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Communication

Historical daily gas and electrical energy flows through Great Britain's transmission networks and the decarbonisation of domestic heat ☆

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ABSTRACT

Publically available data is presented comparing recent historical daily energy flows through Great Britain's electrical and gas transmission networks with a focus on domestic heat and hot water. When this data is expressed graphically it illustrates important differences in the characteristics of the gas and electricity demand; these include the quantity of energy delivered through the networks on a daily basis, the scale of variability in the gas demand over multiple timescales (seasonal, weekly and daily) and the relative stability and predictability of the electrical demand. As the United Kingdom proceeds to migrate heating demands to the electrical network in its drive to cut carbon emissions, electrical demand will increase, but equally importantly the variability and uncertainty shown in the gas demand will also migrate to the electrical demand, which suggests both technical challenges and opportunities for management of future energy networks.

1. Introduction

This communication presents historical daily energy flows through Great Britain's electrical and gas transmission networks illustrating the significant differences in the demand characteristics of these two main energy vectors. Of particular note are the differences in temporal variability and magnitude. On a daily basis the total gas demand can be approximately four times the electrical demand in winter; 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 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 January 2013.

2. 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).

3. UK heating and hot water demand

UK energy consumption in 2011 for space heating and hot water for all sectors (domestic, service and industry) was provisionally 497 TWh (ECONUKa, 2012). Energy used for domestic space heating and hot water accounts for the majority of this total (354 TWh). By comparison, the overall final energy consumed for

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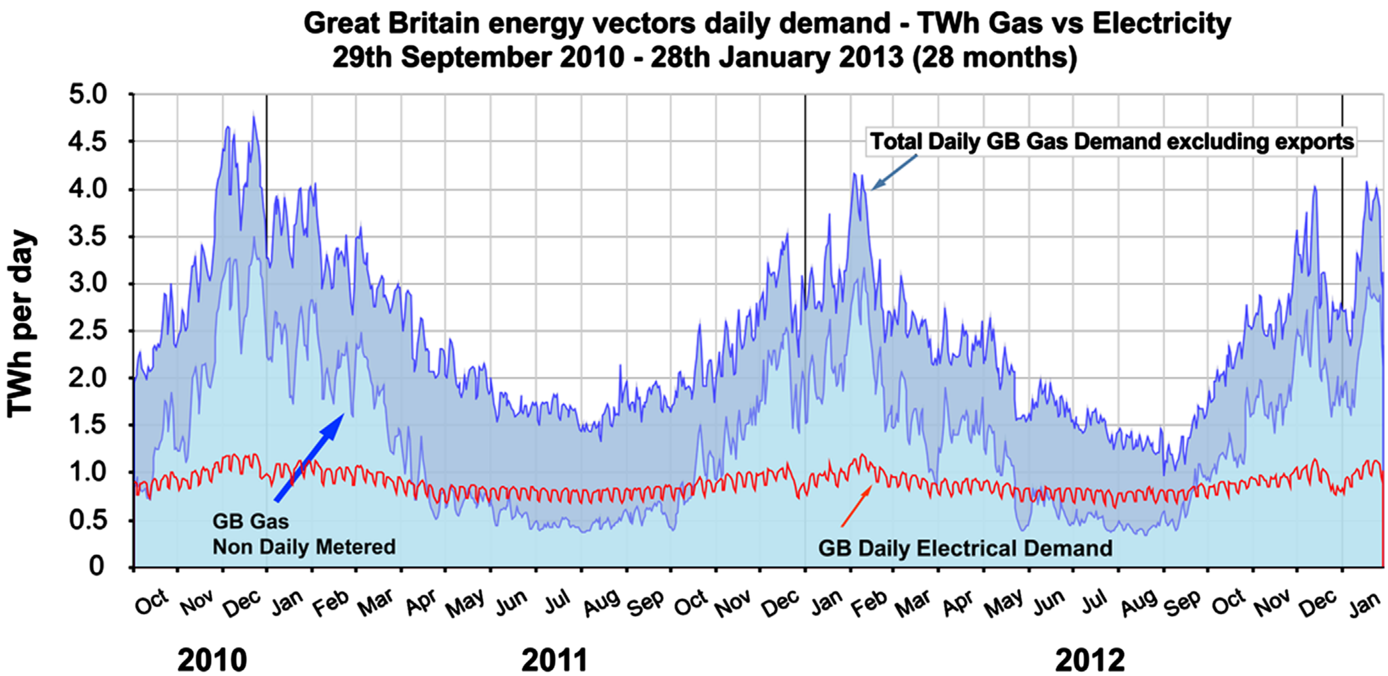

Fig. 1. Daily GB Gas and Electricity Demands (TWh). Data sourced from National Grid website (NGDIE, 2013; MHHED, 2013).

ALL sectors for electricity in 2011 was 318 TWh (ECONUKb, 2012). The vast bulk of the energy needed to meet UK domestic space heating and hot water demands is provided by the combustion of natural gas (286 TWh), with the balance met using electricity (20 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 (ECONUKa, 2012).

Tackling overall energy use and emissions associated with domestic heating and hot water therefore has to be an integral part of the UK's decarbonisation strategy. Effectively, decarbonisation of domestic heating requires that a major part of space and water heating energy demands be transferred over from the natural gas network to the electrical network.

4. Daily gas and electrical demand

In order to explore the variation in gas demands over time, gas data from the National Grid's data explorer (NGDIE, 2013) was chosen due to its public availability and granularity of a single day. Fig. 1 uses this data to show Great Britain's (GB) daily gas demand in Terawatt hours for natural gas through the national transmission system. This TWh/day total includes gas to power stations, industry, storage and the daily and non-daily metered demands, but excludes exports.

Fig. 1 also shows the non-daily metered (NDM) component of this total daily gas demand, and the total amount of energy delivered through the UK's electrical system over the same period [1].

The non-daily metered (NDM) component of the total GB gas demand is comprised of gas meters 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, gas for domestic space heating, hot water and cooking is the major part of the NDM component.

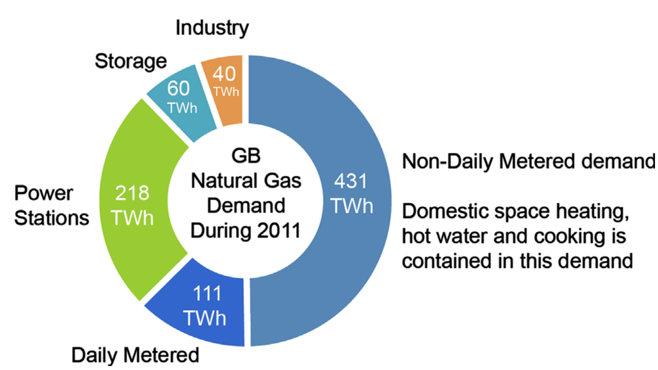

Fig. 2. Breakdown of 2011 UK gas total demand by component (excluding exports). Data sourced from National Grid website.

Fig. 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 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 shows a seasonal variation between 0.675 TWh/day and 1.2 TWh/day. It is also noteworthy that over two contrasting winters of 2010 and 2011 covered by Fig. 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 heating and hot water 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 Fig. 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 UK.

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

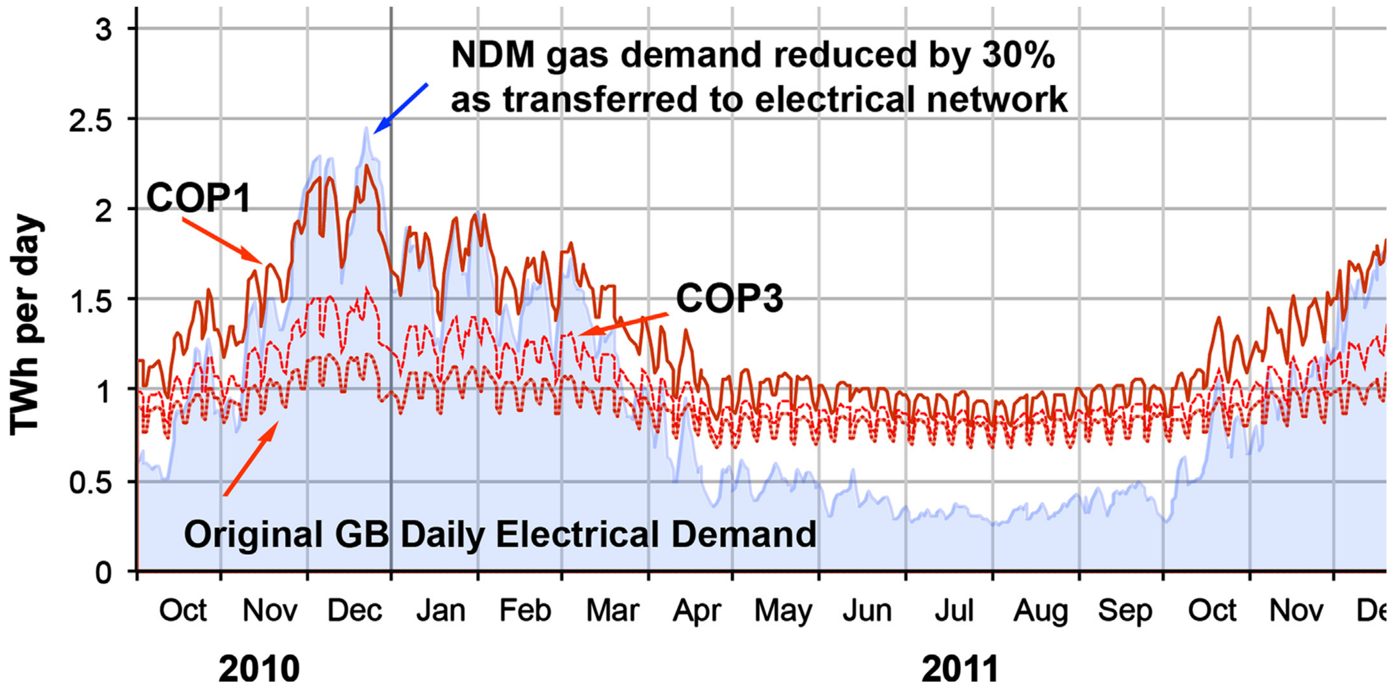

Fig. 3. Transfer of heat and hot water demand from gas to electrical network using historical data.

The extreme variation shown in Fig. 1 gas demand 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 critically different in its operation and management.

5. Annual aggregate from daily gas demand values

Unfortunately the categories for the data in Fig. 1 do not conveniently map with the categories for annual gas data presented in '*Energy Consumption in the UK*' (ECONUKa, 2012) from the Department of Energy and Climate Change (DECC). In order to explore this difference the annual aggregate value of NDM gas data from National Grid was calculated and compared to DECC's 'domestic consumption' values for gas demand.

Fig. 2 shows the total UK gas demand for 2011 calculated by aggregating the daily National Grid gas values used in Fig. 1. The NDM component was 431 TWh and accounted for 50% of the total annual demand for natural gas (excluding exports). The other demand components of the total gas demand for 2011 are also shown (Daily Metered, Power Stations, Storage, and Industry) but were not included in Fig. 1 for the sake of clarity.

This NDM value of 431 TWh can be contrasted with the 286 TWh of '*domestic space heating and hot water*' by DECC. The difference in values is due to sector gas demands included in the NDM value such as commercial and light industrial users. The variation of the overall heating demand is correlated to the weather, which suggests that the daily and seasonal *variation* shown by the NDM could be used as a proxy for the *variation* in domestic heating demand. This however needs some care, as there are many determinants of domestic gas usage including inter alia, the number of occupants, the type of building, building use, occupant preferences, and indeed the weather.

6. Impact of the shift to electrical heating

A wholesale transfer of the NDM gas demand seen in Fig. 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, Fig. 3 shows the same data used for Fig. 1, but with 30% of the NDM gas demand transferred over to the electrical network. Thus the NDM data values have been reduced by 30% and the electrical data values have increased by a corresponding amount scaled by a coefficient of performance (COP) [2]. Fig. 3 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 heating and hot water 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 Fig. 1 is shown as the lower curve for comparison.

Shifting 30% of NDM heat demand to purely resistive heating results in the *daily* electrical demand almost doubling during

[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).

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 days of high 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 net impact is therefore likely to lie between these two extremes (COP-1 and COP-3) shown in Fig. 3.

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 gas 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 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 800 L of thermal storage are required to provide one hour load shifting in a heat pump serving an average UK dwelling; Hong et al. (2013) estimate that around 700 L of hot water buffering is required to entirely shift the demand of a heat pump to off- peak periods when serving a very well-insulated UK dwelling. 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 Fig. 3 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 the electrification of transport.

7. 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 decreasing the extent of infrastructure growth.

7.1. *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.

7.2. *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.

7.3. *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).

7.4. *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; Pinel et al, 2011; Novo et al., 2010) used in conjunction with solar energy has the potential to decrease some of the variation in energy supply seen in Fig. 3, as some of the winter heat demand could be met using a local heat store, rather than drawing from the gas or electricity grid. However, this would require a step change in both cost and volumetric energy density compared to sensible and latent heat methods (Agyenim et al, 2010; Hasnain, 1998; Farid et al., 2004). Thermal storage using reversible chemical reactions such as hydration or carbonation (Cot-Gores et al., 2012; Wongsuwan et al., 2001) 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.

7.5. *Power to gas*

The developing research area of using excess electrical energy to produce hydrogen or methane (from syngas), and then to inject this back into the natural gas infrastructure has a number of benefits and challenges, and may also offer some potential to mitigate part of the impacts of the electrification of heat.

8. Conclusion

Regardless of the future path of energy systems in the UK, the domestic heat demand in winter will continue to be 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 high winter heating demands and variations over different timescales will be critical.

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 and load factors.

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 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 foundation of all policies.

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