Heat pumps and global residential heating

Tina Fawcett, Nick Eyre
& Russell Layberry
Environmental Change Institute
Oxford University Centre for the Environment
South Parks Road
Oxford OX1 3QY
UK
tina.fawcett@eci.ox.ac.uk
nick.eyre@eci.ox.ac.uk
russell.layberry@eci.ox.ac.uk

Keywords

heat pump, efficiency, residential, modelling, peak savings

Abstract

Electrification is seen as an important global contributor to mitigation of climate change, because low carbon electricity can, in theory, replace current fossil fuel use in buildings and surface transport. Heat pumps are the key technology for delivering electrification of heating. This paper investigates how heat pump adoption in the residential sector would affect total and peak electricity demand globally and for individual countries. It also analyses the role of improving efficiency in reducing heating energy demand.

A model of global heating energy use has been developed. This geographical model uses historical population-weighted temperature data, and assumptions about heating energy use and the efficiency of heat pumps to give peak instantaneous demand, calculated at three-hourly time steps. Results show that heating energy need is dominated globally by China, which is responsible for almost 40 % of the total. For the UK, 100 % adoption of heat pumps, all other things being equal, would increase national electricity demand by 25 %, and peak electricity demand by 65 %. The peak: mean heating ratio is 4.1 and would change from the current total electricity peak: mean ratio from 1.58 to 2.11. Globally, 100 % heat pump adoption would require 11 % of current world electricity use and increase peak demand by 65 %. This peak electricity capacity is unlikely to be delivered, given the huge costs entailed.

Options for reducing the peak: mean ratio, including international interconnection, and using back-up heating systems at times of extreme cold, have been modelled. The model is then used to look at how results would change with future temperatures, and with energy service demand. In particular, scenarios with a much more insulated building stock are explored – highlighting the importance of efficiency in enabling a scenario with high heat pump uptake. Thus the modelling results are linked with real world concerns and policy options, to deliver a more sophisticated understanding of the challenges of mass heat pump adoption.

Introduction

Electrification is seen as an important global contributor to mitigation of climate change, because low carbon electricity can, in theory, replace current fossil fuel use in buildings and surface transport. On the supply side, strategies for low carbon emissions by 2050 typically focus on the expansion of renewable and/or nuclear energy along with carbon capture and storage for fossil fuel electricity production. This is accompanied by electrifying both the heat and transport sectors as much as possible, requiring the provision of a charging network for vehicles, installation of new heating systems in buildings, and many other technical, economic and social changes. Residential heating is an important sector in this transformation as it accounts for a significant proportion of national energy use in countries with cold winters. In the UK 19 % of delivered energy in 2012 was used for residential heating (based on Palmer and Cooper, 2013). In the EU-28 residential heating accounts for 17.5 % of total delivered energy (Lapillonne and Pollier, 2014).

Electrification in the residential sector is expected to be delivered via heat pumps. Heat pumps take low temperature heat from the environment and turn it into higher temperature heat by using electrical energy. An efficient heat pump will have a seasonal performance factor of 3 or above, meaning that annually 3 units of heat will be delivered for every unit of electricity used. The most common types of heat pumps are air source heat pumps (ASHP), which absorb energy from the air, and ground source heat pumps (GSHP) which absorb energy from the ground using a dedicated borehole or network of buried pipes. ASHP are expected to have biggest global reach as, unlike GSHP, they entail no specific land requirement. There is no technology to rival heat pumps for efficiently using electricity to deliver residential and commercial space heating. The low carbon alternatives to heat pumps include district heating using renewables as the heating fuel, household-level use of biofuels, and super-insulation of all new and existing homes to reduce heat demand to very low levels. While these options are also important, it is difficult to imagine a low carbon future in which heat pumps are not a significant part of the solution.

Heat pumps are already used for heating in many countries around the world, but are most often a minority technology. Ownership of heat pumps is very varied within the EU, but generally increasing. Latest European figures for 2012 show a range of household ownership, from 20.1 % in Sweden and 17.8 % in Finland, to 5 % in France, 3.2 % in Austria, 1.2 % in Germany and 0.3 % in the UK (ODYSSEE-MURE, 2015). Note that the ownership figures for Sweden and Finland have more than doubled since the previous version of the statistics, as published in 2014, so should perhaps be treated with caution. These statistics cover all heat pumps, including those primarily used for cooling, so they may overstate the percentage of households which use them for heating, particularly in warmer countries. This is certainly the case in Italy, where 61.8 % of households are reported to own heat pumps, but the 'vast majority' are solely or primarily used for space cooling (Eurobserver, 2013). Six countries are responsible for more than 80 % of the energy produced from heat pumps within 21 European countries: France, Sweden, Germany, Italy, Norway and Finland (EHPA, 2014).

Within the EU, heat pumps are classed as renewable as long as they have a seasonal performance factor (SPF_{H2}) of greater than 2.5 (EU Renewable Energy Resources Directive). In order to make use of renewable, low temperature environmental heat, whether from air, water or the ground, heat pumps need to make use of electricity or another form of energy, which may be non-renewable. The EU definition aims to ensure that only heat pumps with an output that exceeds the (potentially non-renewable) primary energy input are classed as renewable. This definition could be contested, on the grounds that heat pumps might currently produce little net renewable energy. However, as electricity systems move towards renewable/low carbon sources of energy, to meet climate goals, it should become less of an issue. All member state governments have targets to meet on renewable energy, and heat pumps are expected to help meet these targets. Many nation states have policies in place to encourage the uptake of heat pumps through a variety of financial incentives (e.g. Germany, France and the UK) and regulations restricting the use of alternative heating systems (e.g. Denmark). Thus this technology is expected to be increasingly important in the residential sector.

Widespread use of heat pumps for residential heating would pose a number of challenges to the electricity system. Electricity demand would significantly increase. This is because the majority of heating in the EU (and worldwide) is currently not provided via electricity, so a switch away from natural gas, heating oil or biomass towards heat pumps would increase electricity demand. For heat pumps to contribute to reducing carbon emissions, new electricity capacity would have to be predominantly low carbon, and therefore relatively high capital cost. In addition, the demand in countries with an existing winter peak (nearly all EU countries) would be at peak times. In electricity systems where summer demand currently constitutes the peak, high use of heat pumps could result in a change to a winter peak (Waite and Modi, 2014). The challenges heat pumps pose come at a time when many other changes are also anticipated. Current developments include the installation of smart meters, smart grids, increasingly distributed and intermittent generation with the rise of small and large-scale renewables, and internationally interconnected grids.

This paper focuses on the potential contribution of heat pumps to delivering space heating energy use in the residential sector. The paper will present original modelling work on the effect of heat pump adoption on electricity system peaks globally and for individual countries, and discuss these findings in the context of other challenges to electricity networks and policy options to encourage a transition to heat pumps.

Modelling global uptake of heat pumps

Our modelling looks at heat pumps as a global technology.

The specific aims are:

1. To calculate residential heating energy need in each country of the world.
2. To calculate total electricity demand and peak: average demand per country if all heating were supplied via heat pumps.
3. To look at how the peak: average ratio would change if there is an assumption of perfect interconnection between countries.
4. To look at the effect on model outputs of variations in future temperatures, and changes to the relationship between external temperature and heating requirements.

This model is well suited to looking at peak demand as well as annual demand, due to the 3-hourly time resolution used.

METHODS

The modelling method is explained in three steps.

Step 1: Calculating degree hours

Population-weighted heating degree hours are calculated for each country at three-hourly intervals. Heating degree hours (more commonly reported as heating degree days) are a measure of the severity and duration of cold weather. They are a summation over time of the difference between a reference or 'base' temperature and the outside temperature, so the colder the weather the larger the degree hour value. The base temperature is the temperature below which heating is assumed to be needed. This research uses 15.5 °C, the figure generally used in the UK[1].

1. In well insulated buildings, incidental gains from occupants, internal energy use and solar gains can keep a building warm to higher temperature and therefore a lower base temperature would be justified.

We have used the following data

- World population data for 2000 at a spatial resolution of 0.25 degrees (data from http://iridl.ldeo.columbia.edu/SOURCES/.CIESIN/.Poverty/.global/.beta/.grid0p25deg/.ancillary/.pop2000/). The population grid is on the finest spatial resolution (0.25 degrees), so the other grids were re-interpolated to the population resolution.
- Country mask files – which relate the spatially defined temperature and population data to country borders.
- 3 hourly gridded temperature data from ECMWF (European Centre for Medium-Range Weather Forecasting) for 2012.

Three-hourly temperature data was used to derive heating degree hour figures per weather station, and these figures combined with population and geographical data to create a population-weighted degree hours grid, which can be split into individual countries.

Step 2: Calculating residential heating need

Assuming all countries have UK levels of heating service demand, UK residential energy figures[2] for 2012 (Palmer and Cooper, 2013) are used to scale from degree hours to delivered energy use. The resultant modelled figures are called 'energy need' (to distinguish them from actual energy demand statistics). This step of the calculation is clearly a simplification of the real situation where the heated square metres per person, efficiency of heat production and use, energy sources, internal temperature and hours of heating will vary from country to country, giving varied relationships between degree hours and heating energy delivered. UK figures are used because there is either no or incomplete data available on residential energy use for many countries, including China, which dominates global results.

For EU countries, it should be possible to use national figures, instead of using the UK figures as a proxy. Figures for annual residential heating energy use are collated by Odyssee, and are available for most countries for 2012. However, they are published only as 'climate corrected' figures, not actual consumption figures. The method used by each country to calculate residential heating figures is also unstated. So, using these figures without further work could introduce different sources of error.

Step 3: Calculating electricity demand

The assumption in this step is that all heat pumps are air source heat pumps, using a seasonal performance factor which varies according to external temperature based on an equation identified in (Baster, 2011). Because of this, colder countries have a lower seasonal performance factors than warmer ones – so the UK's figure is 3.3, whereas that for China is 2.8 and Russia 2.5. These figures are technologically optimistic, as they exceed average current performance. Assuming that all heating demand is met by heat pumps is a deliberately extreme scenario, and is not intended as a realistic vision of the future.

2. A simple assumption that 80 % of delivered heating energy was 'useful energy' was made, based on the average efficiency of installed gas boilers, the UK's most common heating system.

RESULTS

Heating energy need

The results from calculation of heating energy need (Table 1), shows that it is dominated globally by China, which is responsible for almost 40 % of total demand (compared with China's share of global population – 19.3 % according to UN, 2013). About 550 million people (40 % of China's total population) live in China's cold and severe-cold zones (Baeumler et al., 2012). Only two EU countries feature in the top ten. Germany is fourth, and the UK is ninth on this list of countries ranked by residential energy need. Between them, the top ten countries account for 72 % of global demand.

Some other facts which emerge from this analysis:

- 90 % of global residential heating need comes from 27 countries – all in the Northern hemisphere.
- Together the EU-28 countries account for 14.9 % of global heating demand, with the top five countries being Germany (3.1 %), the UK (1.8 %), Poland (1.7 %), France (1.5 %), Italy (1.3 %).
- Southern hemisphere countries have very low heating energy need – less than 2 % of global total.
- 63 countries have zero heating need, with tens of others close to zero.

PEAK AND AVERAGE

As explained, using the UK relationship between heating degree hours and energy demand is unlikely to represent the current situation in other countries accurately – so the figures generated by this model for peak and mean electricity demand have to be viewed with caution (Table 2). However, the ratio between these is much more reliable (given the assumptions made). For the UK, the ratio between peak and mean electricity demand is 4.1, for the EU-28 6.1, for China 5.0 and for the world 5.7.

Figures are also given for peak demand if 95 % of heating demand is met, that is to say energy demand is met for all but the highest 5 % of three-hourly instantaneous demands. This makes a considerable difference to the peak: mean ratios, which fall from 4.1 to 2.8 for the UK, and to 3.2 for the EU-28. The

Table 1. Residential energy heating need – top ten countries (modelling results).

Country	% global heating demand	Cumulative % global heating demand
China	39.2	39.2
Russian Federation	9.8	48.9
United States	6.6	55.5
Germany	3.1	58.6
Japan	2.9	61.5
India	2.8	64.3
Pakistan	2.1	66.4
Ukraine	2.1	68.5
United Kingdom	1.8	70.3
Iran	1.7	72.0

95 % calculation reflects to some extent how heating systems are sized in real life.

Peak electricity demand is also calculated for the world assuming that there is a perfect electricity grid. The peak here (world – with grid) is the highest demand across all countries in one three hour period, rather than the sum of the highest demand in each country in any three hour period.

To contextualise the outputs in Table 2, the UK figures are compared with 2012 data on electricity demand. In 2012, average total electricity demand for all uses in the UK was 36.3 GW and the maximum load was 57.5 GW – a ratio of peak to mean of 1.58 (DECC, 2014). The mean electricity demand of 9.1 GW would increase national electricity demand by 25 %, and peak electricity demand by 65 % if 100 % of heating energy was delivered. In that case, the peak: mean ratio increases to 2.11. Peak electricity would rise by 44 % if 95 % of demand was met. Globally, the current electricity capacity is 5,331 GW (US Energy Information Administration, 2014) which shows the huge scale of the peak global demand of 3,353 GW. Meeting the mean electricity demand of 100 % heat pump adoption would require 11 % of current world electricity use.

Results for different climates and more highly insulated housing stock

The poster presented at the conference will include variations of the analysis with higher external temperatures and with a more insulated housing stock (achieved by changing the figure used for the 'base temperature'). Higher external temperatures are modelled by adding 1 or 2 °C to the 2012 temperature data used in the model. A climate forecast is not used, because these are subject to considerable uncertainty, (see e.g. IPCC's range of possible future temperatures given particular CO_2 concentrations) and have limited credibility at the regional scale.

Both higher external temperatures, and lower heating demands at a given temperature (achieved, say, by better insulated buildings) will reduce the amount of electricity required. This will decrease the investment needed to supply peak electricity. However, the issue of peak: average ratios for heating remains – how serious this is will depend on the proportion heating electricity demand is of total national demand.

Discussion

As our modelling shows, the increases in peak demand are considerably greater than those for average demand, and this is the key challenge presented by heat pumps at the national and international scale. Even supplying 95 % of heating will result in a very high peak: load ratio in the UK, the EU-28 and globally. This peak electricity capacity seems unlikely to be delivered, given the huge costs entailed.

So, how can the peak: mean ratio be reduced, while using heat pumps to deliver a high percentage of residential heating? One option is to install gas or biomass systems in parallel with electric heat pumps, to be used at times of high electricity demand (so-called hybrid systems). This option is receiving some policy attention (see Eyre and Baruah, 2014 for further discussion). As our modelling showed, international interconnection should be able to help reduce peak demand (where peaks are calculated per three hourly intervals, i.e. we are not considering very short term peaks). A more radical option is simply not to meet peak projected demand, and to assume people will accept lower indoor temperatures, with demand being managed through price structures or other rationing systems. Better insulated homes have a longer response time to cold weather, so they can help manage demand diurnally, but not seasonally. Presently, seasonal heat storage does not exist beyond the experimental stage. Smart heat pumps and smart electricity grids could help smooth the peaks, although again this is likely to be of limited influence seasonally. It's not clear if any of these measures, or even all of them in combination, will be sufficient to reduce the peak: mean ratio to economically/technically viable levels.

The results of this model are similar to those produced by a more complex one by Eyre and Baruah (2014), which included future socio-economic trends, and made different assumptions on uptake. This does not validate our model, but suggests it provides a useful basis for discussion. Eyre and Baruah's results suggested that very high electrification of residential space heating in the UK might result in a electricity demand space heating load of 75 TWh/year, and increase winter peak to 40 GW, requiring with generation investment costs of almost £2,000 (€2,600) per household. This model's results were 80 TWh/yr electricity demand and a peak demand of 37.6 GW.

A 100 % heat pump scenario belongs to the future. Our modelling used current population figures and current climate – how would using future projections of these change the results? Most growth in population is expected in developing countries without a significant heating demand. Population in China in 2050 expected to be very similar to that in 2013, and falling population is expected in a number of developed countries, including the Russian Federation, Japan and Germany (UN, 2013). Global temperatures are expected to continue to rise (IPCC, 2013). Thus, all other things being equal, heat demand

Table 2. Modelled peak and average electricity demand for residential sector heating, UK, EU-28, China and World.

	UK	EU-28	China	World – no grid	World – with grid
Mean electricity demand (GW)	9.1	81.3	232	582	582
Peak electricity demand (GW)	37.6	499	1,172	3,353	2,325
Peak electricity if 95 % heating demand met (GW)	24.2	260	793	2,029	1,774
Ratio Peak: Mean	4.1	6.1	5.0	5.7	4.0

should fall into the future and with it the electricity needed for residential heating. In the UK this effect is about 10 % per degree of warming, so it is an important effect.

Scenarios for low carbon heating systems (e.g. Eyre and Baruah, 2014) indicate that only energy efficiency and greater use of biofuels (either directly or via mains biogas) offer serious alternatives in the provision of low-carbon thermal comfort. So, given the issues involved with delivering electrification of heating, a more robust policy framework will also include making progress with other significant options. These include:

- deep energy efficiency retrofits, e.g. to Passivhaus standards
- direct use of biomass in heating, e.g. wood-fired boilers in rural applications
- district heating systems in urban centres based on renewable (including waste) fuels, and
- integration of biogas from a variety of sources into the gas network.

Our preliminary modelling work has many limitations. It is a deliberately simple model, used to get an overview of peak: average electricity demand issues for residential heating. We have not looked at interactions with other changes in the electricity system, other changes in electricity demand (particularly for electric vehicles), or the relationship of electricity use to carbon emissions, amongst other issues. Nor have we tried to generate a realistic scenario of uptake of heat pumps. It is a model which has been designed to answer a limited set of questions.

The key research question emerging from this work is: does the peak issue set a limit on the percentage of residential heating demand that can be met by heat pumps, and if so, what is it?

Conclusions

Electrification of residential heating is expected to be an important contributor to mitigation of climate change, with low-carbon electricity replacing fossil fuels. Heat pumps enable efficient use of electricity for heating. However, their mass adoption would increase peak electricity demand by adding to existing winter peaks, exacerbated by their increasing inefficiency at lower temperatures. The high economic and environmental costs of increased peak capacity could delay or prevent electrification, blocking a significant low-carbon option, for heating and other end-uses. Thus, the relationship between heat pumps and peak electricity demand needs further exploration, as do the options for reducing the ratio of peak: average demand.

References

Baeumler, A., Ijjasz-Vasques, E., Mehndiratta, S. (Eds.), 2012. Sustainable low-carbon city development in China. World Bank, Washington DC, USA.

Baster, M., 2011. Modelling the performance of air source heat pump systems, Department of Mechanical Engineering. University of Strathclyde, University of Strathclyde.

DECC, 2014. Digest of UK energy statistics. Department for Energy and Climate Change, London.

EHPA, 2014. European heat pump market and statistics report 2014: Executive summary. European Heat Pump Association, Available: http://www.ehpa.org/market-data/2013/?eID=dam_frontend_push&docID=2224 [accessed January 2015].

Eurobserver, 2013. Heat pumps barometer, http://www.energies-renouvelables.org/observ-er/stat_baro/observ/baro218_en.pdf [accessed January 2015].

Eyre, N., Baruah, P., 2014. Uncertainties in energy demand in residential heating: Working paper. UKERC, London.

Lapillonne, B., Pollier, K., 2014. Energy efficiency trends for households in the EU. Mure / Odyssee, Published on the web: www.odyssee-mure.eu/publications/efficiency-by-sector/household/household-eu.pdf [accessed March 2014].

ODYSSEE-MURE, 2015. Share of dwellings with renewable heat pumps, http://www.indicators.odyssee-mure.eu/market-diffusion.html#market-diffusion/share-of-buildings-with-heat-pump-stock.html [accessed January 2015].

Palmer, J., Cooper, I., 2013. United Kingdom housing energy fact file 2013. Department for Energy and Climate Change, London.

UN, 2013. World population prospects: The 2012 revision. United Nations, New York.

US Energy Information Administration, 2014. International Energy Statistics, On line data at:http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7 [accessed 28th August 2014].

Waite, M., Modi, V., 2014. Potential for increased wind-generated electricity utilization using heat pumps in urban areas. Applied Energy.

Acknowledgements

This work was supported by the UK Energy Research Centre supported by the UK Natural Environment Research Council under grant number NE/G007748/1.