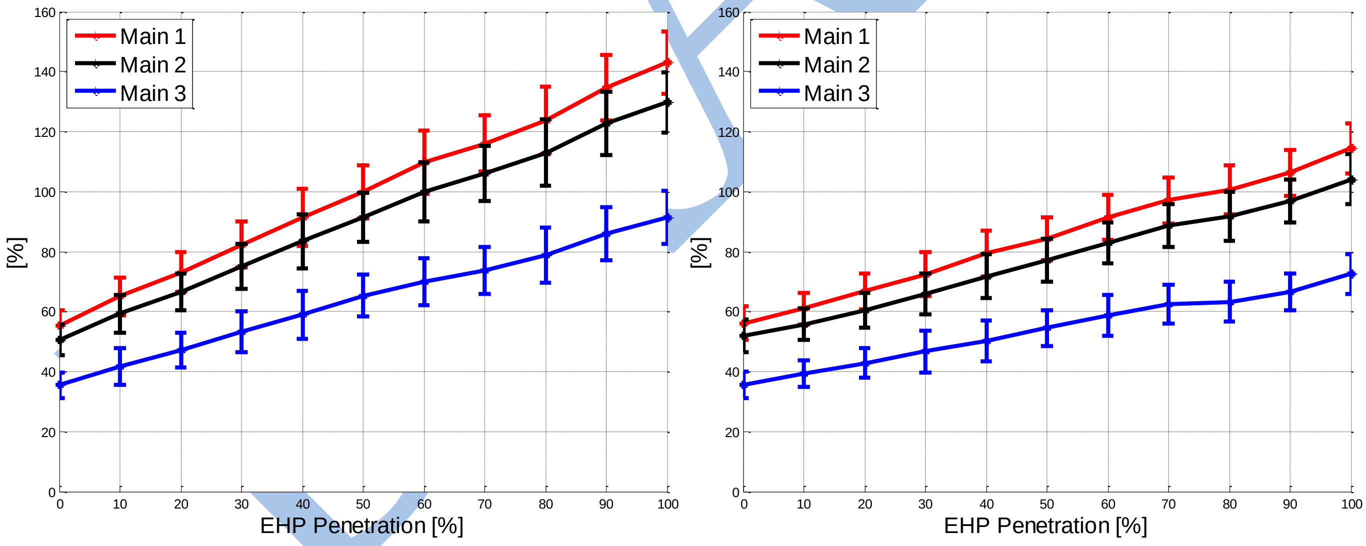


a) b)

Figure 16: Average utilization indices with one-standard deviation range for "very old" houses for ASHP (a) and GSHP (b)

4.3.2. *Sensitivity studies to AH type*

Since the majority of houses in the UK are as of today equipped with gas boiler units, a sensitivity study has been performed to check how the impact would change in the case that the existing gas boiler were to be used for peak shaving ("dual" solution). The main circuit utilization indices are shown for ASHP and GSHP in Figure 17.



a) b)

Figure 17: Average utilization indices with one-standard deviation range for the case of gas boilers used as an AH in the base case for ASHP (a) and GSHP (b)

The reduction in the power demand because of the utilization of gas boiler as auxiliary heater is less significant in the ASHP. This is because in the ASHP case the contribution of auxiliary heater during the peak demand period is lower (comparison between Figure 6 and Figure 10), since during the peak demand period, the ambient temperature is relatively high (about 8 ºC) compared to the ground temperature (approximately constant throughout the day) for the GSHP, and therefore the ASHP efficiency is better, requiring less auxiliary heat. This result, although perhaps unexpected, confirms the need to perform detailed time series network studies with suitable performance models to really get insights into potential network impact, which is explored further below.

4.3.3. Sensitivity studies to outdoor temperature: stress test

As mentioned above, the profiles used in the base case analysis correspond to a "cold" day but not extreme day situation. This is because for strategic indication of the need for network reinforcement it is adequate to refer to "normal" peak load situations rather than worst-case scenarios, in which cases the network can for example still be operated by resorting to flexibility available in overloading the relevant circuits for a few hours (being the thermal issues the most stringent ones, as seen above). Nevertheless, it is interesting to stress-test the network performance under such as worst-case situation where the selected EHP-AH systems are simulated with the data available for the "coldest" day, with a minimum temperature of -4.5°C, a maximum of +4.0°C, and an average of -1.0°C. Temperature profiles for the cold and coldest day can be observed in Figure 18.

Using the coldest day, new "extreme" profiles were created and impact studies run. The main circuit utilization is reported in Figure 19 for the base case EHP/AH sizing scheme. It is important to remark that the ground temperature at 1-meter depth was taken for the same coldest day modelled; this temperature corresponds to 6.5 ºC [33].

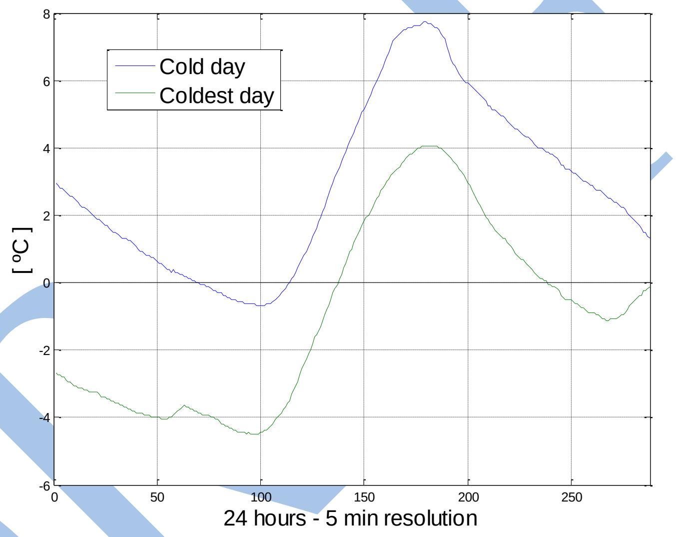
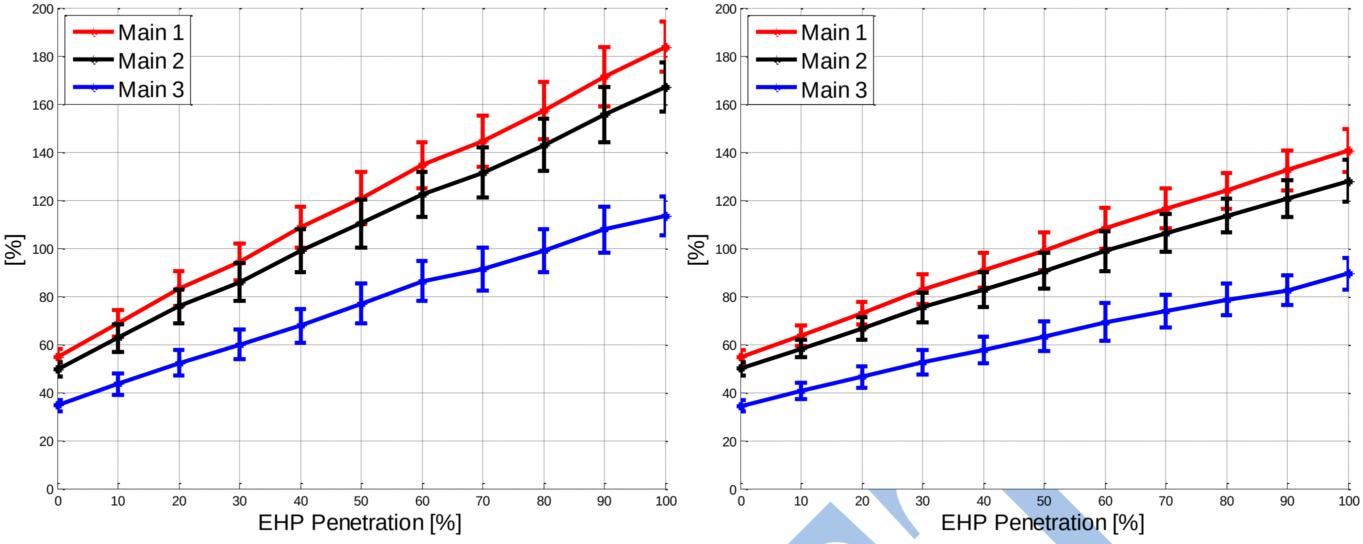


Figure 18: Air temperature variation for the cold and coldest day

In the coldest day scenario, thermal problems basically start earlier than the base case (cold day) in the ASHP case. That is, thermal limits are reached just after 30% in the coldest day and at 40% in the cold day. In contrast, for the GSHP thermal issues remain similar to the base case (cold day) during the coldest day (for both days the problems appear at 50% of penetration level). This happens basically because the temperature variation between the cold and coldest is much lower in the ground than in the ambient, thus the performance of the GSHP only slightly decreases while ASHP are affected significantly.

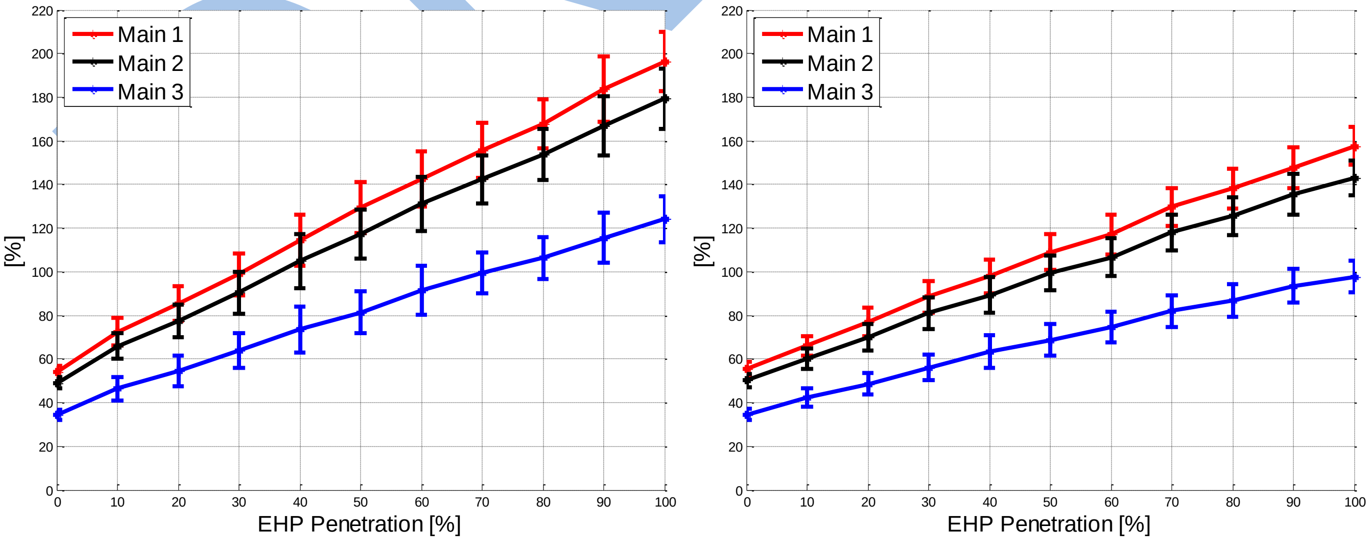


a) b)

Figure 19: Average utilization indices with one-standard deviation range for the "coldest" day case for ASHP (a) and GSHP (b)

4.3.4. *Sensitivity studies to EHP sizing*

While as reported in [26] typical EHP sizing is in the order of 80% of the heat load, also different approaches might be followed (usually different sources report different rules of thumbs to deal with this issue that eventually refers to economic considerations). Sensitivity studies have therefore been performed to assess the impact of relative EHP/AH sizing. The results for ASHP and GSHP sized to cover 60% (see for instance suggestions from [27]) of the peak heat demand are analysed. This decrease in the EHP capacity with respect to the peak heat requirements implies an increase in the AH utilization and therefore might produce an increase in peak loads and so thermal issues. This effect can be appreciated better in the coldest day, when the presence of AH is higher. In fact, Figure 20 shows that the 100% limit is reached at an earlier penetration level in both EHP cases (by about 5% and 10% for the ASHP and GSHP, respectively).



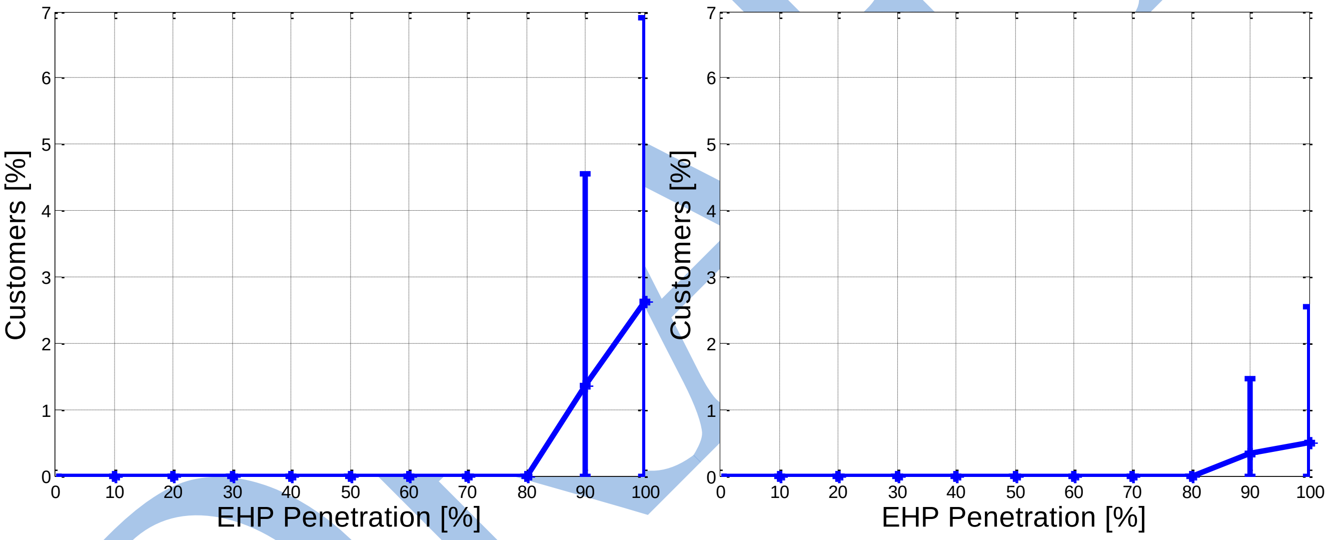
a) b)

Figure 20: Average utilization indices with one-standard deviation range during the coldest day for EHP sized to cover 60% of the peak load for ASHP (a) and GSHP (b)

Therefore, to minimise the impacts on the network, a larger EHP size relative to the peak load should be suggested. This is coherent with the recommendations given in [19], where the proposed capacity should be enough to supply the 100% of the heat requirement at the design temperature which is equivalent to the 73% of the heat requirement during the coldest day [19]. In this outlook, our analysis of EHP capacity design between 60% and 80% of the heat peak for the coldest day gives the right boundaries for the expected impacts of EHP in LV networks.

4.3.5. *Sensitivity studies to voltage reference*

In this work, the voltage reference at the secondary of the transformer is 240V phase to neutral (the maximum possible is 253V taking into account a nominal voltage equal to 230V); if this reference voltage is increased, voltage problems are reduced significantly as can be observed in Figure 21, where the voltage problems are calculated for the ASHP case by assuming 243V (Figure 21a) and 245V (Figure 21b) in the transformer's secondary. For these two scenarios, the voltage problems totally disappear for the GSHP case. This sensitivity confirms that the main bottleneck is the thermal capability in the main segments of the feeder. Nonetheless, it is important to highlight that the reference voltage in reality cannot reach a very high value because the voltage rise could appear sooner in presence of distributed generation, so suitable headroom for voltage rise and voltage drop need to be kept at substation level.



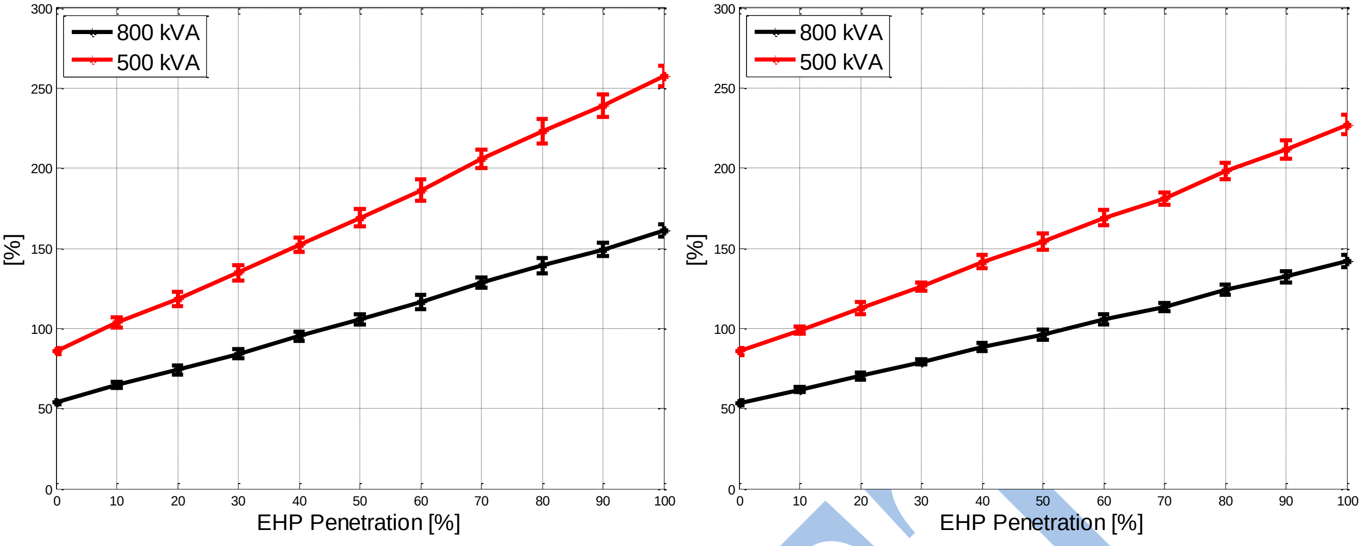
a)

b)

Figure 21: Percentage (with one standard deviation range) of customers with voltage issues for ASHP with 243V (a) and 245V (b) at the transformer's secondary

4.3.6. *Sensitivity studies to transformer size*

The focus of the previous results has been to provide a deep understanding on the impacts of EHPs for different penetration levels in one particular feeder. In addition to the previous studies, and in order to understand the impacts at transformer level, the four feeders of the test network were all simulated simultaneously. Typically, for medium density networks transformer sizes are between 500kVA and 800kVA [31]. These two ratings were therefore used to calculate the transformer's hourly utilization index for each penetration level under analysis. The results are indicated in Figure 22.



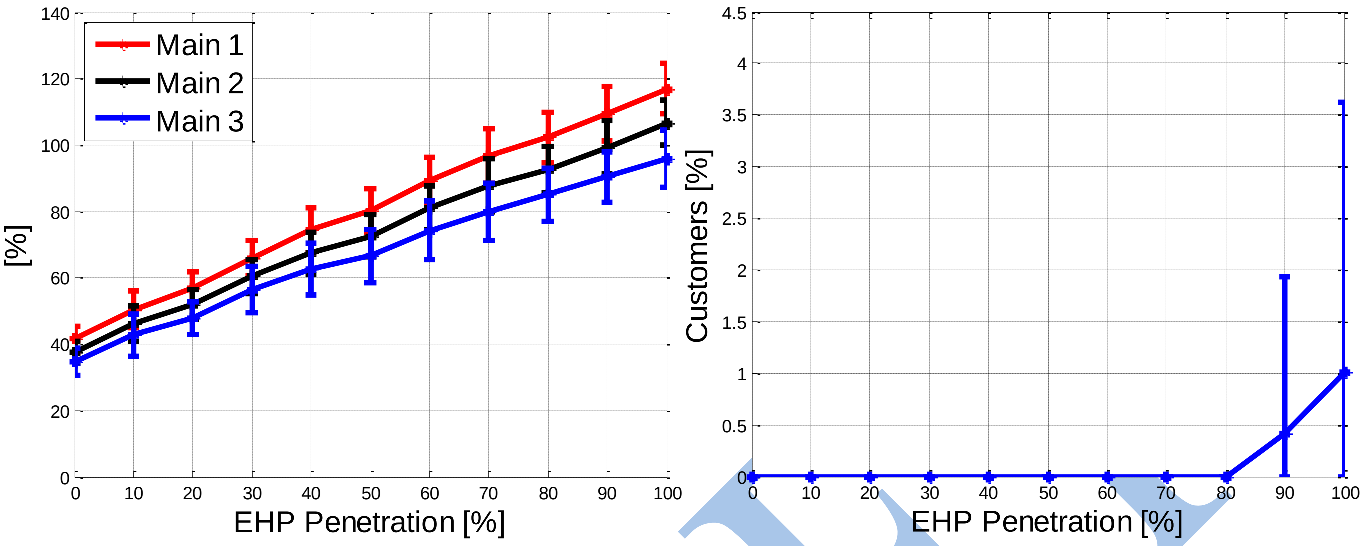
a) **b)**

Figure 22: Average transformer utilization indices with one-standard deviation range for ASHP (a) and GSHP (b)

Figure 22 confirms the relevance of thermal problems when electric heat pumps are incorporated in low voltage distribution networks. In fact, the first problems already appear at 10% of penetration level for the ASHP and GSHP case for the 500kVA rating (considering an initial utilization index, at 0% of EHP penetration, of about 80%). Hence, in this case the transformer thermal capacity would be the main bottleneck for EHP rollout, with problems starting even earlier than in the feeders (and confirming what discussed above with respect to loss of diversity as the main driver for impact). When considering the 800kVA rating, the initial utilization index in the study is around 50% and thermal limits are reached at 40% and 50% of penetration level for the ASHP and GSHP, respectively. Thus, in this case thermal limits for the feeder's main segments and transformer are approximately reached at the same EHP penetration level for the test network under analysis. These results suggest that if the transformer and main feeders' capacity are increased, the network hosting capacity (i.e., capability to host EHPs without suffering thermal or voltage problems in the network) could improve considerably, with therefore relatively small network impact in terms of reinforcement. For example, for the ASHP base case, by increasing the transformer capacity and the conductor capacity in the Main 1 and Main 2, the hosting capacity will move from 40% to 80% (the voltage profile also improves because the new bigger upstream conductor would have less impedance).

4.3.7. Sensitivity studies to conductor size

As it has been observed throughout the paper, the main bottleneck associated with EHP rollout in LV networks appears to be the thermal capacity of the asset. In this respect, the network under analysis is consistent with the planning criteria followed by many DNOs, in which cables are designed based on the ADMD [35]. In fact, as it was mentioned in Section 4.2, the utilization index in the Main 1 (head of the feeder) is on average 56% when no EHP is installed. Nevertheless, it is possible that some DNOs design their network following a different criterion. For instance, this criterion could be based on an economic assessment that takes into account both energy losses and investment costs at the planning stage [36]. By following this procedure, it is therefore possible to identify a new realistic size of cables and at the same time carry out a sensitivity analysis of the impact of EHP with respect to the initial network headroom. In particular, since the thermal problems are the ones observed first in the main cables (Mains 1, 2 and 3 in Section 4.1.1), in this sensitivity study these are replaced with the "optimally economical" ones following the methodology presented in [37]. Thus, the new sizes for Main 1 and Main 2 are SAC 300 mm2, while for the case of Main 3 the optimal economical solution coincides with the cable already installed, SAC 185 mm2. The results for this analysis are presented in Figure 23.



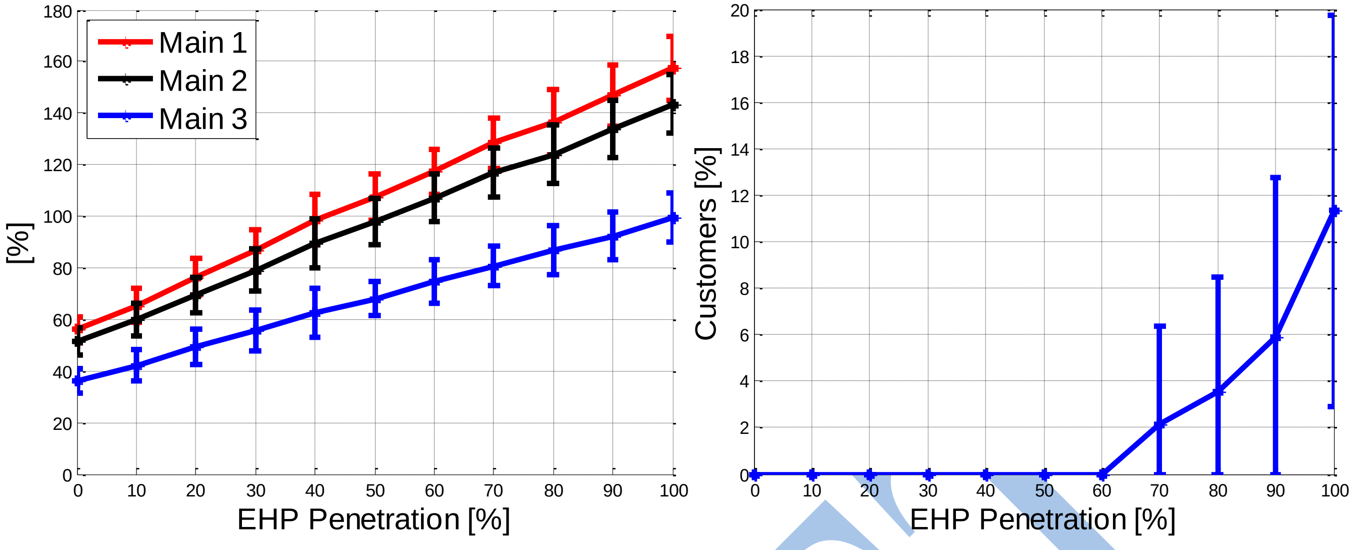
a) **b)**

Figure 23: Utilization indices (a) and Percentage of customers with voltage problems (b) for ASHP for the new cable case

It can be appreciated how the penetration level where the first problems start now increases from 40% in the base case to 70% in this new case. Hence, those DNOs that have taken into account the cost of energy losses during the planning stage (which is equivalent to have a utilization level for the main feeder of around 42% as opposed to 56% as in the base case) would face problems much later than those DNOs that have designed their network based on being able to carry the ADMD current (typical approach).

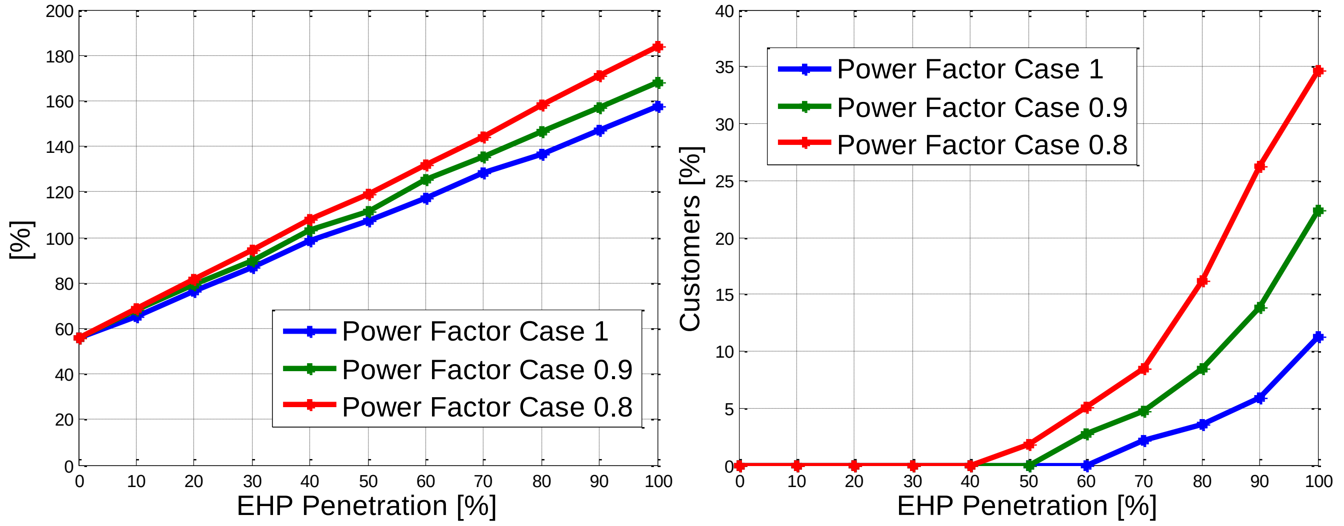
4.3.8. Sensitivity studies to reactive power consumption

A unity power factor was implemented in all the previous simulations. In this section, in order to have a better understanding of the EHP impacts on LV networks in terms of power factor, a sensitivity analysis about the reactive power consumption of both loads and EHP devices has been carried out. In the case of loads, a random power factor between 0.95 lagging and 1.0 is allocated to each house. The value of 0.95 is generally the lowest accepted by the DNO in England before starting to charge medium size costumers for excessive reactive power consumption [38]. Furthermore, to assess the potential changes in the power factor brought by EHP devices, three scenarios of power factor are considered, namely, 1.0, 0.9, and 0.8 lagging. Again, although very little or no data at all is currently available in terms of reactive power consumption of EHPs, it can be expected that the power factor will not drop below 0.9, beyond which it is likely that internal compensation would be installed by the manufacturers. Summarising, three new multi-parametric sensitivity studies have been performed for reactive power analysis, all of them with a power factor for each load randomly selected between 0.95 and 1.0 in combination with a different EHP power factor in each case (Power Factor Case 1.0, 0.9 and 0.8).



a) **b)**

Figure 24: Utilization indices (a) and percentage of customers with voltage problems (b) for Power Factor Case 1 (random power factor between 0.95 and 1 allocated to loads) for ASHP



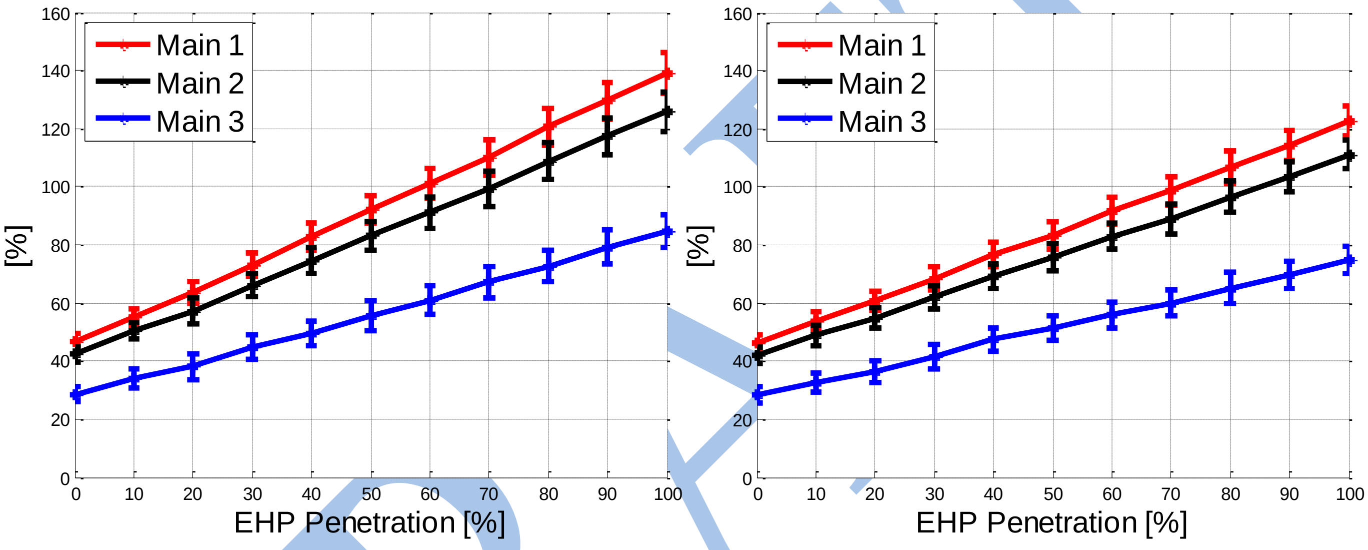
a) **b)**

Figure 25: Average Utilization indices (a) and average Percentage of customers with voltage problems (b) for ASHP for Power Factor Case 1, Case 0.9 and Case 0.8

In Figure 24, the modification of the power factor in the residential loads changes slightly the results presented in the base case (Section 4.2). Indeed, the thermal limit is also reached at 40% of penetration level and the voltage problems also start at 70% of penetration level, the only difference being that the number of customers with voltage problems increases by around 2% in each penetration level (because of the additional reactive power consumption). On the other hand, in the cases where the EHP power factor is also reduced, the results change more significantly as can be observed in Figure 25. There, the average voltage problems for the three power factor cases and the average utilization index for Main 1 (the first cable that faces problems) are presented. For instance, in Power Factor Case 0.8, the thermal limit is reached at about 30% and the voltage problems start at 50% of penetration level. Hence, through such analyses DNOs can have a clearer picture of the potential impact of EHPs once more information is made available on reactive power consumption. However, it is worth remarking that while the potential impact of reactive power variation is mostly on voltage, in the three cases the bottleneck is still thermal.

4.3.9. Sensitivity studies to a perfectly balanced system

Low voltage distribution networks may be highly unbalanced, mainly because customers' connections are not always evenly distributed among the phases and also because the size and behaviour of customers along the day is different. For that reason, the assumption of solving a single phase equivalent circuit (i.e., assuming a totally balanced load) is not accurate in this type of networks. To highlight this aspect, a new comparative analysis has been carried out in this section. This analysis follows the same methodology presented in the paper with the only difference that a perfectly balanced system is now simulated (while all the above simulations are based on a full 3-phase power flow model that automatically takes into account all relevant unbalances arising from single-phase connections and diverse consumption). The new results from balanced studies are presented in Figure 26 for the ASHP and GSHP.



a) **b)**

Figure 26: Average Utilization indices for ASHP (a) and GSHP (b) for the perfectly balanced case

In the base Case (Section 4.2) the thermal limit is reached at 40% and 50% of penetration level for the ASHP and GSHP, respectively. From Figure 26, it is possible to observe that the thermal problems are significantly underestimated in the balanced case in comparison with the unbalanced case. In fact, the limits are now reached at 60% and 70% of penetration level for the ASHP and GSHP, respectively. Moreover, in the balanced case there are no voltage problems at all for any penetration level. These results are mainly due to the fact that single phase load imbalances in turn create current and voltage imbalances in individual phases as opposed to the whole lines, so that limits in individual phases become the bottleneck and arise earlier with respect to the penetration level. Hence, the balanced case (significantly) underestimates the voltage and thermal problems arising in LV distributions networks and therefore it is fundamental to use an unbalanced power flow engine to assess relevant impacts on these types of networks.

5. Concluding remarks

This paper has introduced a novel probabilistic methodology and relevant tool to assess the impact of EHPs on LV distribution networks. Real electricity and heat profiles have been taken as a starting point of the studies. Both Air Source Heat Pump (ASHP) and Ground Source Heat Pump (GSHP) technologies have been modelled as black boxes with performance and heat capacity characteristics changing with operating conditions according to manufacturers' curves, addressing in particular the need for and impact of different types of Auxiliary Heating (AH) systems (such as based on electricity or fuel). A specific LV network analysis tool has been built that integrates the three-phase unbalanced load flow solution engine OpenDSS with the developed EHP models and is capable of properly addressing single-phase connections and time-series studies. The developed model is capable to assess generic types of distribution networks with different levels of EHP penetration and types of EHP operating under generic conditions. Different metrics have been used to quantify the impact of the considered technologies, with emphasis on thermal and voltage limits, according to current engineering standards. Case studies based on Monte Carlo analysis have been carried out for representative suburban areas in the UK and for different scenarios in order to exemplify the developed methodology and illustrate the main drivers for impact and trends in the different cases. In particular, intertemporal assessment with a fine resolution (five minutes) as opposed to single snapshots, which is critical to capture diversity effects and voltage and thermal "integral" issues (for instance voltage impacts need to be assessed statistically over ten minutes), has been carried out. The results from the studies, whose primary objective was to perform a strategic impact analysis with indications of the main bottlenecks and trends, indicate that thermal problems are likely to arise at much earlier penetration levels than for voltage problems, and moving from upstream components (transformers) to downstream ones (feeders and starting branches of laterals). This is essentially due to the much less diversity present in heating loads which, when electrified, brings issues in those part of networks designed for higher diversity. While the results cannot be generalised to all situations, they give key indications about the adequacy of the network in the long term, pointing out when and where problems could arise (in probabilistic terms) and the drivers for impact, so that network replacement or other solutions can be put in place.

The strategic information provided has been reinforced by a number of sensitivity studies, quantifying, amongst the others, how the impact could be much more substantial in houses with lower insulation than modern ones (taken as base case) and how the use of gas boilers as auxiliary means (as opposed to electric auxiliary heater) could postpone the need for network reinforcement. The effects of different power factors have also been analysed, showing that, although an increase in reactive power consumption by EHPs increases the voltage problems, the bottleneck remains related to thermal issues. Considering the relevance of the thermal constraints in the EHP impact analysis, a sensitivity analysis to the available thermal headroom was then further performed by using larger cables in the Mains segments; this new cable selection was based on an "optimal economical" design strategy (that also accounts for the long term cost of losses besides the investment cost) as opposed to a classic "peak design" (investment cost only) strategy used as the base case. The results show that DNOs that have taken into account the cost of energy losses at the network planning stage would face problems much later than those DNOs that have followed a classic peak design approach. Hence, an optimally designed network somehow also turns out to be more "future-proof" in terms of potential EHP impact. As another key contribution of this work, through sensitivity studies it has been shown how a perfectly balanced load assumption tends to significantly underestimate the impacts of EHP in LV networks. Therefore, it is fundamental to use a three-phase unbalanced power flow engine to assess relevant impacts on LV networks, as well as to have suitable load profiling approaches that can capture geographical and temporal consumption diversity effects at individual single phase connection points. It is finally interesting to remark that for the base case and for all sensitivity analyses the problems appear for earlier penetration levels in the ASHP case relative to the GSHP case. For example, in the base case the thermal problems start at 50% penetration level for the GSHP and at 40% penetration level for the ASHP. Also, in the GSHP case the voltage problems almost disappear for every penetration level and the daily energy losses are significantly less than in the ASHP case, particularly for higher penetration levels (as losses are quadratic with respect to the load). These results are essentially due to the better performance of GSHPs that exploit higher temperature sources, which is particularly noticeable in the "coldest day" simulations that have been performed. Hence, GSHPs do not only generally prove to be more efficient in terms of energy performance, but also feature less network impact.

While the developed model is already suitable to perform studies for different situations, networks, and scenarios and can be used as decision making support by network operators, energy planners, policy makers, and so on, further research is already going on to develop suitable strategies for network reinforcement also taking into account wider reliability aspects relative to the general adequacy considerations illustrated here, quantify the potential benefits of thermal storage, and identify suitable and realistic strategies to decrease the network impact in a smart grid context.

6. Acknowledgment

The authors would like to thank Electricity North West Limited (ENWL) for partly supporting this work.

References

[1] Department of Energy and Climate Change, "The Future of Heating: Meeting the challenge," pp. 1-123, 2013.
[2] N. J. Hewitt, "Heat pumps and energy storage – The challenges of implementation," *Applied Energy*, vol. 89, pp. 37-44, 2012.
[3] M. Eriksson and L. Vamling, "Future use of heat pumps in Swedish district heating systems: Short- and long-term impact of policy instruments and planned investments," *Applied Energy*, vol. 84, pp. 1240-1257, 2007.
[4] A. Bagdanavicius and N. Jenkins, "Power requirements of ground source heat pumps in a residential area," *Applied Energy*, vol. 102, pp. 591-600, 2013.
[5] G. Strbac, C. K. Gan, M. Aunedi, V. Stanojevic, P. Djapic, J. Dejvises, P. Mancarella, A. Hawkes, D. Pudjianto, D. Openshaw, S. Burns, P. West, D. Brogden, A. Creighton, and A. Claxton, "Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks," London, United Kingdom, 2010, pp. 1-49.
[6] O. Van Pruissen and R. Kamphuis, "High concentration of heat pumps in suburban areas and reduction of their impact on the electricity network," presented at the 2011 IEEE PES PowerTech, Trondheim, Norway, 2011.
[7] S. A. Tassou, C. J. Marquand, and D. R. Wilson, "Energy and Economic Comparisons of Domestic Heat Pumps and Conventional Heating Systems in the British Climate," *Applied Energy*, vol. 24, pp. 127-138, 1986.
[8] P. Mancarella, C. K. Gan, and G. Strbac, "Evaluation of the impact of electric heat pumps and distributed CHP on LV networks," presented at the IEEE PES Power Tech 2011, Trondheim, Norway, 2011.
[9] A. Hawkes and M. Leach, "Impacts of temporal precision in optimisation modelling of micro-Combined Heat and Power," *Energy*, vol. 30, pp. 1759-1779, 2005.
[10] E. Veldman, M. Gibescu, H. Slootweg, and W. L. Kling, "Impact of electrification of residential heating on loading of distribution networks," presented at the 2011 IEEE PES Power Tech, Trondheim, Norway, 2011.
[11] M. Akmal, B. Fox, D. J. Morrow, and T. Littler, "Impact of High Penetration of Heat Pumps on Low Voltage Distribution Networks," presented at the IEEE PES PowerTech 2011, Trondheim, Norway, 2011.
[12] H. Singh, a. Muetze, and P. C. Eames, "Factors influencing the uptake of heat pump technology by the UK domestic sector," *Renewable Energy*, vol. 35, pp. 873-878, 2010.
[13] Carbon Trust. Micro-CHP Accelerator - Final Report [Online]. Available: http://www.carbontrust.com/resources/reports/technology/micro-chp-accelerator
[14] P. Mancarella and G. Chicco, *Distributed Multi-Generation Systems. Energy Models and Analyses*. New York: Nova Science Publishers, 2009.
[15] G. Chicco and P. Mancarella, "Distributed multi-generation: A comprehensive view," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 535-551, 2009.
[16] P. Mancarella, "Cogeneration systems with electric heat pumps: Energy-shifting properties and equivalent plant modelling," *Energy Conversion and Management*, vol. 50, pp. 1991-1999, 2009.
[17] EPRI, "Open Distribution System Simulator [Online]," ed: Available: http://sourceforge.net/apps/mediawiki/electricdss.
[18] British Standards Institution, "BS EN 50160: Voltage characteristics of electricity supplied by public distribution systems," ed, 2000.
[19] P. Dunbabin and C. Wickins, "Detailed analysis from the first phase of the Energy Saving Trust's heat pump field trial," Department of Energy and Climate Change, United Kingdom 2012.
[20] L. Munuera and A. D. Hawkes, "System Impacts of A Large-Scale Rollout of Heat Pumps In The UK: Diversity and Peak Loads," presented at the The 3rd International Conference on Microgeneration, Naples, Italy, 2013.
[21] P. Dunbabin, H. C. Kiwa, and R. Green, "Detailed analysis from the second phase of the Energy Saving Trust 's heat pump field trial," Department of Energy and Climate Change, United Kingdom 2013.
[22] The Microgeneration Certification Scheme, "Heat Emitter Guide for Domestic Heat Pumps," United Kingdom, 2011.

[23] Elexon. UK Load Profiles [Online]. Available: http://www.elexon.co.uk/wp-content/uploads/2013/11/load_profiles_v2.0_cgi.pdf

[24] R. Sansom and G. Strbac, "The impact of future heat demand pathways on the economics of low carbon heating systems," presented at the 9th Academic Conference 2012, Oxford, United Kingdom, 2012.

[25] Calorex. Domestic Heat Pumps – Low carbon solutions for heating and hot water [Online]. Available: http://www.calorex.com/heat-pumps/documents/DomHeatv.4.pdf

[26] Worcester Bosch Group. The Greensource series of air to water heat pumps form Worcester – Technical and specification information [Online]. Available: http://www.bhl.co.uk/images/tagged/c/technical-12176-technical-Worcester%20Greensource%20Air%20to%20Water%20Source%20Heat%20Pumps%20Technical%20Informationl.pdf

[27] D. P. Jenkins, R. Tucker, and R. Rawlings, "Modelling the carbon-saving performance of domestic ground-source heat pumps," *Energy and Buildings*, vol. 41, pp. 587-595, 2009.

[28] EA Tecnology, "The Effects of Cycling on Heat Pump Performance," United Kingdom 2012.

[29] D. Wang, S. Parkinson, W. Miao, H. Jia, C. Crawford, and N. Djilali, "Online voltage security assessment considering comfort-constrained demand response control of distributed heat pump systems," *Applied Energy*, vol. 96, pp. 104-114, 2012.

[30] UK Parliament, "The Electricity Safety, Quality and Continuity Regulations 2002 " in *2665*, ed, 2003, p. 27.

[31] Mott McDonald for the Department of Trade and Industry. System Integration of Additional Micro- generation [Online]. Available: http://webarchive.nationalarchives.gov.uk/+/http://www.dti.gov.uk/renewables/publications/pdfs/dgcg00028rep.pdf

[32] Domestic Building Services Panel of the Institution of Building Services Engineers (CIBSE), "Domestic Heating - Design Guide," United Kingdom, 2011.

[33] UK Meteorological Office. Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current) [Online]. Available: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas

[34] Smart Grids Forum - Work Stream 3, "Assessing the Impact of Low Carbon Technologies on Great Britain’s Power Distribution Networks," Ofgem 2012.

[35] Electricity North West Limited, "Code of Practice 226: Low Voltage Network Design," 2011.

[36] P. Mancarella, C. K. Gan, and G. Strbac, "Optimal design of low-voltage distribution networks for CO2 emission minimisation. Part II: Discrete optimisation of radial networks and comparison with alternative design strategies," *IET Generation, Transmission & Distribution*, vol. 5, pp. 47-56, 2011.

[37] A. Navarro-Espinosa, L. F. Ochoa, and P. Mancarella, "Learning from Residential Load Data: Impacts on LV Network Planning and Operation," presented at the Sixth IEEE PES Transmission and Distribution, Montevideo, 2012.

[38] Western Power Distribution. Western Power Distribution - Use of System Charging Statement FINAL NOTICE Effective from 1st April 2013 [Online]. Available: http://www.westernpower.co.uk/docs/system-charges/LC14-v6-5-SWEB-Final-13-14.aspx