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The effectiveness of decentralised electro-thermal load shifting strategies in low voltage network violation management

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A R T I C L E I N F O

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A B S T R A C T

The IPCC 1.5 °C report highlights the need to reduce UK carbon emissions by 80% 2050, and so it is essential to examine the routes that could be taken to achieve this goal. Replacement of traditional boiler systems with heat pumps (using electricity from clean sources) in residences may aid decarbonization of the energy sector. However, typical LV distribution networks are not designed to carry the increased loads will result from this change, and so it is necessary to explore strategies to mitigate any adverse effects of such loads.

In this study, we examine the effect of air source heat pumps on voltage and thermal violations experienced by a typical UK LV network. The effect of decentralized heating system operational strategies (pre-heating, thermostat setback, and space heat buffering) on results is then investigated. Finally, the sensitivity of results to external temperature, network topology, and building fabric standard are examined.

It is found that no mixture of strategies is sufficient to significantly improve localized voltage conditions at remote/branch points on LV feeders, as a result of the much greater sensitivity of branch node voltages to power demand of localized loads. Even where EN 50160 voltage standards are applied, elimination of violations is rarely possible.

1. Introduction

As environmental concerns become more urgent, it is necessary to consider ways to reduce the populations carbon footprint associated as a whole [1]. The widespread electrification of heating across the UK will likely contribute to this goal [2], and as such the UK government have committed to a heat pump (HP) deployment rate of 600,00 per year by 2028 [3]. Whilst this commitment would theoretically benefit carbon reduction, governments [4], the national grid [5], and various DNOs [6–8], have raised concerns regarding the implications of this strategy on infrastructure operation. Without a good understanding of the effect of heat pumps on network operation, or an understanding of how control may alleviate operational issues, it is not possible to confidently fulfil the aforementioned commitment.

A specific area of concern is congestion and voltage violations on low voltage (230 V single phase) distribution networks. The LV networks which serve residential areas are typically designed for an after diversity maximum demand (ADMD) of 2–3 kW, but heat pumps may cause many networks to exceed this. If so, then the resulting power flow will accelerate aging, or even immediately damage, existing cables (due to overheating caused by current flows in excess of rated cable capacity) or substations that are undersized for the load. Furthermore, the resistive nature of distribution cabling results in a voltage drop proportional to the current transmitted, and some studies suggest that HPs could cause localized drops that violate both EQSCR and EN 50160 power quality regulations [9,10].

Abbreviations: **ASHP**, Air Source Heat Pump; **ADMD**, After Diversity Maximum Demand; **CCC**, Climate Change Committee; **CLNR**, Customer Led Network Revolution; **COM**, Component Object Model Interface; **COP**, Coefficient of Performance; **CREST**, Centre for Renewable Energy Systems Technology; **DECC**, Department of Energy and Climate Change; **DHW**, Domestic Hot Water; **DNO**, Distribution Network Operator; **EE**, Element Energy; **ENWL**, Electricity North West Limited; **EN 50160**, European Standard Defining Voltage Characteristics Supplied by Public Electricity Networks; **EPC**, Energy Performance Certificates; **ESQCR**, Electricity Safety, Quality, and Continuity Regulations; **EWASP**, Electrified Water and Space Heating Profiler; **GSHP**, Ground Source Heat Pump; **HP**, Heat Pump (any source); **IPCC**, Intergovernmental Panel on Climate Change; **LCL**, Low Carbon London; **LV**, Low Voltage; **MILP**, Mixed Integer Linear Programming; **microCHP**, Micro-Scale Combined Heat and Power; **MPC**, Model Predictive Control; **OpenDSS**, Open-Source Distribution System Simulator; **RIIO**, Revenue = Incentives + Innovation + Outputs; **UKPN**, United Kingdom Power Networks; **WPD**, Western Power Distribution.

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Previous academic and industrial work has focused on determining the ADMD of heat pump installations. Love et al. [11] estimated this using the customer led network revolution (CLNR) dataset of heat pump profiles [12]. The average thermal delivery of the pumps in this dataset were noted to be 8.11 kW_{th} (ASHP) and 8.21 kWth (GSHP), and were predominantly installed in social housing. The authors found that under cold conditions, ADMD falls to 50% of a single pumps peak at an aggregation of 40, and 45% at an aggregation of 100. Pimm et al. [13] used profiles from a modified CREST model (see [14]) to synthesize electrified heating and appliance electricity profiles for sets of 100 residences. An optimization was then used to find the charging and discharging limits at which a battery store should operate to minimize ADMD as best as is possible. The authors predicted that ASHPs would increase ADMD to about 2.1 kW, reducing to 0.85 kW if all houses were fitted with a 6 kWh Li ion battery operating at a maximum of 6 kW. These findings contradict the assumption of DNOs such as SP Energy network, whom assign the entirety of a heat pumps peak demand to the ADMD [15]. This is likely due to the assumption of milder conditions made in [13] and [11]; in neither does average daily temperature fall below −0.3 °C, houses have lower load than the national average, and a COP of 3 is assumed in [13], which is much higher than a typical heat pump could achieve at low winter temperatures. However, there is no justification for the SP Energy network assumption, and therefore the ADMD of heat pumps as a function of building archetype mix under very cold winter conditions is debatable.

The impact of ASHP and GSHPs on LV networks has been explored in some academic studies. Navarro-Espinosa *et al.* investigated the effects of ASHPs and GSHPs on a typical European LV feeder using profiles synthesized using the same method as in [10]. Monte Carlo methods were used to vary the location of heat pumps at penetrations between 0 and 100% on the 3-phase 4-wire unbalanced network model, and the voltage and thermal constraints were analyzed. It was found that the main feeder stretch could become over-utilized at heat pump penetrations as low as 40%, and voltage drops on laterals occurred between 60% and 90% HP penetration. Over-utilization occurred at 10–20% HP penetration for poorer insulated, older houses, and 30% for normal houses but with an outside temp minimum of −4.5 °C. The authors expanded upon this study in [16] by analyzing 128 feeders under typical cold day conditions, and found that 70% of feeders analyzed had the potential to experience violations. Similar work by Protopapadaki et al. examined the effects of increase heat pump demand (modelled using Modelica) on the voltage and thermal issues experienced by a typical Belgian LV feeder, and observed violations at penetrations as low as 30% [17]. Sinha et al. investigated the peotential for elimination of violations on Danish LV feeders by joint management of ASHP, thermal store, and EV loads, and found that all 7 investigated feeders maintained voltages $\geq$ 0.95p.u. with adequate scheduling [18], though feeder length was much shorter than would be typical in the UK. Hong et al. explored the potential for load shifting of heat pumps with varying degrees of building preheating and central heating buffering, using physical models of a detached home and a typical UK flat [19]. The authors found heat pump use could be deferred to a small degree (0.5 to 1 hr) longer than would be possible without the additional system components and control increase. The resulting profiles were not utilized in network studies.

Schwalbe et al. investigated the effect of various building level control methods on the voltage and thermal conditions of 3 Belgian LV networks at 30, 40 and 50% HP penetrations [20]. HP profile were generated using a simple 1 building zone & 1 node tank model, and 4 heating strategies were examined – heating on normal demand, arbitrage (heat when cheap), block-out (no heating allowed for 1 h at midday - which is Belgian peak), and block-out with buffer preheating. It was noted that the block out method had a negative effect, as it caused heat pump demands to synchronize with one another, and no other methods made significant difference.

Haque et al. designed an algorithm that coupled centralized heat pump demand with a local voltage droop/voltage step controller to manage conditions on a low voltage distribution feeder in the Netherlands [21]. The control strategy was able to reduce the duration of overloading by a factor of 6 across a 24 h period. Sinha et al developed a decentralized point of connection voltage, thermal comfort, and water tank temperature based control scheme, and applied this to a Danish LV network with 6 feeders and 164 domestic loads [22]. The authors found that acceptable grid conditions could typically be maintained, though certain starting conditions could result in drops in tank temperature below critical levels. Furthermore, such centralized control schemes require extensive knowledge of the network – and tend to favor houses towards the front end of the feeder (they are usually less voltage constrained).

Building and network control schemes employing more advance optimal/centralzed control techniques and strategies are also being investigated. Colmenar-Santos et al. formulated a hybrid genetic algorithm and mixed-integer linear programming (MILP) model predictive control (MPC) method for the levelling of household demand, and minimization of customer costs, by scheduling operation of electrified heating, battery storage, appliances, and electric vehicle demand [23].

Further research concerns the potential of modern ASHP topologies, such as transcritical CO2 ASHPs, and optimization of their operation. Wang et al. proposed an MPC method for COP optimisation in a CO_2 ASHP, which uses system state and predicted future state conditions to determine the optimal control inputs for future time steps [24]. The authors were successful in obtaining near optimal COP conditions in the majority of modelled scenarios. An alternative, reduced-order COP optimization model for typical air to water heat pumps was developed by Rastegarpour et al., and determines optimal pump operation as a function of ambient temperature, and load demand predicted within the control horizon [25]. Such developments have the potential to accelerate ASHP deployment by (a) reducing the need for heat emitter modifications (lower temperature emitters such as underfloor heating are not required at the high delivery temperatures achieved by CO_2 transcritical systems) and (b) improving the efficiency of typical ASHP topologies.

Whilst some research highlights the voltage flicker issues surrounding start up current of induction motor driven heat pump compressors [26], it is often noted that flicker issues can be easily mitigated with soft starters [27], which are always installed in the UK where required. Further research addresses identification methods for detection of unacceptable starting current transients, for instances in which soft start technology malfunctions [28].

Distribution network operators (DNOs) are also considering the impacts of heat pumps induced low voltage networks. Western Power Distribution (WPD) were involved in the installation and monitoring of HPs in EPC grade A households, and aim to use the results to develop ADMD profiles that include HP demand [6]. UK power networks (UKPN) used derived HP demand profiles to determine the impacts of electrified heating on LV networks in the Low Carbon London (LCL) study [8]. The methodology was based on preexisting RIIO, and DECC HP penetration evolution scenarios, and used a purpose built statistical tool developed by Element Energy (EE). Load effects alone were seen to result in the need for an extra 200–300 London LV substation reinforcements by 2050 under all RIIO, LCL, and DECC scenarios examined. The scenarios predict a much lower penetration evolution rate than the Climate Change Committee (CCC) believe may be necessary to achieve carbon goals [2] - this is likely because the study was performed 5 years prior to the IPCC 1.5 review [1]. Electricity Northwest Limited (ENWL) generated heat pump profiles using a statistical algorithm developed by the University of Manchester (detailed in [29]), and applied these to 128 3-phase 4-wire openDSS LV feeder models [7]. It was determined that about 55% of all feeders with more than 25 customers had the potential to exhibit either voltage or thermal violations, or both.

Through review of the aforementioned literature, the following research gaps were identified.

- No studies considered mixing of control strategies, which has the potential to add an extra layer of diversity that ultimately reduces ADMD.
- The effectiveness of control has not been examined as a function of building fabric quality, or network topology.
- There is little consideration of statistical aspects in control studies e.g. average severity of constraint across multiple simulations. Therefore, the results cannot be considered truly robust.
- Despite the fact that results are very likely to be influenced by severity of winter weather conditions, the effects of these are never quantified with respect to control.

Therefore, in this study, we aim to

- Determine the most effectives mixes (from an LV network management perspective) of a set of air source heat pump system control strategies, and determine whether mixing of strategies is indeed beneficial.
- Determine the sensitivity of results to weather conditions.
- Determine if, and how the optimal mix varies between 2 distinctly different UK LV network topologies.
- Use monte-carlo methods (described within) to examine the potential for random and uncontrollable variability in results.

2. Method

To analyze the effects of decentralized control methodologies on network performance under ASHP penetration, it was necessary to develop various novel methodologies. This section summarizes the profile generation and assignment methodology, the network modelling approach, and the sensitivity analysis procedure.

2.1. Generation of ASHP profiles

The majority of ASHPs electricity consumption can be attributed to the operation of its compressor, which is used to increase the temperature and pressure of the pumps refrigerant to a level appropriate for the heating of a space heating water loop. The electrical demand and heat generation efficiency are both dependent on outdoor air temperature and the instantaneous temperature of the heating loop, and consideration of these factors are therefore important when modelling demand profiles. Therefore, ASHP profiles were generated using the multi-zone physical building model 'Electrified Water and Space Heating Profiler' (EWASP) – detailed in [30] and available at [31]. EWASP is a dynamic building model, with detailed consideration of ASHP heat generation, electricity demand, and control state as a function of indoor, outdoor, and loop flow temperatures. Furthermore, EWASP is able to automatically size the ASHPs electrical and thermal capacities based on the modelled buildings age and fabric quality. On average, EWASP sized the ASHPs thermal capacities for Network 1/Network 7 as 12.1 kW_{th}/9.0 kW_{th} in the lower fabric standard scenario, 9.3 kW_{th}/7.5 kW_{th} in the base fabric standard scenario, and 5.0 kW_{th}/5.0 kW_{th} in the higher fabric standard scenario (5.0 kW_{th} is the smallest nominal heating capacity allowed in EWASP i.e. the residences do not necessarily need this much heating power, but smaller pumps are not widely available in the UK).

Because EWASP allows system topology and control customization, it was adapted to represent four different control strategies, which were chosen based on their potential to increase heat pump diversity when combined with one another. These were:

None – Heat pump activation is controlled based on reference zone temperature (usually the living/dining area), and ASHP water return temperature. The reference temperature is randomly assigned based on UK heating trends [32], and the return hysteresis band is set to 37.5 °C on, 40 °C off. Radiators are sized for lower flow temperatures (in this case 45 °C).

Setback – Room thermostat set point is reduced to 18 °C during peak hours. Residents partaking in the setback scheme are randomly assigned a 1.5 h block between 06:45 and 08:45, and a 5 h block between 15:45 and 21:15. The random variation in start time prevents partaking customers from switching their heat pumps on at the same time (the moment when the setback period ended). This prevents diversity loss.

Preheating – The residence is pre-heated to the set temperature (determined by the thermostat setting), with heating commencing between 1 and 3 h before the demand peak begins (i.e. between 13:30 and 15:30). Randomized start times are included to prevent loss of diversity, and unnecessary demand peaking.

Buffering – The space heating system includes a 300 L buffer tank, which is configured to charge to 50 °C 1–3 h before the demand peak begins. If the house is also partaking in preheating, then the start time for both is the same. The tank will then discharge gradually to serve heating demand. The tank will always discharge when the temperature in the reference zone falls below the zone thermostat lower threshold. Once the top of the buffer tank falls to 37.5 °C, the heat pump activates and heats until the entire tank exceeds 40 °C. The tank can operate in 3 modes – recharging, discharging, and simultaneous (much like the tank example outlined in [33]). These operational modes are outlined in Fig. 1. The tank is modelled as a simple 1 dimensional 3 node system (explorative studies showed that a greater number of node had an insignificant effect on results), with physics based on the CARNOT block set models [34], and observations of buffer tank flow behavior [35].

Inlets and outlets for both the heat pump and the central heating system are included in the model. The charge rate is set significantly higher than the typical discharge rate (so that the tank and SH loop can be provided with heat simultaneously if required), and it is assumed that the water in each node layer is perfectly mixed. Convective mixing between layers occurs in the instance of an inverse thermocline (the bottom of the tank is a greater temperature than the top).

Heat pump and appliance profiles for residences that fell into every possible permutation of the following categories were generated:

- Space heating buffer tank: 2 categories – tank absent, tank present. Buffer tank size is fixed at 300 l. This tank size is large enough to store significant heat, but small enough to contain within a residence.
- Control: 4 categories – preheating, set back, preheat and setback simultaneously, and none.
- Build year: 4 categories – 1900–1920, 1920–1965, 1965–1995, and 1995+. These categories were chosen to reflect interval within which building layouts and fabric were relatively similar.
- Build Type: 4 categories - end terraced, mid terraced, semi-detached, and detached.
- Day Type: 2 categories - typical winter, extremely cold. Both situations are explored, as they represent standard winter conditions (which is the only scenario explored in some literature [11,13]), and extremely cold (but possible) conditions.

100 ASHP electrical demand profiles were generated for each permutation of the above variables which resulted in 25,600 daily profiles. A visual representation of demand profile geneartion scenario heirarchy is shown in Fig. 2.

Occupancy level (number of residents living in the house), room thermostat set point, random fabric quality variations, appliance ownership (which affects internal free gains), and DHW tank ownership, were also considered. However, these were assumed non-controllable, and were addressed probabilistically using the methods described in Table 1.

Profiles similar to those used in this study were generated by ENWL (synthesized using microCHP accelerator profiles [39]), and real ASHP profiles were recorded as part of the CLNR project [7]. The profiles generated by the EWASP model were a better match for the CLNR profiles than the ENWL study profiles (see Fig. 3). This is because, in EWASP, occupancy and heating system request profiles (which are

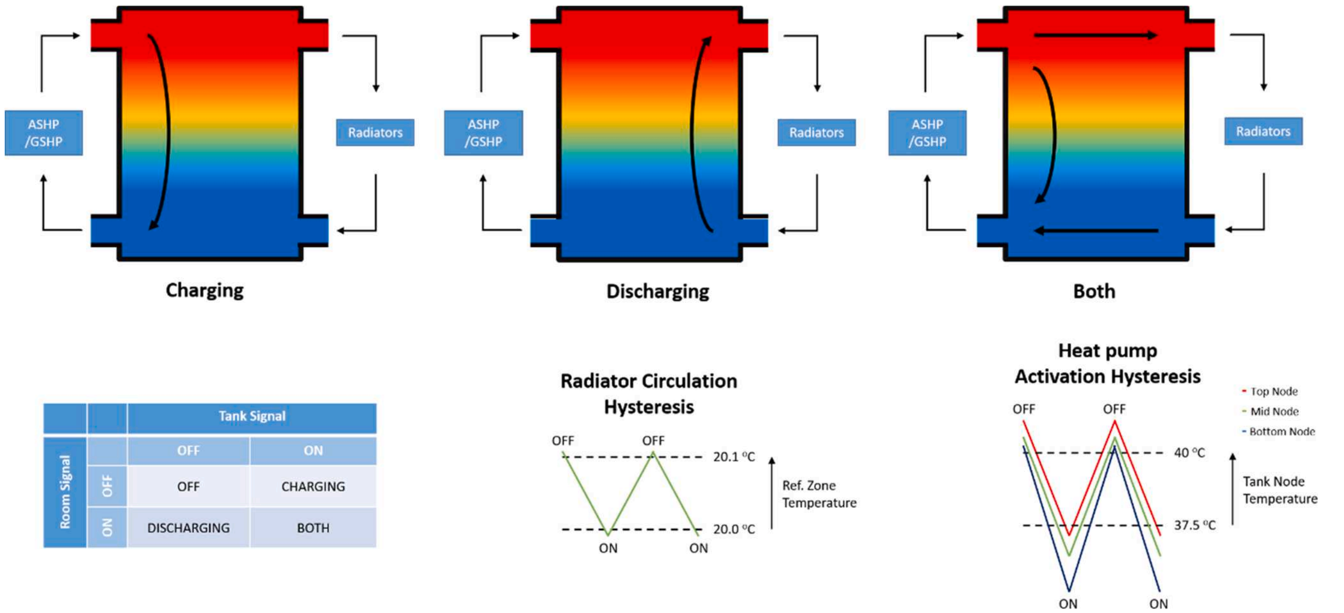

Fig. 1. (Top) Predominant direction of water flow in the 'charging', 'discharging' and 'both' scenarios. In the 'both' scenario, charging rate is greater than discharging rate, so hot water tends to migrate downwards in this instance. (bottom) The control logic table for the tank, and the hysteresis band for the (middle) room signal, and (left) tank signal.

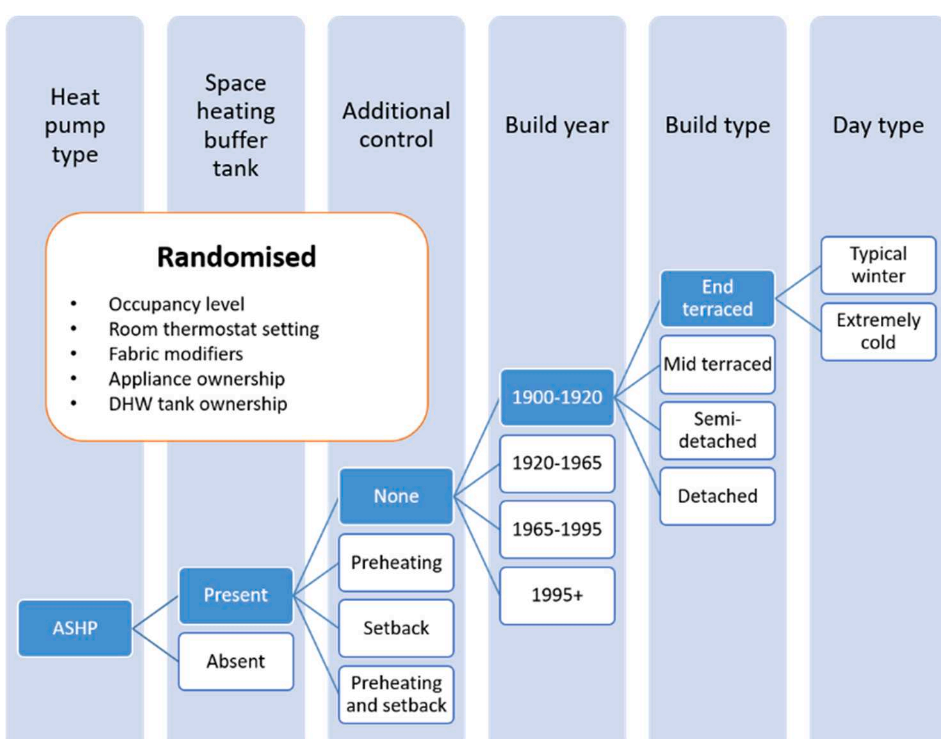

Fig. 2. The hierarchy of demand profile generation scenarios. Variables that are randomized across all scenarios are shown in a bulleted list.

generated using the CREST model) tended to assign greater occupancy to the middle of the day than that observed in microCHP accelerator profiles. For this reason, a further set of EWASP profiles, which better represent microCHP style heating patterns, were generated and used in the sensitivity analysis (see Section 2.4) to examine the effect of different profile shapes on network violations.

2.2. Network modelling

Two suburban LV networks models [40] are used to test the methodology presented. The models are built in openDSS [41], which allows rapid power flow simulations. Models were simplified by removing unnecessary line details to increase solution rate e.g. over-segmented lines, lines with no apparent destination.

MATLAB was used to stochastically assign appropriate residential demand profiles to network load points via the MATLAB-openDSS COM

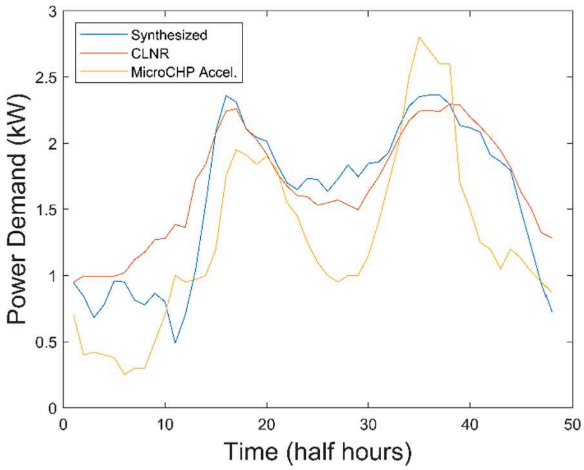

Fig. 3. Average demand profiles of houses measured from the CLNR project (orange), measured from the microCHP accelerator project (yellow), and synthesized using EWASP (blue).

Table 1
Variables that are randomized in the simulation, and justification for the randomization methodology.

Randomized variable	*Randomization methodology*
Occupancy	Randomly assigned with probability weighted to house government statistics [36]
Reference zone Thermostat Setting	Randomly assigned with weighted probability based on [32]
Fabric Quality Variation	15% variation of the mean. 15% is appropriate to represent the range of effect that no retrofit, and extensive retrofit could have on the mean [37].
Appliance ownership	Randomly assigned using CREST model's appliance sub model [14]
DHW tank	Size based on occupancy (50 l/occupant) [38]

interface. A power flow simulation was performed for every minute of the day, and the voltage magnitude at each load, and line loading across each line object, were extracted. This data was used to determine the percentage of residences that experience voltage drops in violation of ESQCR (230 V + 10%/-6% for single phase loads [42]) and EN 50160 (230 V $\pm$ 10%, for 95% of all 10 min average periods [43]) standards, and the total length of cable that is in thermal violation of both statutes (currents in excess of rated cable capacity for any sustained period of at least 30 min during the day). ASHPs were modelled as single phase, as these are the current most commonly installed models in UK homes; 3-phase supply points rarely exist in typical UK residences, require substantial labour and costs to retrofit, and are not currently deemed necessary from a capacity increase perspective given the peak demand of a typical UK home. ASHPs were modeled with a leading power factor = 0.95, as is sensible given field trial data [8,44].

The networks (topologies shown in Fig. 4), were chosen for their very different spatial properties (summarized in Table 2). Network 1 is composed of 4 feeders, serving a total of 200 loads, with a load density of 2463 loads/km^2. Network 7 has 7 feeders serving a total of 471 loads, with a load density of 4198 loads/km^2. The main simulations were performed using the network 1 model, and the network 7 model was used during sensitivity analysis to examine the effects of higher network stresses [45].

2.3. Main simulation details

In the main simulation, power flow simulations are performed on Network 1, with all residences assigned the average expected fabric

Table 2
Physical properties of each network and its constituent feeders. Load count represents the number of residences on the network, total length is the total length of network/feeder cable, and substation load is the number of residences per kVA of substation capacity. Mean path length is the average length of cable between a residence and the substation. Feeder load is the number of residences for each kVA of feeder power carrying capacity at 230 V, measured at the head of the feeder. Feeder load and mean path length do not directly sum to substation load and network mean path length, because they are weighted averages.

	Load Count (Loads)	*Substation Load (Loads/ kVA)*	*Feeder Load (Loads/ kVA)*	*Mean Path Length (m)*	*Total Length (km)*
N1 total	**200**	**0.25**	**–**	**209**	**5.84**
N1f1	55	–	1.61	171	1.43
N1f2	31	–	0.91	197	0.94
N1f3	39	–	1.14	194	0.91
N1f4	75	–	1.38	249	2.56
N7 total	**471**	**0.588**	**–**	**235**	**10.43**
N7f1	71	–	1.69	283	1.71
n7f2	58	–	0.93	203	1.42
N7f3	50	–	0.81	181	1.10
N7f4	186	–	2.06	305	4.19
N7f5	61	–	0.64	117	1.06
N7f6	23	–	0.33	113	0.40
N7f7	22	–	0.31	155	0.55

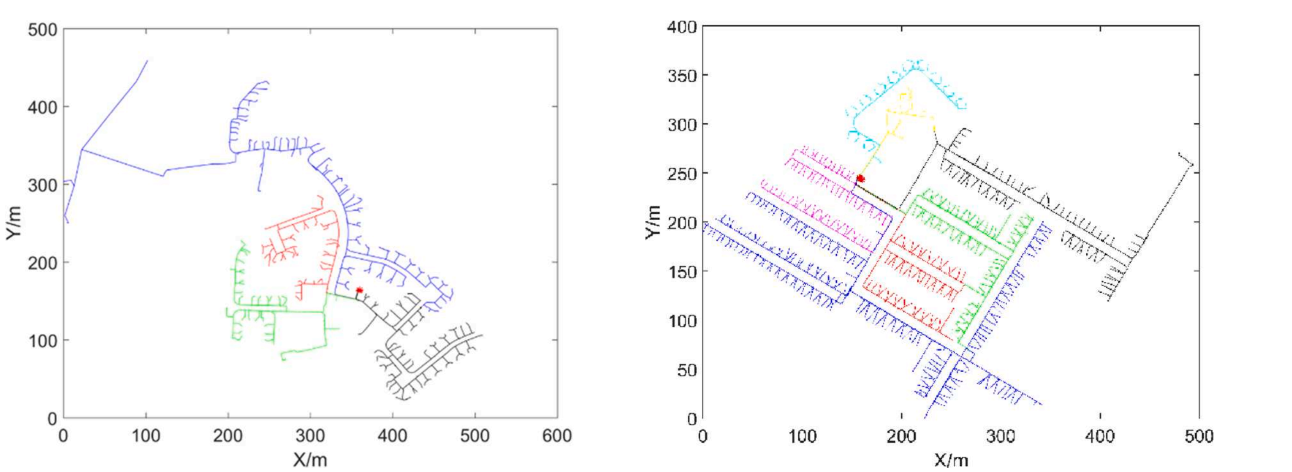

Fig. 4. Topology of (left) network 1, and (right) network 2. Different colors represent the different network feeders (feeders 1–7 shown in colour order black, green, red blue, magenta, yellow, cyan), and the red circle shows the location of the substation.

quality for the area (determined using [46]), under both typical winter (average outdoor temperature 2 °C) and very cold temperatures (average outdoor temperature −5 °C) conditions. For this simulation, every permutation of the following scenarios is examined:

- HP penetration: 20–100%, at 20% increments.
- Buffer Presence: All residents use buffer tanks, or no residents use buffer tanks.
- Percentage of customers preheating space: 0–100%, at 20% increments.
- Percentage of customers using setback: 0–100%, at 20% increments.

This results in 360 scenarios per network.

Explorative work showed that the output metrics for any given scenario tended to converge at 20–30 runs, and so we performed 30 daily runs for each scenario.

Profiles were randomly assigned to each house based on the scenario. For example, for a HP penetration = 20%, Preheating percentage = 40%, and Setback percentage = 80% scenario, the probability of a residence being assigned a profile that includes ASHP demand, and operating both preheating and setback is 20% × 40% × 80% = 6.4%, and the probability of having no heat pump is 80%.

Once all runs for all scenarios were complete, the average number of customers experiencing voltage violations, and average number of lines experiencing thermal congestions were calculated for each scenario. The results of the main simulation are discussed in Section 3.1.

2.4. Sensitivity analysis

The sensitivity analysis investigates the influence of fabric, profile, and network topology factors on results, so that:

- The discrepancy between results of previous academic studies can be better understood.
- The simplifications and assumptions that may/may not be used in future network studies are understood.

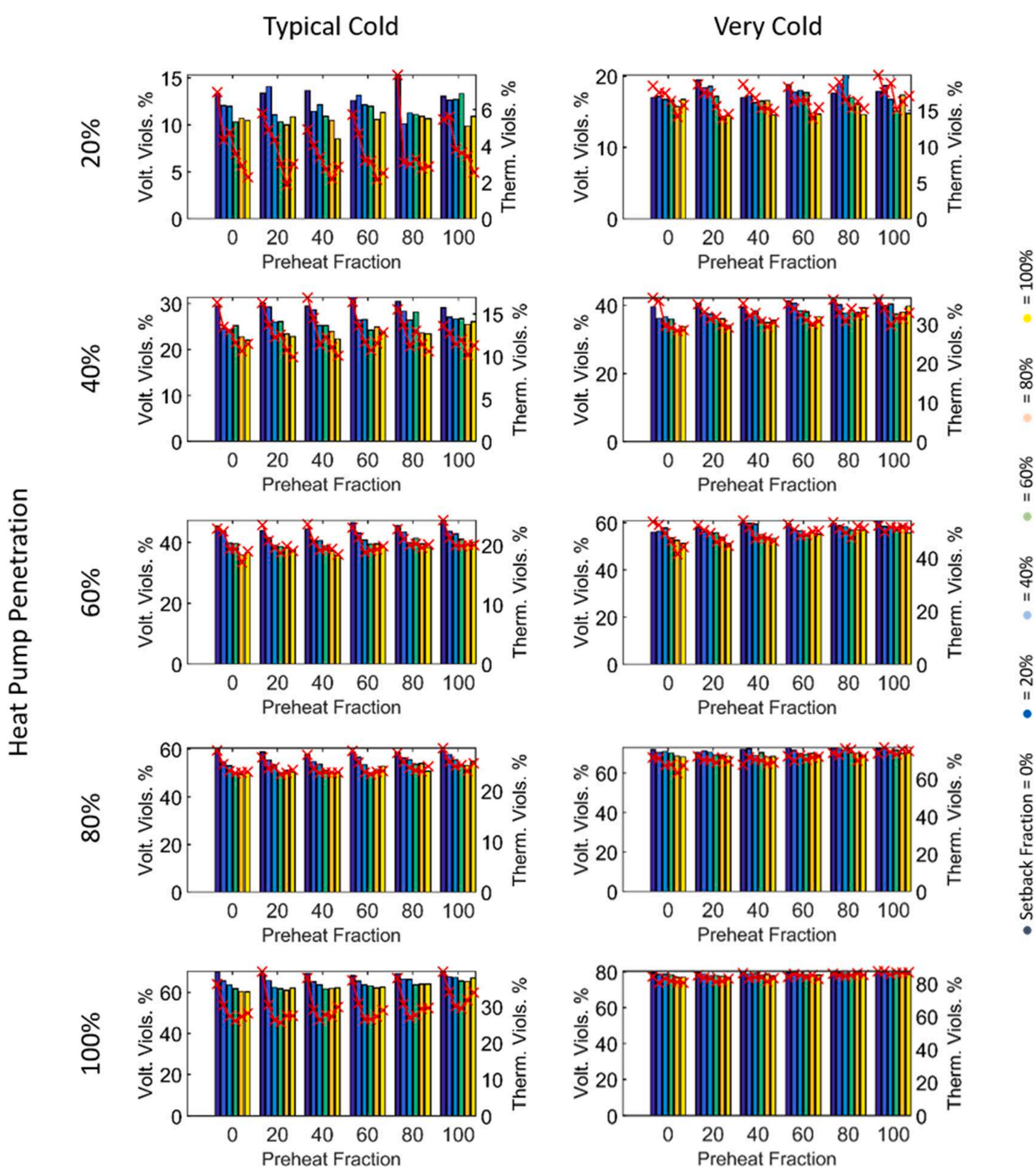

Fig. 5. The % of residents experiencing ESQCR voltage violations (bars) and lines with thermal violations (lines). Groups of lines represent no setback control (blue) through to 100% of customers operating setback control (yellow). All of the results shown are for the buffer tank % = 0 scenario set.

Four alternative scenarios are explored in this analysis:

- Alternative profiles: demand profiles are changed to a set that better represents those seen in the microCHP accelerator case.
- Higher fabric standard: demand profiles are switched with those for buildings of mid 2000's fabric standard.
- Lower fabric standard: demand profiles are switched with those for buildings of 1920's standard.
- Heavily loaded network: main simulation demand profiles are applied to network 7, which is more heavily loaded and constrained.

All results were generated and analyzed using the same methodology as outlined in Sections 2.1, 2.2 and 2.3.

3. Results

3.1. Network results

Simulations showed that network 1 had a much greater sensitivity to ESQCR violations than thermal violations. Some customers experienced ESQCR violations at 20% ASHP penetration, and the prevalence increased rapidly with ASHP penetration (see Fig. 5). The percentage of network cables experiencing thermal violations was typically half to one third the percentage of customers experiencing voltage violations. This was the result of an unexpected diversity loss phenomena; voltage on branches was only significantly affected by nearby loads on the same phase and branch, and so the voltage profile at a load point often reflected the instantaneous summed demand of the nearest 3–4 loads. Because there is very little diversity benefit to aggregation of such a small number of profiles, the additional power demand seen on network branches can be as great as the sum of the max demands of each pump on the branch, and so voltage can vary by as much as 10% on the minute to minute timescale. Conversely, because thermal violations are measured as 30 min average figures, the same diversity loss phenomena was not observed.

It should be noted that the results represent the percentage of lines that experience a violation at any point over the day. It was observed that frequency of thermal violations does decrease with increasing numbers of customers operating the setback strategy. However, unless the average number of time periods of violation reaches zero, a control strategy is not particularly useful for thermal management, so we do not present the violation frequency data.

Switching to EN 50160 regulations reduced the instance of voltage violation significantly, because most customers only experience voltage violations for a few minutes at a time at lower ASHP penetrations.

Increasing the penetration of buffer tanks has no effect between 0 → 50% penetration, and a negative effect thereafter. This can be understood by observing a typical aggregated demand profile at buffer tank penetrations 0%, 50%, and 100%. The network peak does not alter significantly in to 50% case; it decreases slightly but not sufficiently to reduce demand. Peak demand remains roughly the same in both the 0% case and 100% case (see Fig. 6), and is often slightly higher. This is because the evening peak is shifted forward, but retains a similar magnitude.

The violation percentages for the base case (no control) and optimum control mix (i.e. the 'best' mix of technologies) at each ASHP penetration level are shown in Fig. 7.

4. Sensitivity analysis

4.1. Lower fabric standard

Reducing fabric standards to those typical of early 1900s builds has a small effect on violation metrics (an average of 5% increase in violations across all control, statute, and temperature scenarios). This can be explained by inspecting the fabric changes between early 1900s and the 1970s homes; the fabric guidelines outlined in [37] show that overall U-Values decreased by only 20% across the two time periods. After diversity, this translates to a peak demand drop of only 11%, which results in little difference between observed violations.

For the reasons mentioned in Section 3.1, the network is much more constrained by ESQCR voltage compliance than by thermal limits, but more constrained by thermal limits than EN50160 voltage compliance (see Fig. 8). In all cases, increasing the fraction of residences operating the setback control scheme decreased the incidence of voltage violations, though this effect was smaller at high HP penetrations. Increasing

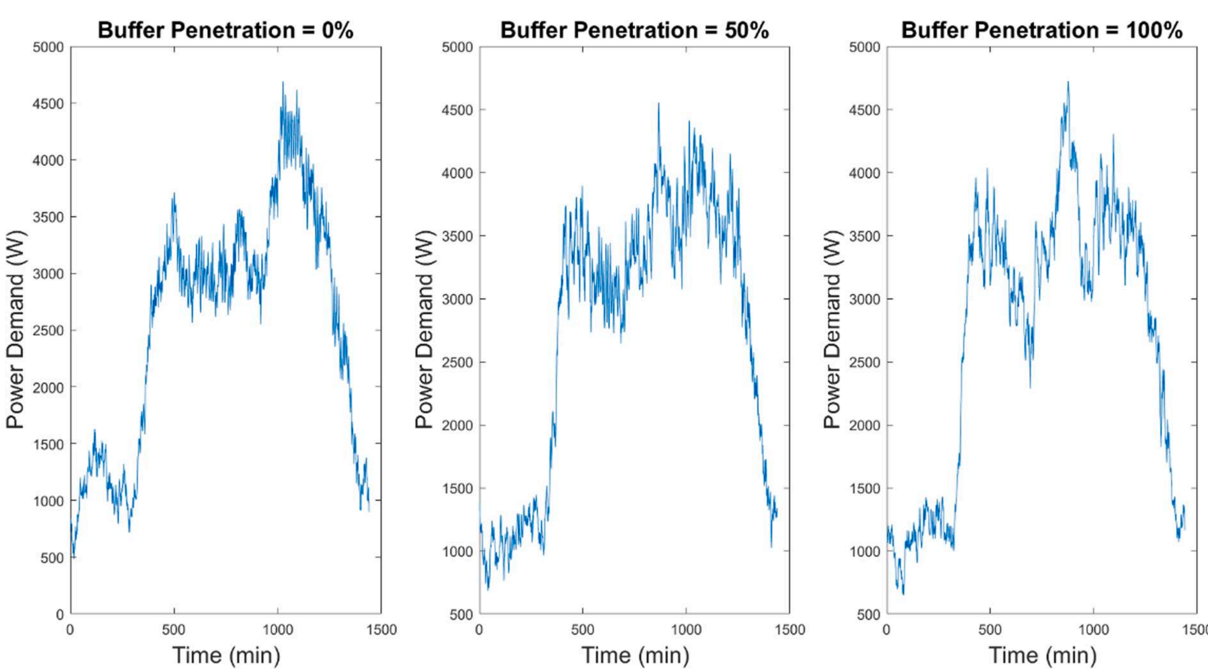

Fig. 6. The difference between average household demand profiles with varying buffer tank ownership levels over the course of one day. The buffer charging peak appears at around 900 mins (3:00 pm).

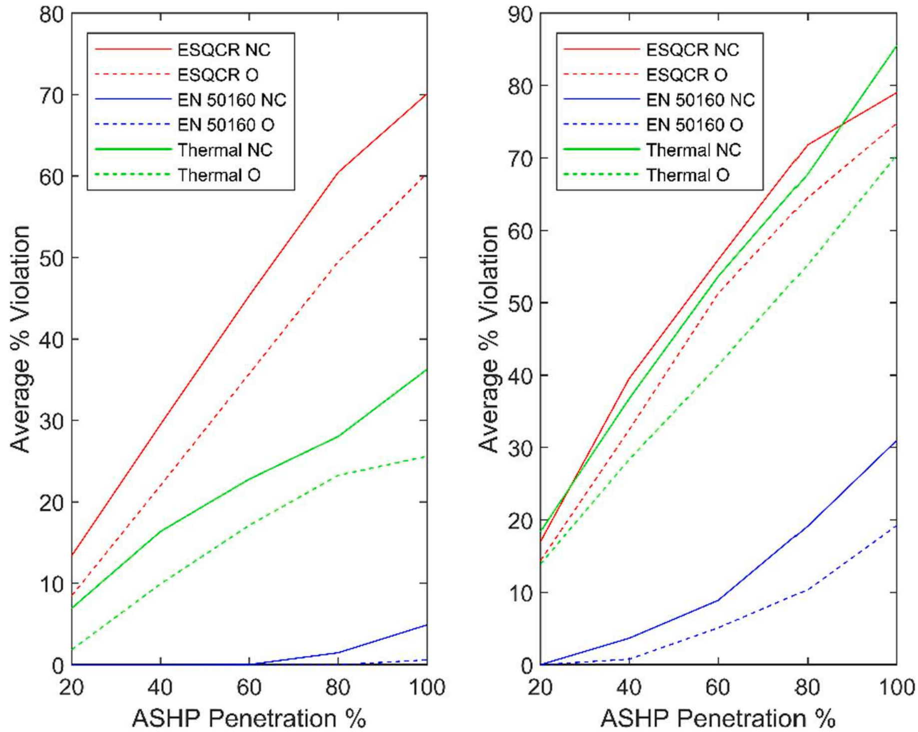

Fig. 7. Shows (left) the percentage of households on 'Network 1' experiencing voltage violations by ESQCR and EN 50160 standards in the no control (NC) and optimal mix (O) scenarios in the 'typical cold' case, and the same for the percentage of total network cable length experiencing thermal violation. (right) The same data for the 'Very cold' case.

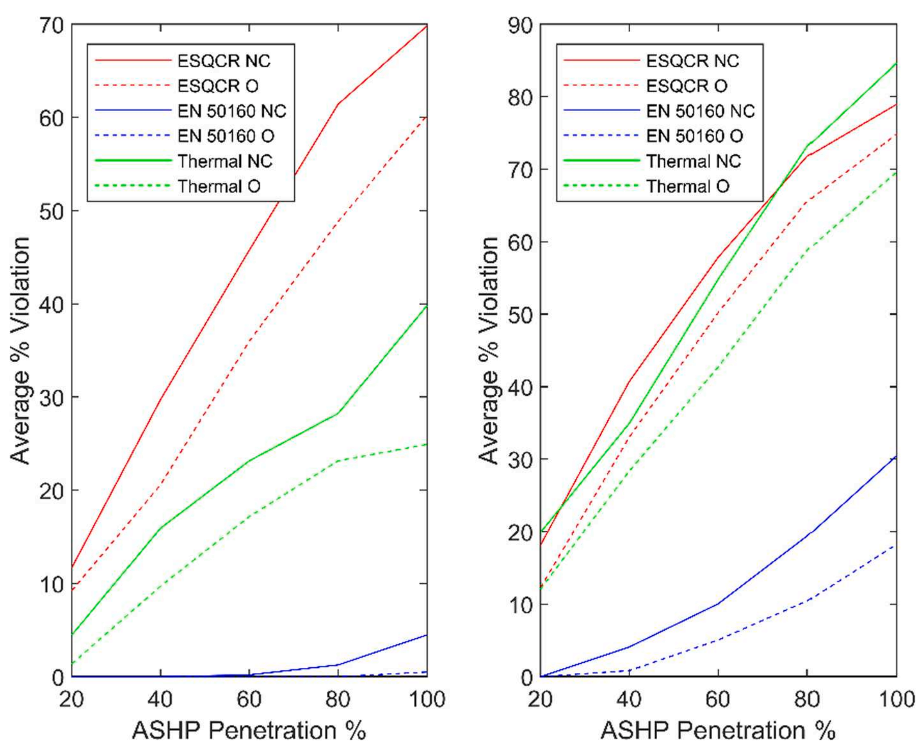

Fig. 8. The same data as described in the caption for Fig. 7, but for buildings with early 1900s fabric standards.

buffer tank penetration increased the incidence of thermal and voltage violations, due to the reduction in demand diversity associated with this change.,

Increasing the preheat fraction produces no clear effect on the prevalence of violations. Optimum control mix point typically falls at 100% Preheat fraction, 0% buffer tank penetration, and a preheat fraction somewhere between 0 and 40%, though there is no clear pattern to the latter. Optimum control mix points under differing ASHP penetrations, and the extent to which they reduce the average prevalence of thermal and voltage violations, are shown in Table 3.

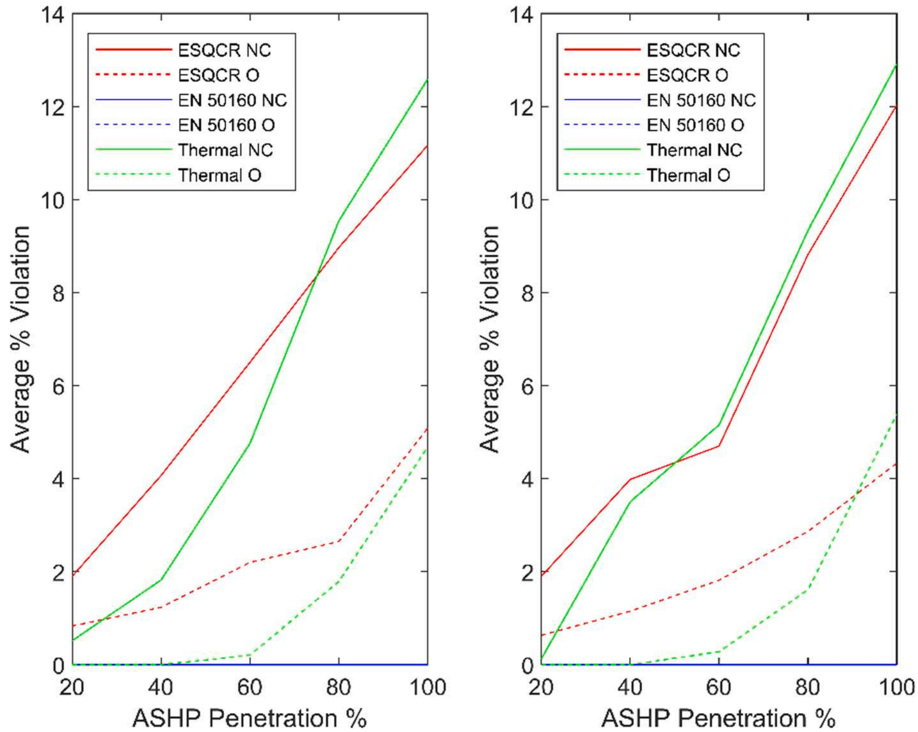

Fig. 9. Shows the same data as described in the caption for Fig. 7, but assuming the network is composed of buildings with mid 2000s fabric standards.

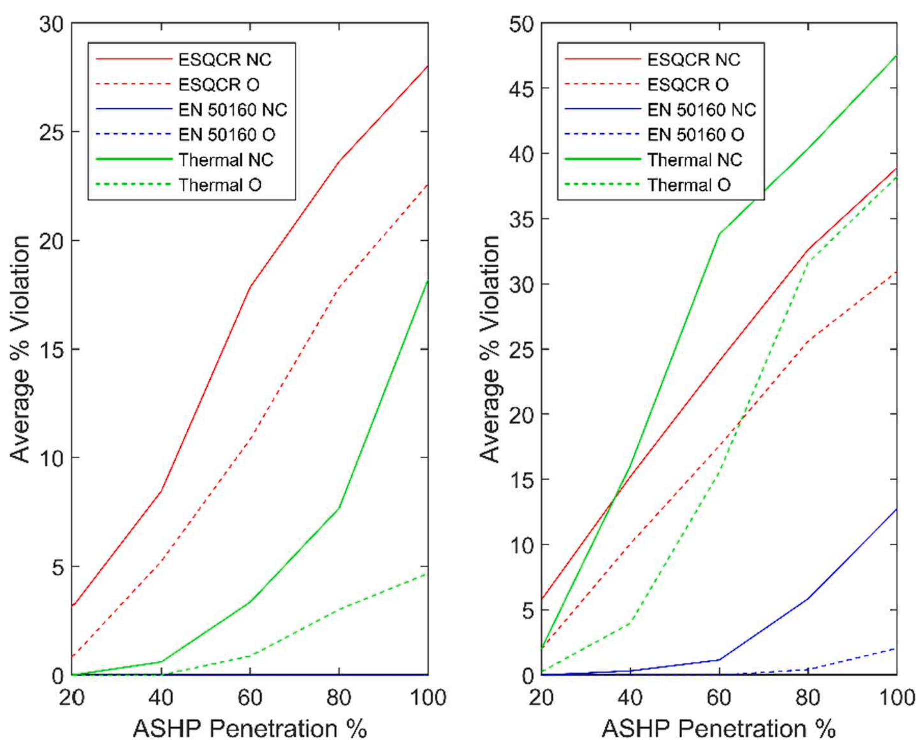

Fig. 10. Shows the same data as described in the caption for Fig. 7, but for network 7.

4.2. Higher fabric standard

When upgrading from a typical 1970's fabric to a 2000's fabric, the weighted average U value of components falls by a factor of 4.5. This is enough to reduce the network ADMD by a factor of 2.5, greatly reducing the prevalence of violations (see Fig. 9, Table 4). At a maximum 100% ASHP penetration, only 12% of customer's experience ESQCR voltage violations. Furthermore, thermal violations can be reduced to 6% of the network length across all scenarios at 100% HP penetration. There is no clear pattern to the optimum control mix. However, low buffer tank penetration, and a high % of customers operating setback control tends to be the most effective strategy. The reasons for this are the same as those detailed in Section 3.

Violation prevalence changes only slightly in the v. cold scenario

Table 3
The optimum control strategy and reduction in violation relative to the base scenario (no control) in the early 1900's fabric case. Shown in format 'buffer tank penetration % (b) = x, preheat penetration (p) = y, setback penetration (s) = z (average reduction in % of customers experiencing violation/average reduction in % of network cable length experiencing thermal violation)'. If a percentage is shown in bold, the violation it represents no longer occurs (i.e. the control scheme is sufficient to reduce the prevalence of this violation to zero).

		ESQCR		EN 50160	
		Typical	**Very Cold**	**Typical**	**Very Cold**
HP Pen %	**20**	b = 0, p = 40, s = 100 (2.5%/1.2%)	b = 0, p = 0, s = 100 (5%/7%)	b = 0, p = 40, s = 80 (**0%**/4.5%)	b = 0, p = 0, s = 100 (**0.4%**/0.15%)
	40	b = 0, p = 0, s = 100 (8%/4%)	b = 0, p = 0, s = 100 (5%/7%)	b = 0, p = 20, s = 100 (**0%**/6%)	b = 0, p = 40, s = 100 (**3.8%**/0.8%)
	60	b = 0, p = 0, s = 100 (6%/2%)	b = 0, p = 0, s = 100 (8%/14%)	b = 0, p = 0, s = 100 (**0.2%**/6%)	b = 0, p = 0, s = 100 (5%/14%)
	80	b = 0, p = 0, s = 100 (8%/2%)	b = 0, p = 0, s = 100 (5%/4%)	b = 0, p = 20, s = 100 (1%/2%)	b = 0, p = 0, s = 100 (8%/10%)
	100	b = 0, p = 0, s = 100 (8%/11%)	b = 0, p = 0, s = 100 (4%/3%)	b = 0, p = 0, s = 100 (2.5%/11%)	b = 0, p = 0, s = 100 (12%/10%)

Table 4
The optimum control strategy and reduction in violation relative to the base scenario (no control) in the early 2000's fabric case. The term 'N/A%' Implies that no violations of the given type occurred in the base case, and so it is impossible for control strategies to further reduce the prevalence of this violation type.

		ESQCR		EN 50160	
		Typical	**Very Cold**	**Typical**	**Very Cold**
HP Pen %	**20**	b = 0, p = 20, s = 100 (1.5%/**0.5%**)	b = 0, p = 20, s = 100 (2%/2%)	b = 0, p = 0, s = 20 (N/A%/**0.5%**)	b = 0, p = 20, s = 60 (N/A%/**0.5%**)
	40	b = 0, p = 80, s = 80 (3.2%/**1.7%**)	b = 0, p = 60, s = 100 (2.5%/3.2%)	b = 0, p = 80, s = 80 (N/A%/**1.7%**)	b = 0, p = 20, s = 80 (N/A%/**3.5%**)
	60	b = 0, p = 80, s = 80 (4%/4%)	b = 0, p = 80, s = 100 (4%/5%)	b = 0, p = 40, s = 100 (N/A%/4.6%)	b = 0, p = 60, s = 60 (N/A%/4.5%)
	80	b = 0, p = 60, s = 80 (4.5%/8%)	b = 0, p = 60, s = 100 (6%/7%)	b = 0, p = 60, s = 80 (N/A%/8%)	b = 0, p = 60, s = 100 (N/A%/7%)
	100	b = 0, p = 40, s = 80 (6%/8%)	b = 0, p = 60, s = 100 (5%/7%)	b = 0, p = 40, s = 80 (N/A%/8%)	b = 0, p = 20, s = 80 (N/A%/6%)

Table 5
The optimum control strategy and reduction in violations relative to the base scenario (no control) in the microCHP accelerator type profile case.

		ESQCR		EN 50160	
		Typical	**Very Cold**	**Typical**	**Very Cold**
HP Pen %	**20**	b = 0.5, p = 60, s = 60 (1%/2%)	b = 0.5, p = 20, s = 100 (4%/6%)	b = 0.5, p = 100, s = 100 (N/A%/2.5%)	b = 0.5, p = 20, s = 100 (N/A%/6%)
	40	b = 0.5, p = 80, s = 80 (5%/6%)	b = 0.5, p = 20, s = 100 (5%/4%)	b = 0.5, p = 40, s = 80 (N/A%/6.2%)	b = 0.5, p = 20, s = 80 (**0.9%**/4%)
	60	b = 0.5, p = 40, s = 60 (12%/7%)	b = 0.5, p = 0, s = 100 (9%/5%)	b = 0.5, p = 40, s = 60 (N/A%/7%)	b = 0.5, p = 40, s = 80 (3%/5%)
	80	b = 0.5, p = 20, s = 60 (10%/7%)	b = 0.5, p = 0, s = 100 (10%/10%)	b = 0.5, p = 20, s = 60 (**0.25%**/7%)	b = 0.5, p = 0, s = 80 (5%/7%)
	100	b = 0.5, p = 20, s = 80 (6%/8%)	b = 0.5, p = 0, s = 100 (10%/10%)	b = 0.5, p = 20, s = 80 (**0.8%**/8%)	b = 0.5, p = 0, s = 100 (7%/10%)

Table 6
The optimum control strategy and reduction in violations relative to the base scenario (no control) in the 'network 7' case.

		ESQCR		EN 50160	
		Typical	**Very Cold**	**Typical**	**Very Cold**
HP Pen %	**20**	b = 0, p = 100, s = 100 (0.0%/0.8%)	b = 0, p = 40, s = 100 (2.0%/0.8%)	b = 0, p = 0, s = 0 (0%/0%)	b = 0, p = 20, s = 80 (N/A%/0.2%)
	40	b = 0, p = 0, s = 80 (5.0%/0.2%)	b = 0, p = 0, s = 80 (12%/6.2%)	b = 0, p = 20, s = 60 (0%/0%)	b = 0, p = 40, s = 60 (N/A%/6.0%)
	60	b = 0, p = 40, s = 80 (8%/1.2%)	b = 0, p = 0, s = 100 (17%/18%)	b = 0, p = 20, s = 80 (0%/0.8%)	b = 0, p = 20, s = 100 (N/A%/16%)
	80	b = 0, p = 40, s = 100 (10%/6.2%)	b = 0, p = 20, s = 100 (25%/31%)	b = 0, p = 0, s = 60 (0%/3.5%)	b = 0, p = 20, s = 100 (4.5%/31%)
	100	b = 0, p = 80, s = 60 (10%/16%)	b = 0, p = 0, s = 100 (31%/36%)	b = 0, p = 20, s = 60 (0%/6.0%)	b = 0, p = 0, s = 100 (2.0%/36%)

because:

- House thermal loading does not greatly increase due to temperature drops – network ADMD increases by only 5%.
- Most stretches of line have thermal headroom, and the small loading increase (caused by the 5% increase in aggregated ASHP demand) is absorbed by this headroom.
- Most houses have headroom for voltage drop, so a small further drop is acceptable.

4.3. Twice-on type profiles

A lower prevalence of violations is seen in most twice-on profile scenarios (see Table 5). This is because the evening peak is much shorter (despite being slightly higher), and therefore the window of opportunity for coincidence of HP demands is much narrower. In the EQSCR case, 20/80 to 60/40 mixes of preheating/no preheating result in the optimum violations reduction, though the reduction is small. Switching to 100% buffer tank ownership increases the incidence of all violations, because of the demand spike this practice creates. 50% buffer ownership yields the same result as 0% ownership. Violations tend to reduce as the numbers of residents operating setback control increases.

In the EN 50160 case, voltage violations are much less prevalent, and thermal violations are minimized at preheat fractions of 40–60% and high levels of setback control. Again, high levels of buffer tanks increase violation prevalence. It is worth noting that it is always possible to prevent EN 50160 voltage violations using setback and preheating control in twice-on profile scenarios, and the percentage of the network experiencing thermal violations is always significantly lower.

In the very cold scenario, the optimum varies between 50% and 0% buffer ownership, though the improvement from the no buffer case is only very slight (average 1% improvement).

4.4. Larger network

The larger 'network 7' experienced fewer violations than the smaller 'network 1', with roughly ½ as many constrained customers and lines (see Fig. 10 Table 6). Though this seems counterintuitive, it can be explained by observing that the thermal demand of the smaller, mostly mid-terrace houses is only 65% of the semi-detached houses that make up the majority of network 1, and the network 7 cables have on average 25% greater capacity. Furthermore, some lateral feeder stretches on network 1 (particularly feeder 2 and 3) are near capacity without the addition of any heating technologies.

The optimum network strategy tends to exist at high setback fractions and no buffer tank ownership. Preheating is usually ineffective.

4.5. *Elimination of violations*

Whilst the results show the violation mitigating potential of decentralized management, the approach was unable to entirely eliminate violations by ESQCR standards. If assessing by European (EN 50160) standards, it was possible to reliably eliminate all violations at 20–40% ASHP penetration where houses were of a higher fabric standard.

5. Discussion

During this study, we only considered control strategies that relied on the system itself i.e. no grid signals or centralized processing. This is because we felt it important to first understand how effective a mixture of the simplest, easiest to apply algorithms could be, before benchmarking against more elaborate strategies [21,22]. Therefore, our further work will focus on comparison of the best results using heating system only control, the best results using centralized control, and the theoretical best possible control with perfect prediction.

The severity of network violations was lower than predicted in our previous study [9]. In this study, pump diversity factor was assumed to be 1.0. However, the detailed EWASP modelling performed in the current investigation suggests a diversity factor between 0.4 → 0.8 (dependent on the outdoor temperature) – where comparable, this is broadly in line with [11,47]. We therefore expect that our previous work overestimates the impact of electrified heating on LV networks. Conversely, the impact predicted in this investigation is higher than in some other studies [13]. This is because we assume lower winter temperatures and predict lower COPs (COP = 3 is assumed in [13], whilst the ASHP model in EWASP generally predicts COP = 1.8 at an outdoor temperature of −5°C).

The investigation suggests that buffer tanks are ineffective in LV network violation management, where the EWASP/CLNR type profiles are implemented. This is due to the diversity loss associated with their operation, and their relatively small heat storage capacity (about 5 kWh usable) – tanks always discharged within 2 h of the evening peak's beginning. Because of the much shorter evening peak, buffer tanks are somewhat effective when residences were modeled using microCHP accelerator type profiles. The study therefore highlights the importance of understanding expected customer heating load patterns when designing a network management strategy.

Preheating was slightly effective for lower heat demand buildings. However, in both the of these cases, the benefit was very marginal, and further work would be required to confirm that this result was not simply an artifact of the stochastic simulation framework.

Operating a setback period during peak hours was always effective, as doing so results in a real reduction in building heat demand. The effectiveness, and the optimum amount of setback, however, does not show any clear trend, and is likely to be a complex relationship between network topology, building fabric standard, and customer demand profiles. We aim to develop methods to determine how setback may play a part in network topology and operation optimization in our further work.

The methodology developed in this study could theoretically be applied to network design, or network retrofit. However, its current inefficiency limits this; the effect of every possible technology mix on the LV network is modelled, and the optimum mix is determined from observation of the results. We did not develop a fast, efficient way to determine the optimum, as the aim of this work was simply to determine whether a recurring optimal technology/control mix existed. The scale-up potential of the strategy is therefore limited by the slow generation of results datasets, and it may therefore be useful to develop a search algorithm that can rapidly locate the optimal operational mix without exploring every possible mix.

Whilst the presented strategy is often able to reduce violations, it is rarely able to eliminate them entirely. The strategy would likely need to be combined with traditional network reinforcement (reconductoring, overlaying), and include real world costs if a true optimum were to be determined.

Whilst a feeder may serve as many as 60 loads per phase, this does not necessarily result in localized diversity benefits. This is because the voltage magnitude at a particular node (usually on a branch or at the end of a network) many only be significantly affected by the power demand of a few surrounding residences. Because the demand of 4–5 aggregated loads is much less diverse than 60, we observe severe minute to minute voltage swings in some locations. Furthermore, reducing simulation resolution to lower than 2 min quickly 'smooths out' these variations, which suggests that a temporal resolution of 5 min (which is used in many studies) is not sufficient for LV network simulations involving electrified heating systems, if short-term voltage phenomena is to be examined. Thermal measurements are not affected by this phenomena however, because thermal loading is averaged to 30 min periods by convention [42,48].

6. Conclusion

This paper presents an investigation into the impacts of decentralized electrified heating control strategies on low voltage network operation, and accounts our search for the optimal control mix. It is evident from results that decentralized strategies are ineffective with respect to ESQCR statute, and are only effective at lower ASHP penetrations when compared to European statutes. Whilst no strategy mix is optimal in all scenarios, it is generally the case that setback management outperforms buffer and preheating management, and that all strategies are more effective when profiles with lower evening peak duration and magnitude are used. This is because the extent to which the evening peak must be reduced is smaller, and thus is within the mitigating capabilities of load shifting operations. It was also found that demand profile shape greatly influenced the effectiveness of load shifting control, with 'twice-on' type profiles allowing greater opportunity for voltage violation mitigation than the base scenario profiles. We therefore suggest that future studies in this research area should consider the sensitivity of results to demand profile shape. Additionally, network topology was seen to greatly influence the prevalence of violations, and as a result, it is necessary to extend future studies to examine trends in interdependence between topological factors and violation prevalence.

Even by (less restrictive) European statute, adequate violation management could only be achieved at ASHP penetrations of 40% and under for residences of post 2000 fabric standard. This suggests that load shifting techniques should be used in conjunction with building fabric retrofit, and network reinforcement strategies, if a significant degree of electrified heating is to be accommodate on UK networks. Future studies will explore the relative effectiveness of combined fabric retrofit, network reinforcement, and decentralized management against a theoretical optimum.

CRediT authorship contribution statement

R.C. Johnson: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing - original draft, Writing - review & editing. **M. Mayfield:** Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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