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Great Britain's energy vectors and transmission level energy storage

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Abstract

As an example of the challenges facing many developed countries, the scale of daily energy flows through Great Britain'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 scale of energy delivered through the networks on a daily basis, and the scale of variability in the different demands over multiple timescales (seasonal, weekly and daily). The paper discusses energy storage in general; the scale of within day stores of energy available to the gas and electrical transmission networks, and suggests Synthetic Natural Gas as an interesting energy carrier that could use existing natural gas infrastructure.

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Keywords: Decarbonising heat; energy vector data; GB pumped storage

1. Introduction

This paper examines the scale of energy storage schemes connected to Great Britain's (GB) electrical system at the transmission level, and compares them to the scale of daily energy demand through the gas, electrical and liquid fuel networks.

In energy terms (rather than financial) there are two basic factors in meeting the annual demand of an energy system; the first is that a sufficient quantity is available over the year (the energy), and the second is that the system can match the rate at which this energy is required (the power). For a sustainable energy system, these in turn can be viewed simply as challenges in the harvesting of sustainable primary energy, and the use of energy carriers to allow storage and balancing between primary energy supply and the demand. In the modern era, the majority of

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nations have energy systems with fossil fuels as their primary energy sources, which affords the flexibility to store Terawatt Hours (TWh) of energy until required. Given the length and complexity of fossil-fuel supply chains, it is no surprise to find stores of fossil fuels along the supply chain from the geological resource all the way to the end user. These stores range in size from coal stockpiles of many TWh to a 50-litre vehicle fuel tank (approximately 500 kWh). These stores of energy are based on the storage of fossil fuels, or more specifically, the inherent chemical energy that can be released through their combustion. The energy density of fossil fuels, in volumetric or gravimetric terms, is a major reason that energy systems are so reliant upon them as a source of primary energy. Pumped Hydro Energy Storage (PHES), Liquid Air (LAES), adiabatic Compressed Air (aCAES), Superconducting Magnetic (SMES), and capacitors are an alternative means to store energy at different scales, that do so without the benefit of using the embodied chemical energy of their storage media as the means of energy storage. In comparison Flow Battery (FBES) and Battery Energy Storage (BES) exploit the chemical energy of the storage media through reversible chemical reactions.

Energy systems have evolved based on the flexibility provided by fossil fuels, and as the sources of primary energy for modern societies change over the long-term, future energy systems will have to radically change to accommodate the loss of TWh of stored energy at a regional level.

Nomenclature

EDLC	Electrochemical Double Layer Capacitor
PHES	Pumped Hydro Energy Storage
ACAES	adiabatic Compressed Air Energy Storage
LAES	Liquid Air Energy Storage
SMES	Superconducting Magnetic Energy Storage
FBES	Flow Battery Energy Storage
BES	Battery Energy Storage
DCES	Dielectric Capacitor Energy Storage
CCGT	Combined Cycle Gas Turbine

2. Energy storage and fossil-fuels

Without the critical component of storage, energy systems have little or no ability to withstand exogenous shocks that can have widespread, damaging consequences to the system itself and also to the end users that rely on the system. The concept of a 'Just-in-Time' system has been applied to electrical systems and management studies of supply chains, but this is always determined by setting particular boundary conditions for the 'Just-in-Time' description to be potentially valid. When looking at these same systems with wider boundary conditions, stocks of material and stores of energy are ubiquitous. In a system where the primary energy is supplied by fossil-fuels, the wider supply chain has a degree of control of when the resource is extracted, transported, stored and finally combusted. The presence of fossil-fuel stocks clearly signifies that electrical energy systems are not 'Just-in-time' when a broader view of the supply chain is taken.

In stark contrast with fossil-fuel supply chains, there is **NO** ability to store wind or solar energy before it is harvested; leaving the only option for a store of energy to be provided after energy has been harvested. If a technology transforms wind or solar energy into electricity (rather than heat), the drawback of this fantastically useful form of energy is its difficulty to be stored in an economic manner. (It is technically possible to store electrical energy directly in capacitors, but their costs and the meagre energy density of such devices preclude their use for storing an appreciable amount of energy.) If electrical energy is to be stored, it is therefore converted into a form of energy that is easier, safer and cheaper to store, and then transformed back to electrical energy when demand requires. As with any energy conversion process at scale, there is an efficiency loss, or more precisely there is an efficiency loss in conversion to the desired form of energy *i.e.* the energy penalty associated with transformation. These processes (and their efficiencies) are constrained by the natural laws of physics and thermodynamics, but continued research, development and deployment can increase efficiencies of conversion towards the hard limits set by these natural laws. Given this, and the benefit of changing electrical energy to other forms of energy in order to store, there is always a round trip efficiency penalty for storing electrical energy, the only question is by how much. Electrical energy storage may therefore increase the overall energy requirements of the system, implying that other benefits to the system are required to overcome this obvious drawback. Fortunately, using storage to decouple supply and demand provides an energy system with flexibility, which can fundamentally change its operation, which is especially desirable when greater amounts of primary energy are likely to be from low-carbon energy sources.

2.1. 'Energy Storage' Taxonomy

Energy storage technologies exhibit a wide range of characteristics in terms of their round trip efficiency, lifetime, costs, energy and power densities (expressed in either volumetric or gravimetric terms). Consequently, there are applications where certain technologies are better suited than others. This is an important concept within the area of energy storage where different applications require different energy storage technologies and approaches. The taxonomy of 'Energy Storage' can be likened in a sense to the taxonomy of 'Transport' - where it is apparent that there is a broad landscape of technologies that are required for different applications. The varied services provided by a car, bus, heavy goods vehicle or container ship are immediately obvious due to our familiarity with the differences between these 'Transport' technologies. On the other hand, the services provided by capacitors, BES, FBES, CAES or PHES are commonly classified as 'Energy Storage', with the unfortunate implication that they are readily interchangeable. In reality, there may be areas of competing technologies, but there are also distinct groups of technologies that are best suited to provide particular storage services. This tendency to classify all forms of energy storage together is thought to be partly due to the unfamiliar nature of the technologies, and an awareness of this tendency is important when considering alternative methods with which to replace the TWh of stored energy conveniently provided by fossil fuels. Given the sheer scale of storage currently provided by fossil-fuels, it is likely that their replacement in the long-term will require another fuel, such as a low-carbon fuel that has limited environmental effects, but substitution of fossil-fuels with alternative fuels may not be without its problems and needs careful consideration.

Another distinction within 'Energy Storage' can be made between the types of energy store in terms of their reversibility; some are irreversible in the sense that the conversion to heat or electricity is one-way only, although the store of energy itself can be physically replenished, whereas others can transform energy to and from a readily storable form. This distinction is not necessarily driven by the technical ability to transform to and from a store, but driven more by the financial and energetic implications of doing so. This distinction between *rechargeable* and *refuelable* is an important consideration, as there tends to be a natural focus on rechargeable systems despite those with refuelable stores accounting for the overwhelming majority of stored energy [1].

2.2. Fossil-fuels

It is interesting to consider that fossil fuels are stored solar energy, and the energy released by the combustion of fossil fuels suggests an efficiency from primary solar energy to a fossil-fuel store to be well under 1%, which is diminished further when heat from combustion is converted to electrical energy. In comparison, the best commercially available solar PV technology coupled with a battery, where electrical energy is generated from primary solar energy, stored and then released is estimated to provide an efficiency above 20%. Fossil-fuels are the outcome of natural energy harvesting over millions of years and have accumulated their vast energy content due to the length of time over which the solar energy was stored, which more than compensates for the low efficiency of the conversion. However, it is painfully obvious that humanity is literally burning its way through this wonderful resource at a rate that is not sustainable.

A major reason why modern societies are so dependent on fossil fuels is precisely their ability to act as stores of energy, coupled with their ability to be transported from areas of resource to areas of demand *i.e.* they are excellent carriers of energy. Additionally, it is also helpful that their risks are well known and perceived to be manageable within local limits. However, it is known that fossil fuels are a finite resource and their availability will become constrained in the future, and it is also clear that the externalities of fossil-fuel combustion have caused changes in the global climate with local and regional variations. Simply put, the use of fossil fuels as a primary energy source will diminish and eventually cease, but the timing of this is predicated on other forms of primary energy being developed at scale to allow substitution. Leaving fossil fuels in the ground when there is a growing demand for global primary energy is difficult to see as a political option, especially from countries whose economies are dependent on exports of fossil fuels. Alternatively, there could be the option to continue to exploit fossil fuels, but to separate the environmentally damaging compounds from the useful energy, and then store or utilise these compounds without causing ongoing changes to the climate. Politically, this seems a more acceptable route than leaving fossil fuels in the ground, and could therefore be viewed as a more likely outcome. This ability to continue to use fossil-fuels but lessen the environmental impact could be a credible bridge between the current situation and a future where primary energy use is supplied by sustainable source, but, a major risk would be that having this bridge to allow continued use of fossil-fuels would in fact delay the necessary transition. This risk should not be underestimated, and requires long-term political agreement to combat the easier option of an incremental change to business as usual. To enable the possibility of this bridge, the continued research, development and deployment of carbon capture technology should be a prioritised outcome of medium-term budgets of modern societies to reduce the damaging emissions from the continued use of fossil fuels. In order to reduce the overall requirement for primary energy there should also be a strong focus on energy efficiency *i.e.* getting more services from less energy should be a top priority.

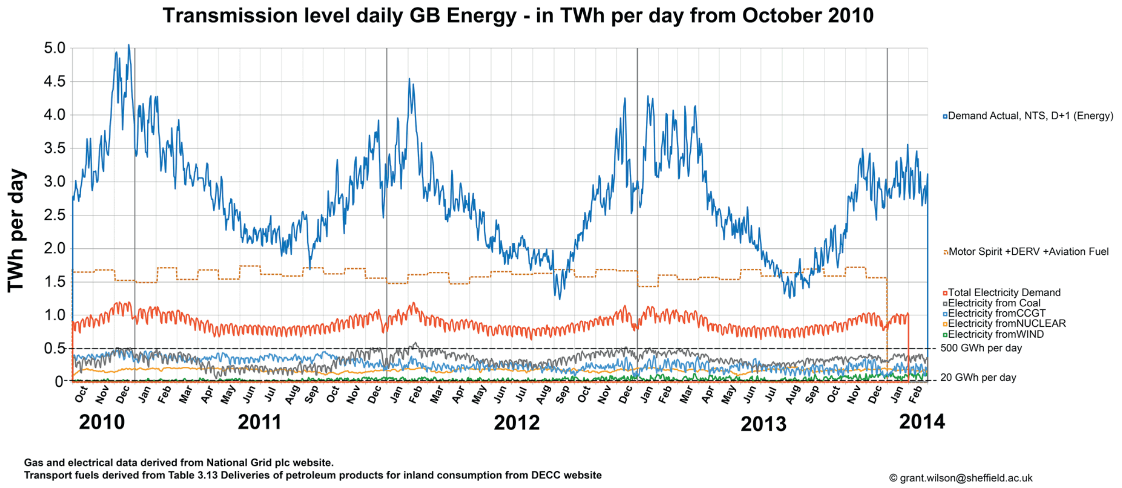
3. Daily energy demand of Great Britain's energy systems

3.1. Data sources

- Natural Gas data were sourced from National Grid's data explorer [3] due to its resolution 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)' [4]. This is available at a resolution of 1 month.
- Electricity Data was sourced from either the 'Metered half-hourly electricity demands' data from National Grid's website [5] or through Elexon's Portal [6]. This is available at a resolution of 5 minutes and half-hour.

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

Figure 1. Daily GB Gas, Electricity and transport fuels (TWh). Data sources [3][4][5][6]



3.2. Daily GB Gas, Electricity and transport fuels

Figure 1 shows Great Britain's daily natural gas, electricity and transport fuels in Terawatt hours per day. Total daily electrical demand (in red) is shown, as well as the top four generating technologies (coal, combined cycle gas turbines, nuclear and wind) that make up this total. The upper blue line is the TWh/day of total natural gas demand that includes gas to power stations, industry, storage and the daily and non-daily metered demands, but excludes exports. The line for liquid fuels is the total of DERV (diesel) Motor Spirit (Petrol) and Aviation Fuel. The data for this is only available on a monthly basis.

The varied characteristics of gas and electricity demand are clearly illustrated in Figure 1. In winter, the total gas demand can be up to 5 TWh/day, which is greater than four times the total electrical demand, whilst in the summer it can drop below 1.5 TWh/day, which is double the total electrical demand. 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. Although not shown for reasons of clarity, the biggest source of variation in total gas demand is that of domestic demand, which itself is made up primarily the needs of space heating. This was explored in greater detail in a previous article [7]. The mild winter experienced by GB in 2013/14 appears clearly in the reduced quantity and peak energy of the total gas demand. The total gas demand (less exports) in 2010/11 from the 1st of November to the end of February was 430TWh and in 2013/14 this had dropped to 330TWh, a reduction of around 22%. This is indicative of the variation that GB energy systems experience within and between years, with part of the explanation for this particular decrease being the shift from CCGT to coal for electrical generation as well as the exceptionally mild weather.

It is important to note that gas flows are not constant throughout a day but are concentrated in the morning and evening when space and water heating demands are highest [8][9]. 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 this data with sub-daily electrical data (which are available at a national level). However, national sub-daily gas demand data are not readily available for the GB natural gas network.

The variation in gas flows presented in Figure 1 is routinely catered for by existing gas infrastructure as, to-date, there have been no widespread problems. The gas network is balanced throughout the day, with increased gas pressure in parts of the network (Linepack) used as a buffer to provide increased gas supply to meet daily peaks in demand. By comparison, the electrical network needs to be kept in balance on a near instantaneous basis and thus is crucially different in its operation and management. The following section explores the scale of the 'within-day' energy stores available to the gas and electrical networks at the transmission level.

3.3. Natural Gas Linepack

Linepack describes the total amount of natural gas in a transmission or distribution system, which varies with its pressure. The ability to change the pressure and thus the amount of natural gas (and therefore the energy stored) is used to meet peak gas demands. This technique is used in both the gas transmission and distribution systems; in the UK there is only data available for Linepack in the National Transmission System (NTS) for natural gas. The data are available from the National Grid Data Item Explorer [3]. Over the time period analysed from November 2010 to October 2013 the greatest daily variation or 'swing' in Linepack was 530 GWh and the lowest was 20 GWh, with an average daily variation over the timeframe of 132 GWh. The variation was defined as the difference between the highest and lowest values for Linepack on a given day. Figure 2 presents the within-day Linepack variation in GWh. It is important to note that this is short-term, as the variation in Linepack gas will be used over the course of the day. This is confirmed by comparing the Linepack swing to the total daily demand of 1,000s of GWh rather than the GWh variation in Linepack. The largest daily variation over the period analysed suggests that within the NTS alone, there is the ability to store up to 500 GWh of chemical energy by varying Linepack pressure. The total energy contained in the Linepack of the NTS system is closer to 5,000 GWh with this total being relatively static over years and seasons. This relatively stable Linepack is required to provide the pressure for the natural gas system to operate, so although the values are not known, it is expected that the Linepack variation itself will have hard limits to the over and under pressure relative to the normal working pressure of the network. This transmission system Linepack is complementary to the separate gas storage facilities [9] that provide > 40,000 GWh of storage, as well as the Linepack in the distribution networks. The amount of Linepack contained in Distribution gas networks and the Linepack variation are both unknown.

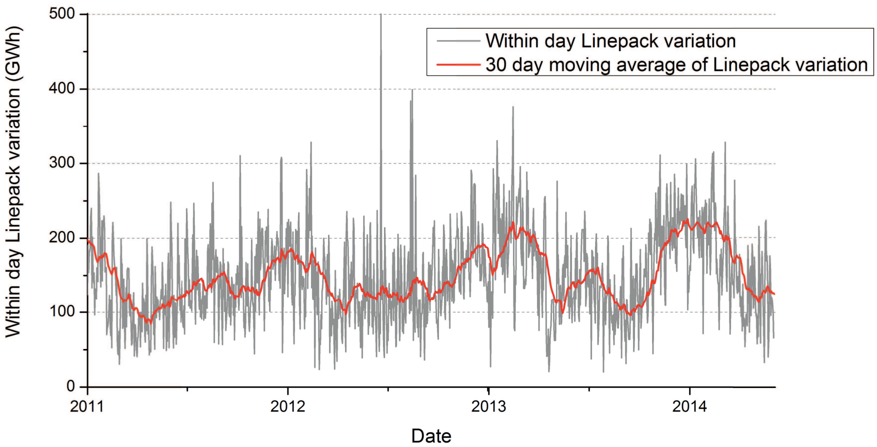


Figure 2. Within-day Linepack variation in GB Natural gas transmission system

3.4. Existing and planned Great Britain pumped storage schemes.

The total energy capacity of existing GB pumped storage schemes in 2014 is ~28 GWh with a total power capacity of around 2800 MW, shown in Table 1. If the Final Investment Decision of Coire Glas (which passed through planning in late 2013) is ultimately successful and is built as a 30 GWh, 600MW scheme, then this would double the energy capacity of GB PHES schemes to ~60GWh. If the other schemes pass planning and are also built – then the GB PHES energy capacity could increase to somewhere in the region of 100 GWh (0.1TWh) and almost 4800 MW of power output.

Table 1 - Hydro Pumped Storage Schemes in UK, existing and potential

Name	Energy Capacity	Power	Duration	Location	Status
Ffestiniog	~1.3 GWh	360 MW	3.6 Hours	Wales	Operating since 1963
Ben Cruachan*	~10 GWh	440 MW	22.7 Hours	Scotland	Operating since 1966
Foyers	~6.3 GWh	300 MW	21 Hours	Scotland	Operating since 1974
Dinorwig	~10 GWh	1728 MW	5.8 Hours	Wales	Operating since 1983
Total Existing	~27.6 GWh	~2800MW			
Coire Glas	30 GWh	600 MW	50 Hours	Scotland	Passed planning 2013
Balmacaan	30 GWh	600 MW	50 Hours	Scotland	Yet to enter planning
Sloy	~0.6 GWh	152 MW	4 Hours	Scotland	Passed planning 2012
Total Future	> 90 GWh	~4800 MW*			

* A feasibility study to upgrade Ben Cruachan to a power output of 1040 has been commissioned.

The operation of the pumped storage schemes tends to a daily pattern where part of their capacity is used to charge at off-peak times when prices are lower, followed by discharge back to the electrical transmission grid when prices are higher. In order to maximise their revenue, PHES operators also sell capacity into different markets *e.g.* to provide ancillary services to the Transmission System Operator (National Grid). This reduces their ability to use the entire storage capacity to take advantage of price differentials though the bulk purchase and sale of electrical energy on a daily basis. The characteristics of the proposed scheme at Coire Glas and Balmacaan are significantly different to existing PHES schemes in terms of the ratio between their proposed energy and power capacities; the minimum time to fully charge or discharge could be as much as 50 hours. These characteristics imply that entire capacity of 60 GWh will not be available to be used on a daily basis. The operator may use Coire Glas as a tool in order to balance other generating assets within its portfolio, and so provide additional profit to the group as a whole. It is not expected that an arms length merchant operated PHES without generating assets would choose to have a similar ratio giving 50 hours of charge or discharge. Electrical spot-price differentials are expected to continue to be daily in nature (driven by the underlying demand which is itself daily in nature), and a merchant operated PHES would be expected to build a scheme in order to have the ability to capture this. It is however a complex set of decisions governed by the location of a potential PHES (in network as well as topographical terms) and the likely revenue streams to be captured from different markets.

Given the existing total energy capacity of GB PHES is 27.6 GWh and not all of this is expected to be used on a daily basis, a value of 20GWh has been chosen as an upper boundary value in order to compare with the within-day Linepack of the gas transmission network.

This 20 GWh per day is shown in Figure 3 (which is a magnified segment of Figure 1). A 500 GWh per day line is also shown for comparison, which is approximately the largest amount of energy stored in Transmission system Linepack in the natural gas network.

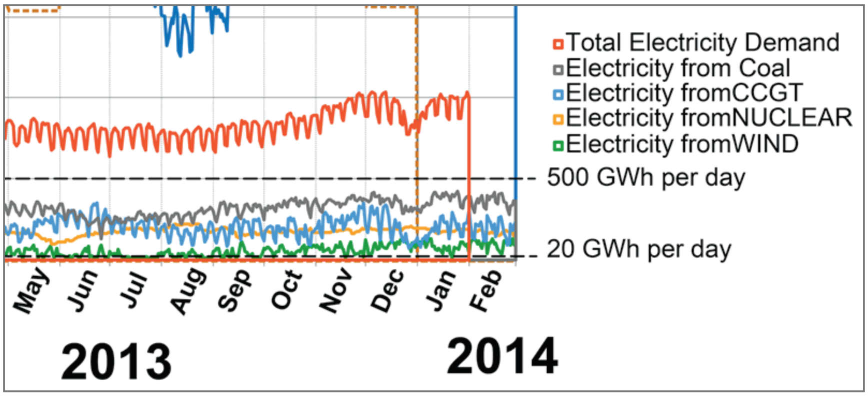


Figure 3 Closer inspection of 20 GWh and 500 GWh per day lines

4. Possibility of using Synthetic Natural Gas to bypass electrical network constraints.

Balancing the electrical grid will become increasingly challenging as the proportion of intermittent renewable generation continues to rise. This is not simply a question of holding power stations in reserve for when the wind drops in order to account for the deficit in power, but also being able to absorb wind power when there are network constraints or potentially even too little overall demand. With the expected increase in wind generation connected to the GB electrical transmission system, there is also an expected corresponding increase in the number of instances in which this generation will have to be curtailed. To be clear, this is not because of a low wind or high wind scenario where the turbines will not be generating either due to insufficient wind energy or reducing their output as a safety precaution due to the design limitations of the turbines; the curtailment will happen due to network constraints as they do at the moment. Reinforcing the network to remove constraints would reduce the probability of curtailment, but this may not be economic or locally desirable due to the upgrading of transmission or distribution lines to cope with an initially small percentage of the year when curtailment is likely. Having access to some form of storage on the wind generator side of the network constraint is an obvious solution to help overcome this problem, as electrical energy could be stored when the network constraint is at capacity, and then discharged when the generators have reduced their output due to the prevailing wind conditions. Increasing the capacity of the network to cope with expected peaks of supply for short periods of the year reduces the overall load factor of the network, whereas having access to storage can improve the load factor of the network as it has the ability to decrease the difference between average power flows and peak power flows. As mentioned earlier, there is always a round-trip efficiency penalty with energy storage, so the balance between the advantages of increased load factor of the network, versus the energy lost through storage and conversion requires some consideration.

An alternative could be to consider a whole systems approach by using the existing natural gas infrastructure to bypass electrical system constraints through the use of Hydrogen as an energy vector. However, there are several technical [11] and regulatory issues that need to be overcome before the addition of Hydrogen to the GB gas grid, not least because hydrogen is characterised as a contaminant in current GB legislation for natural gas supply. This particular regulatory barrier is different in other European countries, which have legislation that permits certain levels of Hydrogen in the natural gas supply.

Due to restrictions in adding Hydrogen to the GB gas grid, this paper considers the addition of Synthetic Natural Gas (SNG) to the gas grid, which is a regulatory possibility at this time. It is recognised that the production of Hydrogen from low-carbon renewable energy can be combined with CO_2 to produce SNG, such as the Power to Gas pilot project at Thuga [12]. Over time, it is expected that regulation will catch up with other European markets and a small percentage of Hydrogen will be allowable within the natural gas mix.

Using CO_2 in the production of SNG provides an avenue for CO_2 that is not limited to sequestration in geological formations. It suggests an ability to use CO_2 one further time before it is released to the atmosphere, with potential CO_2 emission savings. Indeed, if the CO_2 element of the SNG can be captured and used again and again, or even sequestered, then there may be additional benefits in the reduction of CO_2 emissions. However, this is wholly dependent on the manner in which the SNG is combusted and the CO_2 capturing process available. Exploration of the energetic implications for producing SNG is a subject of ongoing work [13].

The existing infrastructure for natural gas (and thus SNG) has the ability to use elevated pressures to store 500 GWh of SNG, by solely considering the Linepack variation of the transmission level network. This provides a helpful store for SNG production that allows SNG production to be driven by times of possible curtailment on the electrical network rather than driven by demand from the gas network. If the scale of the Linepack in the Distribution Networks were of a similar order of magnitude (GWh) then this would also seem to offer a potential buffer between the production of SNG and demand. It is not known whether connection of an SNG facility would be better at the NTS level or embedded within a Distribution network, as this may be affected by many factors including network constraints in the electrical grid transmission system.

5. Conclusion

The comparison of the daily gas, electrical and transport fuels indicates that serious challenges arise when moving away from fossil fuels. Even allowing for future improvements in domestic energy efficiency and electric heating technologies (such as heat pumps), the UK's ageing electrical system is likely to see a significant rise in daily energy flows if heat and transport demands are shifted over from the gas and liquid fuel networks, which would result in significant upgrading costs to cope with increased peak flows. Reducing the overall national energy demand *e.g.* by making the built environment increasingly energy efficient should continue to be a cornerstone of all policies, in order to ease the transition to a low-carbon economy.

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 energy vector itself can provide. Better whole systems data should lead to better insights and therefore some hope of better choices in energy systems transitions.

Regardless of the future path of primary energy supply for Great Britain, the seasonal variation between summer and winter primary energy demands will continue to be significant, and dominated by the requirement of space heating. This variation in demand has to be catered for by networks able to cope with not only the peak demand, but also having access to the energy when required. Given the current use of stores of fossil-fuels to provide this seasonal flexibility (> 40,000 GWh for natural gas) it is crucial that suitable methods without the use of fossil-fuels can be found to cope with the higher winter heating demands and variations over different timescales. Although chemically identical to fossil-fuel natural gas, Synthetic Natural Gas provides a potential route to store TWh levels of energy as well as within-day storage (as happens now). The drawback to SNG is the energy penalty associated with its production, but its advantages in terms of existing infrastructure, acceptance by end users and known safety should not be underestimated. There has been some discussion of global primary energy supplies entering the ‘age of gas’ and it is interesting to consider whether this could also herald the transition to an ‘age of synthetic gas’.

The existing natural gas infrastructure at the transmission level is capable of within-day Linepack variations of up to 500 GWh of natural gas, whereas the electrical network at the transmission level may have about 20 GWh of daily electrical energy storage at its disposal. This should at least provide some food for thought in discussions about bulk energy storage for Great Britain, even with future PHES schemes that could potentially be built.

Acknowledgements:

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