A daily representation of Great Britain's energy vectors: natural gas, electricity and transport fuels.

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ABSTRACT

In much of Europe there is a strong push to decarbonise energy demands, including the largest single end-use demand – heat. Moving heat demands over to the electrical network poses significant challenges and the use of hybrid energy vector and storage systems (heat and electrical storage) will be a critical component in managing this transition. As an example of these challenges facing many developed countries, the scale of recently available daily energy flows through the UK's electrical, gas and transport systems are presented. When this data is expressed graphically it illustrates important differences in the demand characteristics of these different vectors; these include the quantity of energy delivered through the networks on a daily basis, and the scale of variability in the gas demand over multiple timescales (seasonal, weekly and daily). As the UK proceeds to migrate heating demands to the electrical network in its drive to cut carbon emissions, electrical demand will significantly increase. Additionally, the greater variability and uncertainty shown in the gas demand will also migrate to the electrical demand, posing significant difficulties for the maintenance of a secure and reliable electrical system in the coming decades. The paper concludes an analysis of the different means of accommodating increasingly volatile electricity demands in future energy networks.

KEYWORDS

Decarbonising heat; energy vector data.

INTRODUCTION

This paper presents recent historical daily energy flows through Great Britain's electrical, natural gas and transport networks to illustrate the significant differences in the demand characteristics of these main energy vectors. Of particular note are the differences in temporal variability and magnitude. On a daily basis the total natural gas demand can be approximately four times the electrical demand in winter; natural gas demand also exhibits significantly higher volatility. Conversely, daily electrical demand is more predictable and less subject to seasonal variation. These differences have profound implications when considering the potential transfer of heat demands from the natural gas network to the electrical network in order to 'decarbonise heat' as envisaged in the UK Climate Change ACT (UKCCA, 2008). The data analysed spans the period from October 2010 to September 2013.

UK Policy Background

The UK Climate Change Act set forth legally binding targets to reduce UK greenhouse gas emissions to 20% of their 1990 levels by 2050. The 2011 Carbon Plan states 'By 2050, electricity supply will need to be almost completely decarbonised' (DECCa, 2011). It is anticipated that electrical supply decarbonisation will be achieved by deploying a wide range of low-carbon technologies such as renewables, sustainable biomass, nuclear, and fossil fuels with carbon capture and storage. In parallel, the UK has also adopted a range of policies aimed at reducing energy demand, including a radical strengthening of building regulations (DCLG, 2012) and decarbonisation of the energy required for heating. The area of low-carbon heat is justly receiving increased attention, as evidenced by reports from the Department of Energy and Climate Change (DECCb, 2013) and the Royal Academy of Engineering (RAEng, 2012).

UK Heating and hot water demand

UK energy consumption in 2011 for space and water heating for all sectors (domestic, service, industry and transport) was 517 TWh. Energy used for domestic space and water heating accounts for just over 70% of this total (363 TWh). By comparison, the overall total final energy consumed for ALL sectors for electricity in 2011 was 312 TWh *i.e.* only 86% of overall domestic space and water heating in energy consumption terms. The vast bulk of the energy needed to meet UK domestic space and water heating demands is provided by the combustion of natural gas (286 TWh), with the balance met using electricity (29 TWh), heating oil (31 TWh), solid fuels (9 TWh), bioenergy and waste (7 TWh), heat sold (1 TWh), solar thermal or indeed a combination of these. All the values are sourced from ECONUKa (2013), and although these annual data provide useful comparisons and trends, it is only when energy flows are considered on a more granular level that differences between the energy vectors become increasingly apparent.

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- Natural Gas data were sourced from National Grid's data explorer (NGDIE, 2013) due to its granularity down to a single day as well as helpful demand categorisations.
- Transport fuel data were sourced from the energy trends spreadsheet 'Deliveries of petroleum products for inland consumptions (ET 3.13)' (DECCc, 2013). This is available at a granular level of 1 month.
- Electricity Data was sourced from either the 'Metered half-hourly electricity demands' data from National Grid's website (MHHED, 2013) or through Elexon's Portal (EP, 2013). This is available at a granular level of 5 minutes and a half-hour.

The various data sources were recalculated into comparable kWh / day format in order to be comparable on a daily basis.

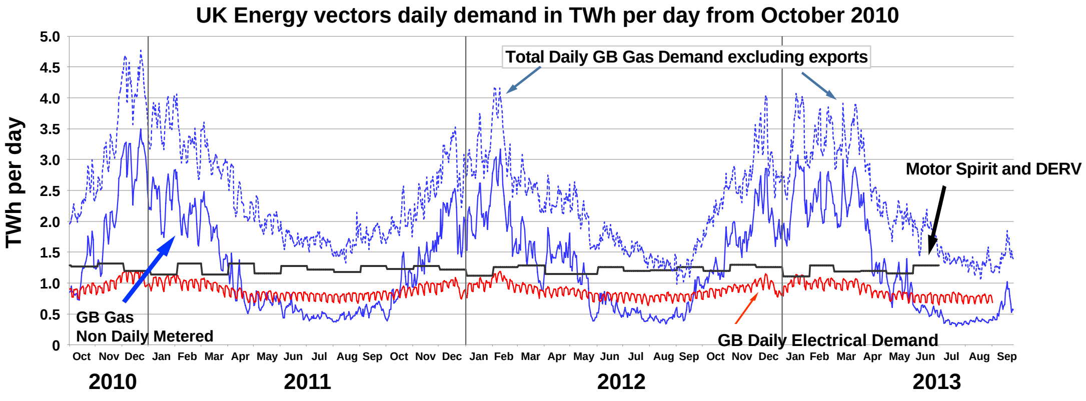

Figure 1. Daily GB Gas and Electricity and transport fuels (TWh). Data sources NGDIE (2013); MHHED (2013); DECCc (2013)

Figure 1 uses this data to show Great Britain's (GB) daily natural gas, electrical[1] and transport vectors in Terawatt hours. This TWh/day natural gas total includes gas to power stations, industry, storage and the daily and non-daily metered demands, but excludes exports. Figure 1 also shows the non-daily metered (NDM) component of this total daily natural gas demand, which is comprised of gas metering equipment that are not measured on a daily basis, *e.g.* domestic, small business, and a proportion of commercial, public administration, agricultural and even some industrial facilities. However, natural gas for domestic space heating, hot water and cooking is the major part of the NDM component.

Figure 1 shows the very different characteristics of gas and electricity demand. In winter, the NDM gas demand alone can be up to three times the total electrical demand, whilst dropping below electricity in the summer. In addition to seasonal variability, the gas demand also shows striking shorter-term daily and weekly volatility linked to weather conditions and the resulting requirement for heat. The NDM component is the largest source of the seasonal variation of the total gas demand, *e.g.* the 2011 daily values ranged between 0.368 TWh/day and 3.49 TWh/day. In contrast, the daily electrical demand showed a seasonal variation between 0.675 TWh/day and 1.2 TWh/day over the same period. It is also noteworthy that over two contrasting winters of 2010 and 2011 covered by Figure 1, which were cold and mild respectively, the peak values were broadly similar although their timing was not.

It is important to note that NDM gas flows are not constant throughout a day but are instead concentrated in the morning and evening, when space and water heating demands are highest (Buswell *et al*. 2013; Sansom, 2013). Analysis of sub-daily gas demand data would show even greater variability of the gas demand than shown in Figure 1, and it would prove useful to further compare and contrast with sub-daily electrical data. However, national sub-daily gas demand data are not readily available for the GB natural gas network.

The extreme variation shown in Figure 1 natural gas flows is routinely catered for by existing gas infrastructure, as to-date there have been no widespread problems of availability of natural gas throughout the year to the NDM end user. The gas network is balanced throughout the day, with increased gas pressure in parts of the network (linepack) used as a buffer of energy to provide increased gas supply to meet diurnal peaks in demand. By comparison, the electrical network has to be kept in balance on a near instantaneous basis and thus is crucially different in its operation and management.

Impact of the shift to electrical heating

A wholesale transfer of the NDM gas demand seen in Figure 1 to the electrical network is highly unlikely given that space heating demand in the domestic sector is set to fall over time due to the increase in energy efficiency of the building stock (Palmer and Cooper, 2011). Furthermore, the electrification of heat will be a gradual process rather than a sudden switchover. However, even a partial electrification of domestic heating demand will have serious implications for the UK's ageing electrical transmission and distribution networks. To illustrate this point, Figure 2 shows part of the same data used for Figure 1, but with 30% of the NDM demand transferred over to the electrical network. Thus the NDM data has been reduced by 30% and the electrical data increased by a corresponding amount scaled by a

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[1] The daily electrical data is aggregated from the half hourly demand data (termed IO14_TGSD) also from National Grid (MHHED, 2013).

coefficient of performance (COP)[2]. Figure 2 shows the result of this transfer using two different electrical heating technologies.

If this transfer of 30% of NDM heat demand was serviced by resistive elements for space and water heating, this results in the upper demand curve labelled COP1. Alternatively, if the transferred demand is met using heat pumps with an average COP of 3 (EST, 2010) [3] then the impact on the total daily electrical demand is shown on the middle demand curve labelled COP3. The original GB daily electrical demand from Figure 1 is shown as the lower curve for comparison.

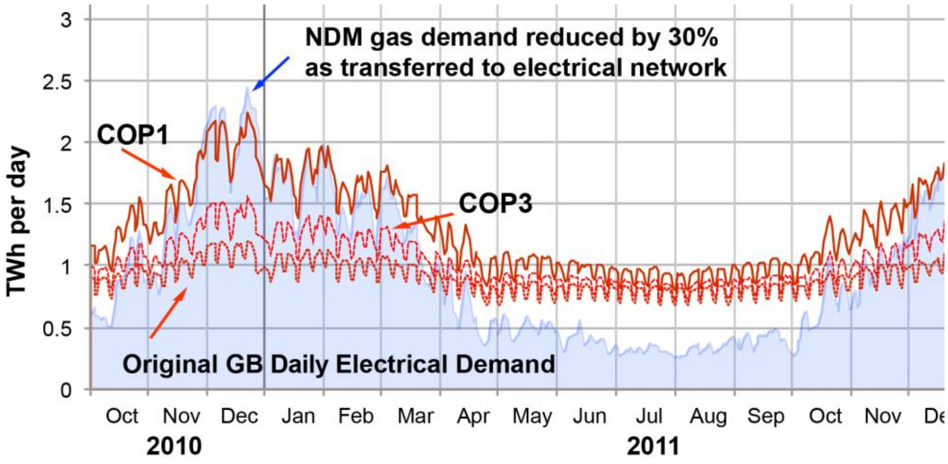

Figure 2. Transfer of heat and hot water demand from Gas to Electrical network using historical data.

Shifting 30% of NDM heat demand to purely resistive heating results in the daily electrical demand almost doubling during periods of high heating demand during the winter months. If heat pumps are used to meet this heating load then the daily electrical demand is still around 25% larger at times of high daily demand. Thermodynamically, the best option for the electrification of heat is to use ground or air source heat pumps. However, the capital and installation costs of heat pumps are significant and, for new build and retrofit dwellings with small space heating demands, developers may favour resistance heating as a low-cost alternative. So, realistically, the electrification of heat would undoubtedly involve a range of technologies including resistive storage heating, direct resistive heating, air source and ground source heat pumps. The actual impact is therefore likely to lie between these two extremes (COP-1 and COP-3) shown in Figure 2.

Whilst this basic analysis uses historical daily demand data to illustrate a future scenario, it is striking that even a partial shift of the NDM demand to the electricity system results in a substantial increase in daily electrical demand. It is worth reiterating that this study only considers the daily energy use, which will significantly understate the variability in instantaneous power demands on the electrical network. In short, electrical networks are engineered to cope with both peak power requirements and particular load factors, so the reality of changing either one of these design parameters will require upgrades to existing network infrastructure. Also when considering the potential to shift at least some of the extra

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[2] Coefficient of performance is the ratio of the useful heating effect of a technology to the primary energy consumption. In the case of electric resistance heating COP is 1. For ground source heat pumps the COP is approximately 4 and for air source heat pumps the COP is 2-3.

[3] This is an optimistic COP value, reflecting improvements in the technology and installation practice. UK field trials revealed far poorer performance in real heat pump systems, predominantly due to poor quality design and installation in buildings (EST 2010).

demand arising from the electrification of heat to off-peak periods, this will be dependent upon the provision of *substantial* quantities of local thermal storage. For example, Arteconi *et al.* (2013) estimate that 800L of thermal storage are required to provide one hour load shifting in a heat pump serving an average UK dwelling; Hong *et al.* (2012) estimate that around 500L of hot water buffering is required to shift the demand of a heat pump to off peak periods when serving a very well-insulated UK dwelling (and only with dramatically improved insulation levels). Clearly, not all dwelling types could accommodate such substantial thermal stores. Further, the use of thermal storage itself can lead to an increase in overall heating demand due to additional parasitic heat losses from the thermal stores and reduced heat pump performance (Kelly and Hawkes, 2013) and so load shifting alone cannot be relied upon to circumvent substantially increased peak electrical demands.

The clear message that can be taken from Figure 2 is that without substantial investment in transmission and distribution infrastructure, the UK electricity system is unlikely to be able to accommodate even a fraction of the additional power requirements associated with the transfer of heat demands at current levels, and this is even before any consideration of the additional electrical demand from possible electrification of transport. The vector flows for the aggregated value of the motor spirit (gasoline) and DERV (diesel) is also shown in Figure 1, and although the data is only available on a monthly basis – it can be seen that the seasonal variation of this aggregate vector is clearly much less than seasonal variation seen in natural gas.

Mitigating the Impacts of the Electrification of Heat

There is a clear need to find solutions to help lessen the impact of heat demand transfer to the electrical network (a major source of the absolute amount and seasonal variability of the NDM gas demand); perhaps deferring or even mitigating the extent of required infrastructure investment.

Domestic Energy Efficiency

Reducing domestic heating requirements by improving the insulation levels of dwellings is an obvious and critical place to begin, as this both reduces fuel costs for householders and improves the quality of the indoor environment. Transformational improvements are possible, for example, low carbon housing has been demonstrated to reduce heating demand by up to 90% (Feist *et al*. 2001). Realistically, however, such dramatic improvements in fabric energy efficiency are achievable only with new-build housing. Whilst substantial improvements in performance in existing dwellings are also achievable by retrofitting energy efficiency measures, the trend improvement is likely to continue to be gradual (Palmer and Cooper, 2011) as performance improvement measures are implemented over time by homeowners; it is therefore likely that there will be a substantial domestic space heating demand well into the future. It is therefore unlikely that heat demand will be significantly less in the short to medium term, particularly in older and so-called ‘hard-to-treat’ houses, which form up to 40% of the housing stock, where a combination of the building fabric and location limit the scope for retrofitted energy efficiency improvements (BRE, 2008). Over the long-term however, it is expected that energy efficient housing may attract a premium price over energy inefficient housing – but this is speculative due to the locational nature of housing prices.

Biomass Heating

Action to reduce peak heat demand on the electrical network could also be augmented by greater use of lower-carbon fuels that can be stored (such as biomass). Consideration of policies to encourage the planting of biomass in the UK, in order to provide local biomass resources in the future may be a worthwhile addition to more technology focussed directions.

Improving Heat Pump Performance

Improving the COP of heat pump technologies could reduce the impact of the progressive electrification of heat on the electrical network. The results of heat pump field trials undertaken in the UK (EST, 2010) indicate that there is significant scope for improvement in the performance of heat pumps integrated into buildings. Advances in heat pump technology such as improved compressor design and better performance at higher temperatures offer one potential route to higher COPs (Hewitt *et al.* 2011). However, further improvements could also be derived from better heat pump system design and integration, and better training of installers and users (Caird *et al.* 2012; Owen *et al.* 2012).

Seasonal Heat Storage

The use of larger heat stores (multi MWh) with storage times into the weekly/monthly or even seasonal time-scales (Lund *et al.* 2010) used in conjunction with solar energy has the potential to decrease some of the variation in energy supply seen in Figure 1, as some of the winter heat demand could be met using a local heat store, rather than drawing from the gas or electrical grid. However, a step change in both cost and volumetric energy density compared to sensible and latent heat methods is seen as important to allow this particular timescale of storage to be further developed. Thermal storage using reversible chemical reactions such as hydration or carbonation (Cot-Gores *et al.* 2012; Wongsuwan *et al.* 2001; Sharma *et al.* 2009) is a promising area. Reactions producing distinct phases on the addition/removal of heat allow products to be separated and stored, which permits the storage of heat over longer periods and renders seasonal heat storage more of a possibility.

CONCLUSION

Regardless of the future path of primary energy supply to the UK, the domestic heat demand in winter will continue to be much greater than in summer, and as the UK moves away from the seasonal flexibility provided by natural gas (for reasons of price, availability or embedded CO_2), then suitable methods to cope with the higher winter heating demands and variations over different timescales will be necessary.

The comparison of the recent daily gas and electrical energy flows in Great Britain's electrical and gas transmission networks indicates that serious challenges arise when an increasing amount of the heat demand is met from the electrical network. Even allowing for future improvements in domestic energy efficiency and electric heating technologies such as heat pumps, the UK's ageing electrical system could still see a significant rise in daily energy flows, which would result in significant upgrading costs to cope with increased peak flows.

Some measures to mitigate the potential impact on the electricity network were highlighted including; radical demand reduction measures, electrical heating technology improvements, biomass heating and heat storage. Each measure has limitations and consequently a combination of measures should be considered desirable in order to ease the transition of domestic heat demands from the gas to the electrical network. However, reducing the overall heat demand by making the built environment increasingly energy efficient should continue to be the cornerstone of all policies.

Finally, the importance of the correct level of data cannot be overstated in order to provide insights into the challenges ahead. The right kind of data is a prerequisite to the understanding and transition of any energy system and having hybrid data from different energy vectors provides a greater understanding than a single vector would provide. Better whole systems data should lead to better insights and therefore some hope of better choices in energy systems transitions.

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