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Testing integrated electric vehicle charging and domestic heating strategies for future UK housing

Nick Kelly*, Aizaz Samuel, Jon Hand

Energy Systems Research Unit (ESRU), Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, UK

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ABSTRACT

A building simulation tool and electric vehicle (EV) charging algorithm were used to investigate the impact of electrified home heating and EV charging on the electrical demand characteristics of a net-zero-energy UK dwelling. A range of strategies by which EV charging and electrified heating could be controlled in order to minimise peak demands were tested, including off-peak load shifting, fast and slow vehicle charging, demand limited charging and heating, and bi-directional battery operation. These were compared to a base case without electrified heating and EV charging. The results indicate that the most effective operating strategy to minimise the impact of electrification on the mean peak household electrical demand was slow vehicle charging, coupled with off-peak heat pump operation. However, heat pump load shifting had an adverse impact on indoor temperatures. Off-peak-load-shifting of both the vehicle charging and heat pump operation proved counterproductive as this inadvertently synchronised both loads, resulting in high peak demands. The most successful strategy proved to be a combination of bi-directional battery operation, coupled with load controlled charging and heat pump operation—this approach limited average and absolute peak demands and almost eliminated the difference in absolute peak demands seen between fast and slow charging.

1. Introduction

The coming decades will herald a substantial change in the thermal and electrical demand of new and refurbished dwellings, brought about by a combination of improved thermal insulation and air tightness, the increased integration of microgeneration technologies such as PV, the possible electrification of heating through the use of heat pumps and the home-charging of part-or-all-electric vehicles (EV). Together, these changes would result in UK household demand characteristics being radically different from those seen today, where space heating dominate [30].

Improved thermal performance in both new build and retrofit housing would reduce the predominance of domestic space heating, placing more of a focus on the electrical and hot water demands. At present, in a typical UK dwelling, space heating accounts for around 65% of overall energy demand (Palmer and Cooper [30]), whilst in better insulated and sealed Passive House designs, space heating can be reduced by upwards of 80% [1]. The trend towards reduced space heating in UK dwellings is occurring now, with total household space heating demand declining by 21% since 2004—driven by more stringent building regulations along with higher energy costs and government incentives encouraging domestic fabric improvements (Palmer and Cooper [30]). Conversely, total household electrical demand has increased by approximately 15% over the same period (Palmer and Cooper [30])—driven by increasing numbers of appliances and behavioural changes such as increasing use of home entertainment devices and the advent of ‘always on’ devices such as broadband routers.

In tandem with changes in domestic energy demand, the supply of energy to UK dwellings is also undergoing a transformation, through the provision of thermal and electrical energy from local, low-carbon sources. For example, more than 2 GW of microgeneration capacity has been installed in the UK since the introduction of a feed-in-tariff (FIT) in 2010 [2]. This provides small scale producers (i.e. householders) with a guaranteed payment for each kW h of electricity produced by a household renewable source such as photovoltaic panels (PV).

For the UK is to achieve its ambitious target of an 80% greenhouse gas emissions reduction by 2050, relative to 1990 baseline, then the use of fossil fuels in domestic heating will need to be virtually eliminated [3] and replaced with zero carbon energy sources such as biomass, which realistically could only supply a fraction of

* Corresponding author. Tel.: +44 141 574 5083; fax: +44 141 552 5105.
E-mail address: nick@esru.strath.ac.uk (N. Kelly).

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Nomenclature

d	distance (km)
D	battery discharge (kW h/km)
F	cumulative probability (0–1)
k	Weibull distribution parameter (−)
L	parasitic discharge (kW h/km)
n	number of legs on a trip
p	probability (−)
P	power demand (W)
v	velocity (km/h)
x, y, z	random numbers (−)

Subscripts

h	hourly
H	household
MAX	maximum
MIN	minimum
OP–START/END	off peak tariff start/end time (h)

Greek symbols

Δt	time interval (s)
λ	Weibull distribution parameter (−)

heat demand [31], and renewable electricity. The latter requires the widespread uptake of heat pumps that shift the heating load from the natural gas to the electricity network. As the majority of current UK dwellings will still exist in 2050, [28] then a widespread heat pump retrofit programme would be required to bring about this shift. Air source heat pumps (ASHPs) have the potential to act as a replacement for the fossil-fuelled boilers most commonly found in UK housing. Additionally, their relatively low cost of installation and the lack of a requirement for ground works makes ASHPs a more feasible mass retrofit option than ground source heat pumps (GSHP). However, Wilson et al. [4] indicated that a shift of only 30% of domestic heating to heat pumps could result in an increase in the total UK electrical demand of some 25%.

The final development likely to have a significant impact on the characteristics of domestic demand is the growth in the use of electric vehicles (EVs). In the UK, the number of electric vehicles is still small as a percentage of the total fleet—some 0.1% of the total passenger cars licensed on UK roads [21]. However, their number is increasing exponentially. EVs shift the energy used for transportation from refined fossil fuels to the electricity network. In the UK, the domestic sector accounts for around 29% of UK final energy consumption, whilst the transport sector accounts for another 36% of demand [27]. The deployment of EVs at an increasing rate and the widespread electrification of domestic heating could lead to a massive rise in the demand for electricity and necessitate the upgrading of the UK's electricity distribution infrastructure. In this paper, the potential increase in electricity demand at the individual dwelling level is examined along with an investigation into the strategies that could be employed to mitigate the worst effects of this increase.

1.1. Previous work on domestic electrification

Many previous papers have analysed the thermal performance of future buildings (e.g. [5]), microgeneration and the electrification of heat (e.g. [4]), and the potential impact of EVs on the electrical network (e.g. [6]). However, there is a paucity of material looking specifically at the combinatorial effects of heat pumps and EVs on future domestic energy demands, and strategies to mitigate their impact—typically, studies treat the two topics separately. There are some examples in the literature that look at the integrated control of EV charging within a domestic context in order to mitigate demand peaks, but the majority of work focuses on the charging of many vehicles at the community (or larger) scale. Robinson et al. [7] analysed the results from a large UK field trail of electric vehicles, where the charging times of vehicles were unconstrained and vehicles could be charged at home or when parked away from home. Their results indicated a significant amount of peak-time charging. Razeghi et al. [8] used real US domestic electricity demand data coupled with stochastic vehicle charging profiles to look at the potential impact of EV charging on distribution transformers. The authors concluded that only in the case of uncontrolled fast charging of vehicles would there be the risk of transformer overloading. The study did not include heat pumps. In a study using economic optimisation, Hedegaard et al. [9] looked at the possible impact of EV charging in Northern European countries, indicating that coordinated charging of EV's can boost investment in wind power and reduce future investment requirements for thermal power plants. However, the study did not look at the implications for the transmission and generation infrastructure.

Of the studies looking at both the dwelling and EV, Asare-Bediako et al. [10] looked at the potential effect of heat electrification using micro-CHP and electric vehicles on domestic load profiles in the Netherlands using a bottom-up modelling approach. The authors concluded that the electrical load profile characteristics changed dramatically with reduced electrical peak demand in summer and increased demand in winter. The authors did not investigate the possibility of co-operation between the house and vehicle to limit peak demand, nor did they address the issue of heat pumps. Munkhammar et al. [11] used a stochastic, high-resolution model to examine the impact of EVs on domestic load and the self-consumption of PV-generated power in Swedish housing. Their paper highlighted the increase in domestic power consumption with the introduction of EVs and also noted that in many cases the use of EVs decreased the amount of load covered by the PV. This was due to the temporal mismatch between when PV power was available and when the EV charged (typically early morning or evening). Haines et al. [12] looked at the so-called vehicle-to-home concept (V2H), using the vehicle battery to co-operatively limit the peak demand of a UK household. The authors concluded that EVs could be used to limit peak demand and improve domestic load factors, other than in cases where the EV was used for a sizable commute. However, the study did not consider electrification of heating.

1.2. Scope of the paper

In the literature, the impact of wholesale domestic electrification (extending to heating and transportation) is rarely considered, and by extension, most mitigation strategies focus on only one aspect of demand. Consequently, this paper explores a range of strategies aimed at limiting the impact of both heat pumps and EVs on the electrical demand of future dwellings. The paper examines the peak electrical demand and the increase in household electrical energy use as both will have an impact on electrical infrastructure. Increased electrical energy use will lead to higher temperatures in electrical equipment and ultimately a shortening of its lifespan. However, a radical increase in peak demand could have the most acute impact, necessitating the wholesale replacement of electrical infrastructure such as cabling and electrical transformers.

A simulation model of a hypothetical future zero-energy dwelling (described later) was used as a virtual test bed to analyse the electrical demand of the household, accounting for electrified space heating, hot water demand, appliance and home charging of vehicles. The simulation model also allowed the impact of demand management measures on other aspects of performance to be