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Preliminary estimation of long-term storage needs in a system with electrified demands and 100% wind and solar electricity supply

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1. Introduction

This report was produced following a request for data and text input to the Royal Society report (2023) on long-term electricity storage.

This report describes modelling, mostly conducted 2017-2018, aimed at initially exploring the impact of long-term meteorology data on energy demands and renewable supply (here wind and solar), and thence on the need for energy storage. The report first introduces the issue, a simple energy system, and storage theory and meteorology. Then a simple model is applied to this simple system. Simulation results are given and discussed. Finally, more complex modelling - a simple model has 100s of lines of code as compared to 1000s of lines- by the authors of more realistic systems is introduced, such as is required to resolve some of the limitations of the simple energy system and model. In particular, this more complex modelling includes interconnector trade which reduces storage need substantially.

A key problem faced by any energy system is to match variable demands and supplies at different locations hour by hour across the year. While fossil fuels dominate the energy supply mix, meeting variable demands is relatively straightforward because fossil fuels are stored energy. A more demanding problem for future UK low emission energy systems is to match variable demands and supplies over periods ranging from seconds to years, particularly where supply is dominated by renewables without integral storage such as solar and wind, or inflexible nuclear. In this report we are concerned with energy storage needed to accommodate long term (weeks to years) demand and renewable variations. There are three non-exclusive options for managing energy surpluses and deficits arising from variable renewable and inflexible nuclear generation:

1. Storage of primary energy (biomass, geothermal, etc.), or secondary energy (heat, cool, electricity, hydrogen, ammonia, etc.), or services (washed dishes, etc.) and products (e.g. iron).
2. Trade over long distance transmission lines to average demands and renewable outputs by dynamically exchanging local surpluses and deficits.
3. Deployment of increased renewable capacity enabling demands to be met at lower levels of incident resource (wind, solar radiation), but with increased renewable energy spillage and lower capacity factors.

In general, increasing one of these options allows a reduction one or two of the others. An objective is to find good designs with near optimal, least cost combination of these options such that constraints such as greenhouse gas emission targets are met - this is difficult to do and is not attempted here, but is in a paper by Gallo Cassarino and Barrett (Gallo Cassarino and Barrett, 2021). In this report, a simple model is used to start to explore the magnitude and drivers of energy flows and storage needs. There is no cost analysis here.

2. Energy systems

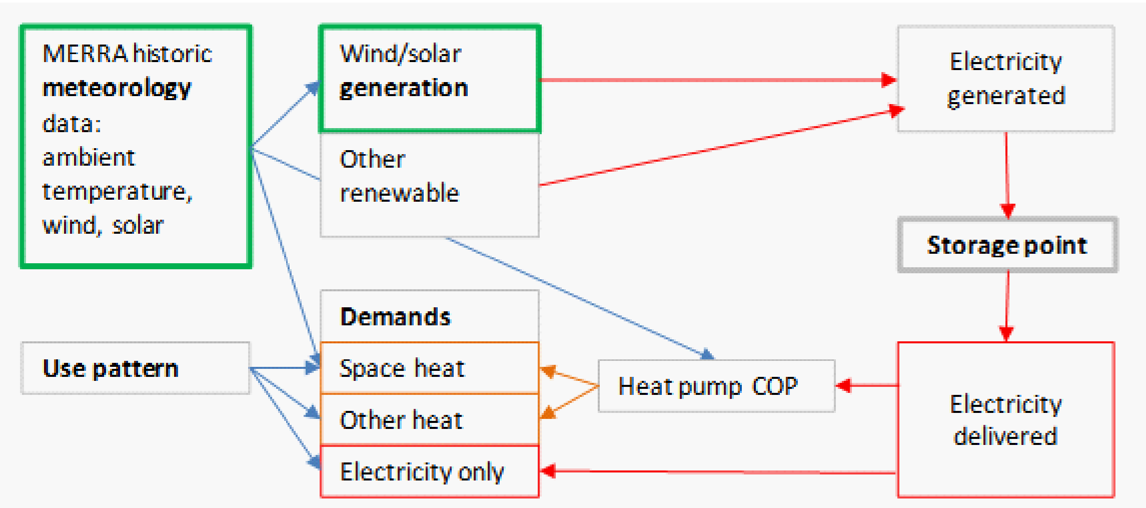
Energy service demands are connected to primary supplies through intermediate conversion, transmission and storage systems which can utilise multiple primary resources – fossil and nuclear fuels and renewables – and multiple vectors for their transmission – gas, liquid, solid, electricity and heat. The difference, or net flow, at any point between upstream and downstream flows may be positive or negative and it can be cumulated over any time period to determine the minimum storage needed to balance flows at that point.

This report focuses on the modelling of a simplified energy system, shown in Figure 1, with the system ***storage point*** where storage need is calculated. The analysis here is exploratory and so the remainder of the energy system is particularly limited and simplified in the following ways:

- The system demands are for electricity and heat services only in a single 'sector' and all services are powered with delivered electricity.
- Supply is UK sourced renewable electricity, solely from variable wind and solar which have no integral storage, unlike biomass, hydro, geothermal and so on.
- Trade between the UK and other countries is not included.

This is a demand and supply system that is challenging to design, having variable, weather driven all electric heating and variable wind and solar with no integral storage, and which therefore may engender an extreme storage requirement in terms of magnitude.

Figure 1: Simplified energy system diagram



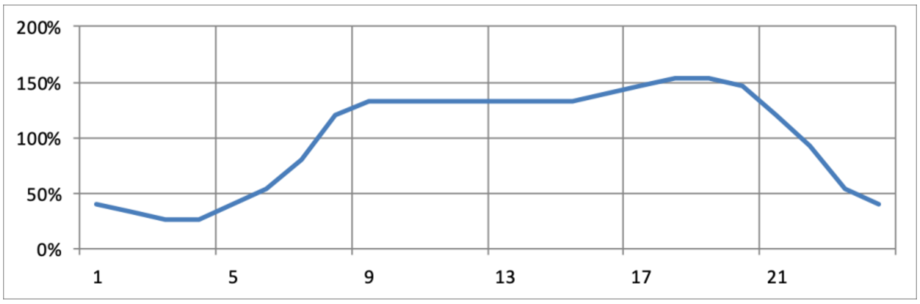
The most complex and separate part of the modelling in this report is collating meteorology data, weighting it by population and wind farm locations, and estimating wind and solar generation at different locations given factors such as wind shear and wind turbine efficiency functions. Social temporal activity patterns are fundamental drivers of demand variation, and meteorology also drives variations in the demands for space heating and cooling in buildings and vehicles, and in heat pump efficiency.

Meteorology also determines the wind and solar resources. A historic data set of meteorology called MERRA (Modern-Era Retrospective analysis for Research and Applications) – see Rienecker et al (Rienecker *et al.*, 2011) - has been used to drive demand and renewables and is described in more detail below.

The simple energy system consists of service demands and generation. There are just three demands: general electricity services (equipment, lighting, refrigeration etc.), non-space heat demand and space heat demand. Electric vehicles are not separately modelled and are included in general services, but in reality they have weather independent demands (propulsion energy is nearly weather independent), and weather dependent heating and cooling demands like buildings, which will vary with ambient conditions. Air conditioning demand is not included here: it is currently small compared to heat in the UK but future climate change will alter this balance. 'By 2070, in the high emission scenario, this range amounts to 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter'(Met Office, 2019).

All demands are assumed to vary with a single normalised diurnal use pattern (Use) shown in Figure 2, the shape of which based on previous work (Gallo Cassarino, Sharp and Barrett, 2018). Space heat demand varies with ambient temperature, and also local solar radiation causing solar gain (not included here), and local wind speed which increases building heat exchange rates through altering ventilation rates and envelop skin resistance. Therefore, in general, net space heat demand is negatively correlated with solar radiation and generation, and positively correlated with wind speed and wind generation as local wind speeds are generally but not precisely correlated with wind speeds at wind farms. Use patterns vary with sector and sub-sector and will change in the future, but for long term, rather than diurnal, storage needs the pattern is not too critical for the simple modelling presented here.

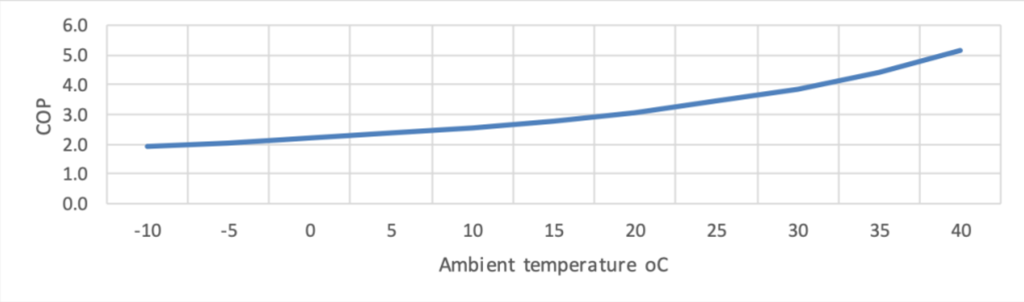
Figure 2 : Normalised energy demand pattern - Use



Space and non-space heat demands are summed and met with an electric heat pump. In real systems, a range of heat pumps utilising different low temperature heat sources and designs will be used with a range of coefficients of performance (COP): in consumer systems a seasonal weighted COP typically ranges 2-3; and in district heating (DH) systems COPs range 3-5. District heat pumps (DH HPs) have a higher COP than consumer HPs partly because larger machines are more efficient, and partly because DH HPs can used higher winter temperature heat sources such as the sea, the ground or sewage.

The heat pump here is assumed to be a consumer air source heat pump with a COP varying with ambient temperature as shown in Figure 3: the equation is a simply the Carnot efficiency multiplied by a constant 0.45. The assumed COP curve is critical to the electricity consumed for both annually and at peak times – if half of heat were supplied by DH HPs rather than all consumer HPs, the consumption of electricity for heat would be reduced by about 25% and the seasonal variation would be reduced because of the higher temperature winter heat sources generally available to DH heat pumps.

Figure 3 : Heat pump COP



The consumption of electricity for general services and for heating are summed to give total electricity demand. At ambient temperatures above about 20-25 °C space heat demand would be zero and the heat output would be for hot water or some other low temperature heat service.

The modelling is of hourly demands and wind and solar generation as driven by historic meteorology over a period of 31 years, in order to make preliminary estimates of the magnitude of differences between cumulative energy demand and variable renewables. These differences are a critical input to determining what is required to balance demand and supply with some mix of storage, transmission and renewables.

Table 1 shows the principal model variables. The energy system is defined by just seven variable values as shown in bold. As discussed below, the demand inputs might roughly represent a future UK with an annual electricity demand of about 700 TWh. Generation comprises onshore wind, offshore wind and solar photovoltaic which generate according to MERRA wind and solar resources.

Table 1 : Model variables and energy system definition

Variables	Code variable		Units	Comment
Ambient temperature	Tamb_oC	MERRA	oC	Population weighted
Wind speed at demand	WindDem_mps	MERRA	m/s	Population weighted
Solar radiation	Solar_Wpm2	MERRA	W/m2	Population weighted
Onshore wind factor	WindPowOn_Prop	MERRA	%	Wind farm weighted
Offshore wind factor	WindPowOff_Prop	MERRA	%	Wind farm weighted
Normalised activity pattern	Use(h)		%	System definition
internal building temperature	Tint_oC	**17**	oC	System definition
Average non heat electricity demand	DemNonHeatAv_GW	**60**	GW	System definition
Average non space heat demand	DemNonSpHeatAv_GW	**18**	GW	System definition
Specific heat loss	SpHeaLos_GWpoC	**5**	GW/oC	System definition
Wind capacity: onshore	WindCapOn_GW	**40**	GW	System definition
Wind capacity: offshore	WindCapOff_GW	**120**	GW	System definition
Solar PV capacity	SolCap_GW	**70**	GW	System definition

3. Theory overview

To estimate the storage need at a point in an energy system, the time varying flows either side of the point need to be calculated. In some cases, energy can flow either way across the point: for example, electricity might flow through a distribution transformer to consumers at night, but flow the other way when consumer solar PV generation is greater than local consumer demand. The storage flows may be of different types and in such cases the flow may be in one direction only: for example, upstream might be electricity input to a heat pump putting heat into a heat store for later output as heat to heat demand. The outputs of some stores are determined by the demands they meet, such as the output of an electric vehicle battery, and so cannot be controlled arbitrarily. Some storage, such as passive heat storage in building fabric, operates in complex ways and its inputs and outputs cannot be easily controlled. Some storage is not available all the time, e.g. space heat storage is only operational in the winter. Stores may have multiple inputs and outputs with different efficiencies. For example, energy stored as ammonia or hydrogen might fuel a CHP plant producing electricity at 35% and heat at 55% efficiency. Some storage is not for energy itself yet can help manage energy systems; for example, electric water pumping in the water industry can be flexibly scheduled using water storage in reservoirs.

3.1. Simple modelling

In the simple energy system and modelling, the assumption is of unidirectional hourly (h) flow of electricity from generation G(h) (GW) to demand D(h) (GW). The gross accumulated difference in energy Cgr (GWh) between G and D may be accumulated over some period:

$$Cgr = \sum_{h}(G(h) - D(h)) \qquad \text{GWh} \qquad [1]$$

- If Cgr is positive, then there is surplus of G over D and Cgr can be stored to the limit of available storage capacity.
- If Cgr is negative, then it is necessary to start the period with energy Cgr in the store to prevent the storage level falling below zero.

Minimum storage requirements are equal to Cgr assuming the store is 100% efficient, which is not the case for any real storage technology.

3.2. More detail

In general, stores have three processes: input, storage across time, and output, each with losses and power limits on input and output, and these need to be modelled to properly simulate storage; this is not done in the model used in this report but is in more refined models discussed in the final section. We need to account for the efficiencies of energy input to the store Eff_{in} and output Eff_{out}. The standing losses L(t) of the store will be some function of time depending on the store type, storage level, environment and so on.

Then for input to the store, the level of energy in the store Qst (GWh) changes from its initial level Qst_0 with input Q_{in}:

$$Qst = Qst_0 + Q_{in}\, Eff_{in} \qquad \text{GWh} \qquad [2]$$

Input loss is: $Q_{in}\,(1 - Eff_{in})$ GWh [3]

Standing loss L(t) over some time t is the integral of some, generally complex, energy loss function, so the storage level Qst after t is given by:

$$Qst = Qst_0 - L(t) \qquad \text{GWh} \qquad [4]$$

After storage useful output Q_{out}, the new Qst is:

$$Qst = Qst_0 - Q_{out} / Eff_{out} \qquad \text{GWh} \qquad [5]$$

Output loss is: $Q_{out}\,(1 - Eff_{out})$ GWh [6]

These processes must be tracked hour by hour over the whole simulation period; initial and final storage levels alone are not adequate: a store level may be the same at the end of a period as at the beginning but may have been discharged and charged multiple times within the period with Eff_{in} and Eff_{out} losses each time, plus any standing losses L(t).

In general, storage efficiencies Eff_{in} and Eff_{out} are variable and can depend on input and output power, store level, store and ambient temperatures, pressures, battery cycles, and so on. The standing losses of a store are also variable: sensible heat storage will lose heat at a rate approximately proportional to the difference between store and ambient temperatures; most batteries lose energy slowly with time depending on conditions and technology. Storage losses may appear as heat and in some cases, this may be useful: for example, the waste heat generated by battery charge/discharge might take place at a district energy hub and the waste heat used in district heating.

Stores may be characterised by energy inputs and outputs of different forms with associated charge and discharge efficiencies. For example:

i. **Electricity in/electricity out.** 1 GWh of electricity output can be stored by inputting 1.2 GWh of electricity into an 80% efficient throughput battery; a useful output to input ratio of 0.8:1.
ii. **Electricity in/electricity out.** 1 GWh of electricity output can be stored by inputting 2.2 GWh of electricity into a 75% efficient electrolyser to produce 1.7 GWh of stored hydrogen which, assuming no storage losses, can later be output from store into a 60% efficient generator (e.g. a fuel cell) to produce 1 GWh. The overall useful output to input ratio is 0.45:1.
iii. **Primary chemical in/electricity out –** this cannot store surplus electricity**.** 1 GWh of electricity output can be 'stored' by storing 2 GWh of biomass for input to a 50% efficient power station; a useful output to 'input' ratio of 0.5:1.
iv. **Electricity in/heat out –** this can absorb electricity but outputs heat**.** 2 GWh of heat produced by a heat pump with a COP of 2 can 'store' 1 GWh of electricity; a useful output to input ratio of 2:1.

Additionally, stores in general have limits on the maximum input and output power capacities and the rates at which these can change. For example, grid batteries may have an energy stored (MWh) to power (MW) ratio of 4:1 – enough energy for maximum output for 4 hours. These technology characteristics critically affect storage type selection and sizing for different points in the energy system. It should be noted that real systems will have many stores of the same type (batteries, etc.) and these will not have the same characteristics in terms of capacity and efficiency. Further, these will not all become full or empty at the same time unless this is explicitly controlled centrally: therefore the aggregate power input or output of many stores will fall as the stores become full or empty one by one; unlike a single aggregate store which has maximum power until full or empty. This is a complex modelling challenge.

In this scoping analysis specific storage technologies are not modelled, and the results are therefore to be seen as order of magnitude calculations for the simple, renewable, electricity only system with no transmission trading.

4. Meteorology and wind and solar generation

The meteorology data used here consists of MERRA hourly reanalysis data for the 31 year period 1980 to 2010 which is available for the world at a spatial resolution of ½° latitude by ⅝° longitude (Rienecker *et al.*, 2011). Ambient temperature, and wind and solar data were collated for the UK and surrounding waters and renewable generation is calculated with a complex suite of algorithms written in python by Sharp (Gallo Cassarino, Sharp and Barrett, 2018).

The MERRA data used are for ambient temperature in degrees Centigrade (model variable Tamb_oC) and ground level wind speed in metres per second (WindDem_mps) which both drive space heat demand - air conditioning is not modelled here. Global solar radiation is in Watts per square metre (Solar_Wpm2) and drives solar photovoltaic generation – the impact of solar gain on building heating and cooling is not modelled here. It is assumed that solar collectors will be near population, and so Solar_Wpm2 and the demand driving variables (Tamb_oC, WindDem_mps) are all weighted by the UK population spatial distribution by km^2; this processing by Sharp.

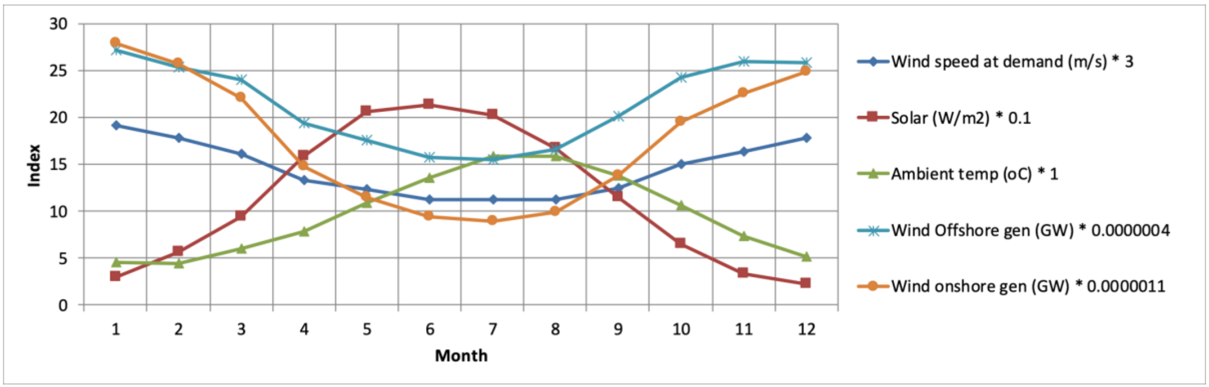
Hourly MERRA wind speeds are collated for UK onshore and offshore wind farm locations. These are then processed accounting for wind turbine height and wind speed power curves to produce normalised hourly output, GW output per GW installed for each wind farm location. These farm outputs are then weighted to produce total hourly percentage of installed capacity factors for the set of onshore (WindPowOn_pcCap) and offshore farms (WindPowOff_pcCap).

Climate change will increase ambient temperatures, as is notable in the MERRA data from 1980 to 2010, and consequently decrease space heat demand, increase air conditioning demand, and increase heat pump COP. To simply reflect climate change, additions of 2 ^{o}C and 4 ^{o}C to MERRA temperature data were modelled with ESTIMO (Gallo Cassarino and Barrett, 2021), with the result that annual space heat was reduced by 22% (2 ^{o}C) and 41% (4 ^{o}C) respectively and annual total heat by 13% and 25%; electricity for heat pumps is reduced by more than this because of a higher COP. Furthermore the seasonal variation and peaks of heat demands are also reduced, easing long term storage needs. Climate change will also have impacts on renewable generation through modifying wind speeds, and solar radiation because of atmospheric absorption and reflection, and because photovoltaic efficiency is affected by temperature. Solaun et al (Solaun and Cerdá, 2019) review research into these impacts, reporting both small positive and negative changes to generation with geographical variations, so there is no clear overall impact and the consensus seems to be the change in generation will be small.

Figure 4 shows monthly averages over 31 years of meteorology and renewable generation; the variables are scaled so as to show them on one chart.

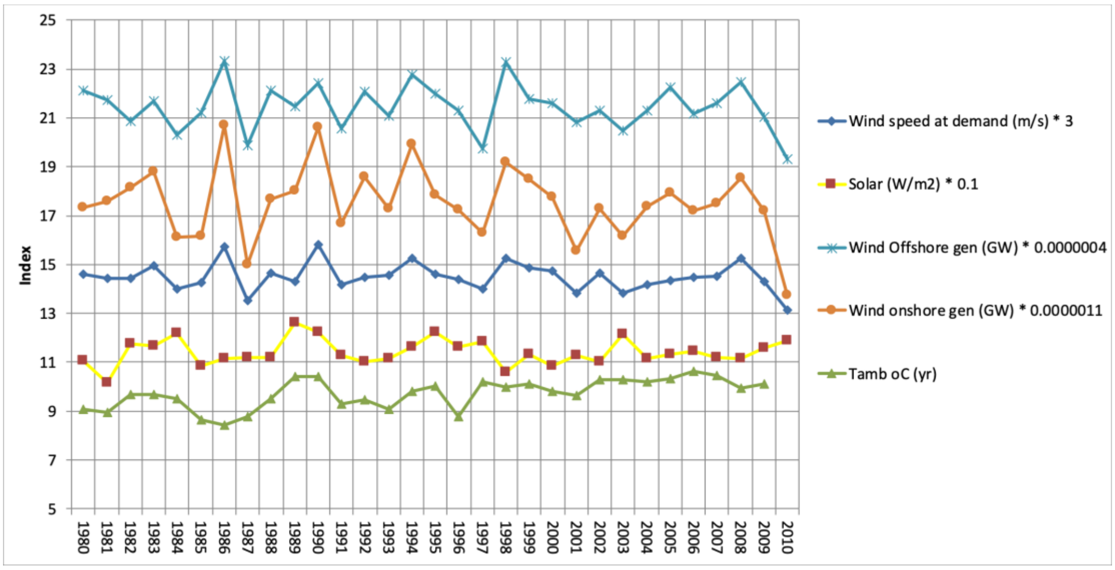
Wind speed at demand is the wind speed at ground level assumed to affect building heat exchange through air change rate and other processes and this leads to some positive correlation between heat demand and wind generation. Wind is on average highest in winter, and solar in summer. Solar is primarily driven by celestial mechanics, so it peaks in June, and the ambient temperature lags solar because the earth takes time to warm up to a maximum in July and August and then cool. These variables are the main drivers of long-term changes in demand and wind and solar supply, and therefore of long term storage needs in the system modelled here.

Figure 4 : Monthly average scaled meteorology and renewable generation



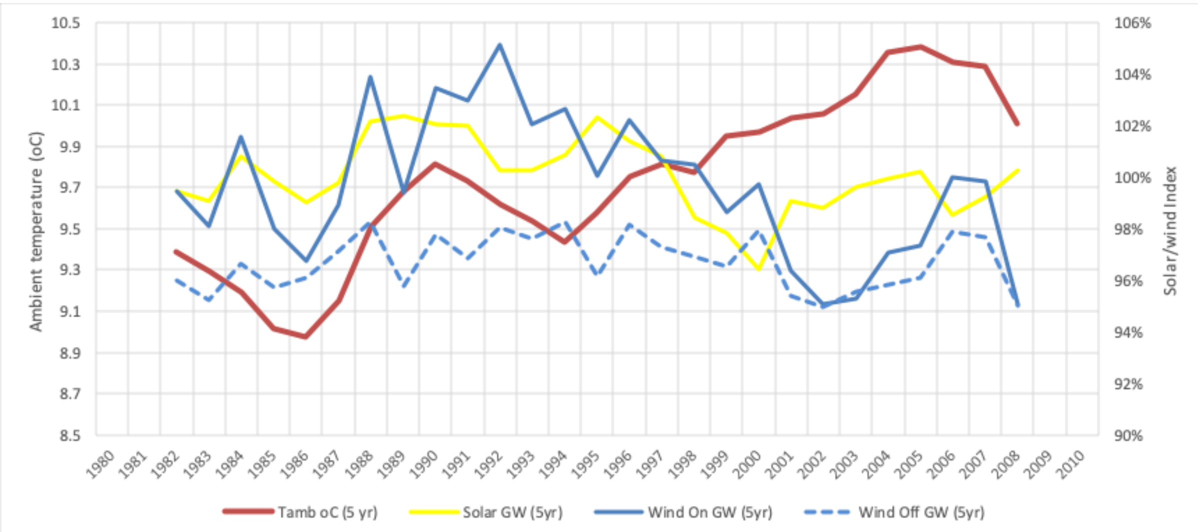
The annual average meteorology and wind power for the 31 years are shown in Figure 5; the variables are again differently scaled to show all the variables on one chart. [Demand wind speed (m/s) is the wind speed at demand WindDem_mps]. We see, for example, that 1986 had a low ambient temperature but high wind output, whereas 2010 had low temperature and low wind so *prima facie* might be a stress year with high space demand and low wind generation. However, note that annual average or total data are not necessarily revealing - the low temperature and low wind might be in summer when demand is generally low and solar high.

Figure 5 : Annual average scaled meteorology and renewable generation trends



To clarify meteorological trends, 5 year running averages of ambient temperature, solar and wind generation are shown in Figure 6. Annual average ambient temperature (population weighted) increases over the period, with the average for the last ten years being 0.71 °C higher than for the first 10 years, which may be due in part to climate change. Solar intensity (population weighted) and on and offshore wind generation show less long term variation. Assuming no substantial changes to the seasonal patterns of these variables, it may be expected that the trend will be for space heating needs to reduce across the years, but for generation to change little.

Figure 6 : Five year rolling average meteorology and renewable generation trends



	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2004	2004	2004	2004	2004	2005	2006	2007	2008	2009	2010
Tamb oC (5 yr)			9.4	9.3	9.2	9.0	9.0	9.1	9.5	9.7	9.8	9.7	9.6	9.5	9.4	9.6	9.8	9.8	9.8	10.0	10.0	10.0	10.1	10.2	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.3	10.0		
Solar GW (5yr)			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Wind On GW (5yr)			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Wind Off GW (5yr)			1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		

5. Simulation results

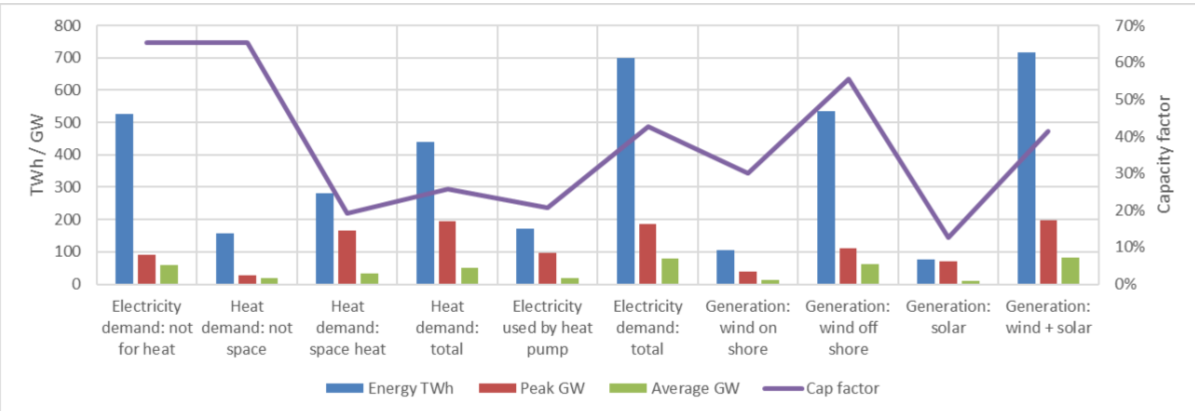
The simple model was used to simulate the system for each hour of 31 years (1980 to 2010) using hourly meteorology and renewable generation.

Figure 7 summarises the annual simulation results averaged over this period. The total heat demand is 439 TWh compared to the current approximate 450 TWh; this is supplied with heat pumps with an average weighted COP of 2.5 so that 173 TWh of electricity is used for heating. Total electricity demand averages 699 TWh which is about double 2018 UK consumption. There has been no attempt to correlate the demand and supply specification with any particular UK scenario because the model is not detailed, and system designs with net-zero greenhouse gas emissions are not yet common and there are especial uncertainties concerning international transport fuel production and atmospheric carbon capture. But, for example, National Grid scenarios produced in 2019 (National Grid, 2019) have 2050 electricity demands ranging 300-400 TWh and gas demands 400-800 TWh.

If these gas demands were mostly heating, they could be met with electric heat pumps at a COP of 2 with 200-400 TWh of electricity: this gives a total electricity demand ranging about 500-700 TWh. Wind and solar generation can be increased greatly and storage needs as a percentage of annual demand will not change very significantly as long as the proportionate mix of demands, renewables and intermediate conversion is maintained.

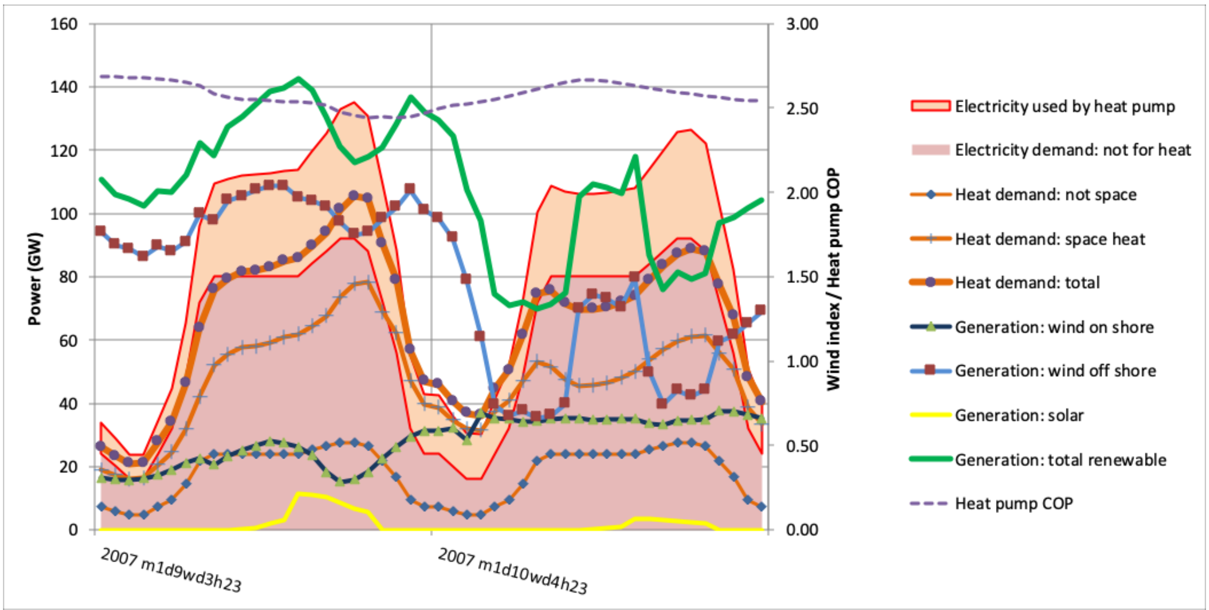
Figure 7 also shows the capacity factors, defined as average flow in the year divided by peak flow, for each annual flow. For example: the space heat demand capacity factor is just over 20%; total electricity demand just under 40%; solar generation about 13%, and offshore wind about 55%.

Figure 7 : Annual averages 1980 to 2010



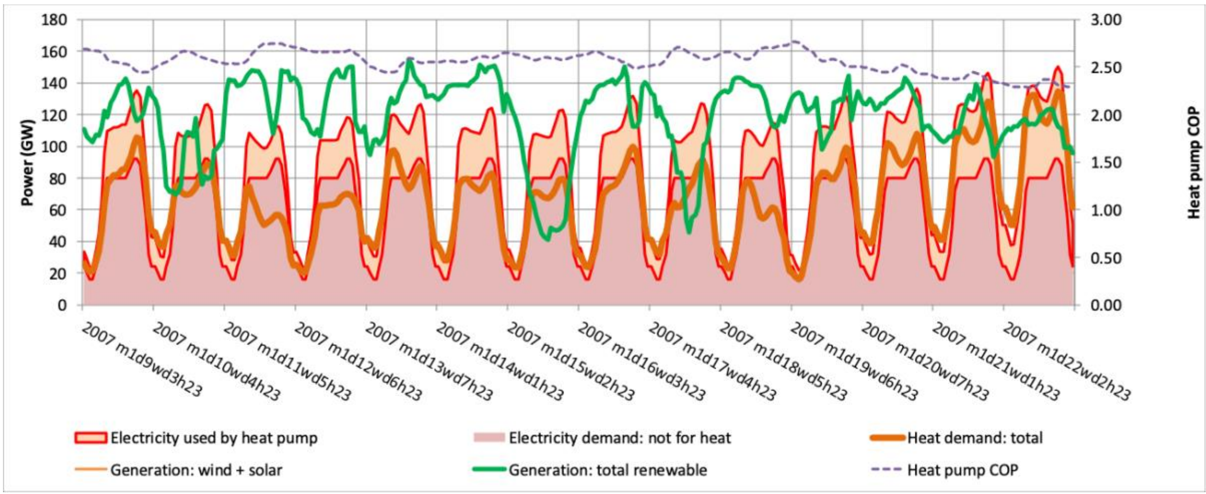
Figures 8 and 9 show randomly chosen simulation samples for 2 and 14 winter days in 2007 (the x-axis label code is Year Month DayOfMonth DayofWeek Hour). The energy flows and heat pump COP are for each hour, not accumulated. The electricity demand (delivered) for heat is the heat demand divided by the heat pump COP. As the ambient temperature falls, space heat increases and the heat pump COP decreases, and as electricity for heat equals heat demand divided by the COP, the electricity required for driving the heat pump is very sensitive to ambient temperature.

Figure 8 : Two days sample simulation – winter 2007



During the 14 winter days shown in Figure 9, the peak occurs during the last day at 17:00 hrs.: at this time the space heat load drives a peak total heat load of 135 GW met by 58 GW of electricity driving a heat pump with a COP of 2.3, the COP is near a minimum at this time. Adding 92 GW of electricity specific (non-heat) demand sums to a total electricity demand of 150 GW. In the second chart of Figure 9 the net surplus or deficit – total electricity demand-total generation is plotted for the 14 days. There is a deficit at the peak time, but it is not as large as on the 7th or 9th days. This illustrates that ambient temperature, driving space heat demand, is not tightly correlated with wind and solar generation on short time scales, though of course they are statistically related seasonally. As might be expected, the surplus mostly occurs during the night as demand is higher during the day and wind is fairly evenly spread across the day, and this is when smaller stores with a capacity of a few hours or days such as EV batteries and consumer heat stores could mostly be charged.

Figure 9 : Two weeks sample simulation – winter 2007



The operation of the system in a summer fortnight of 2007 is quite different from that in winter, as shown in Figure 10. The heat demand is lower and the heat pump COP higher so electricity for heating is lower. Wind generation is lower but solar generation higher. In this selected fortnight, there is a general deficit of generation. This might suggest more solar capacity is advantageous.

Figure 10 : Two weeks sample simulation – summer 2007

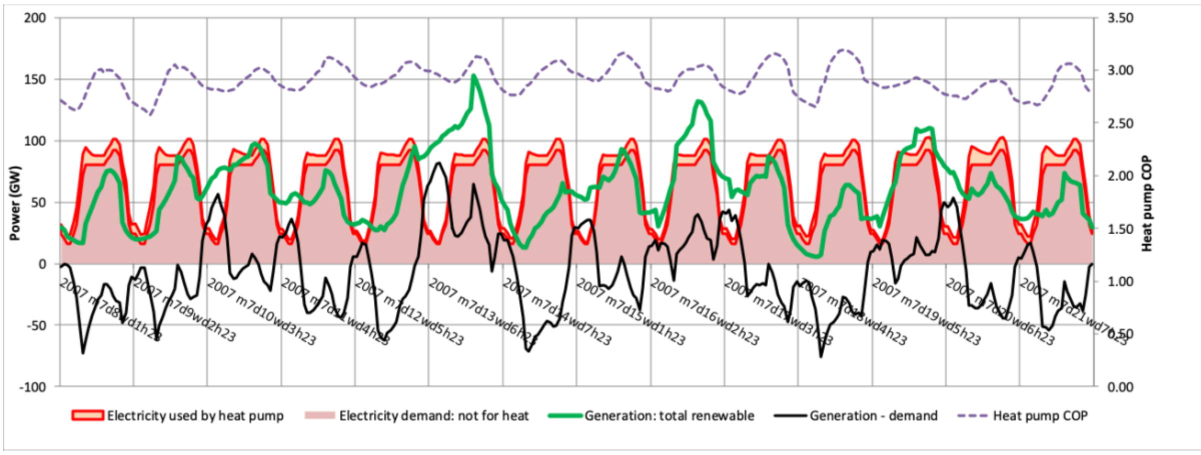
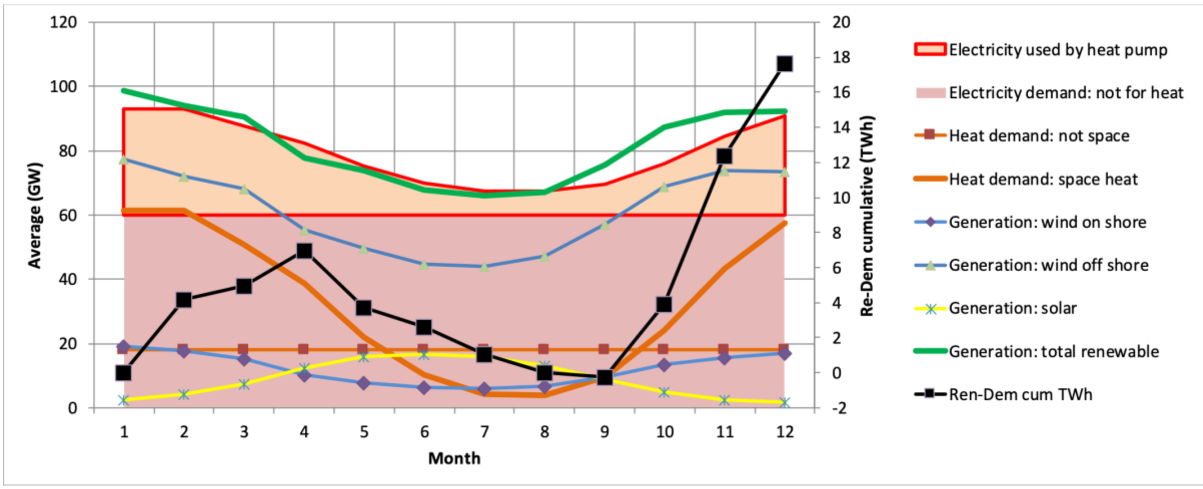


Figure 11 shows the average monthly flows and cumulative levels. On average there is a cumulative surplus at the end of the year. Of note is that the surplus falls from month 4 to reach a minimum in month 9. This indicates that for this simple, illustrative system, solar generation might be increased relative to wind to maintain the surplus in summer.

Figure 11 : Average monthly flows 1980-2010



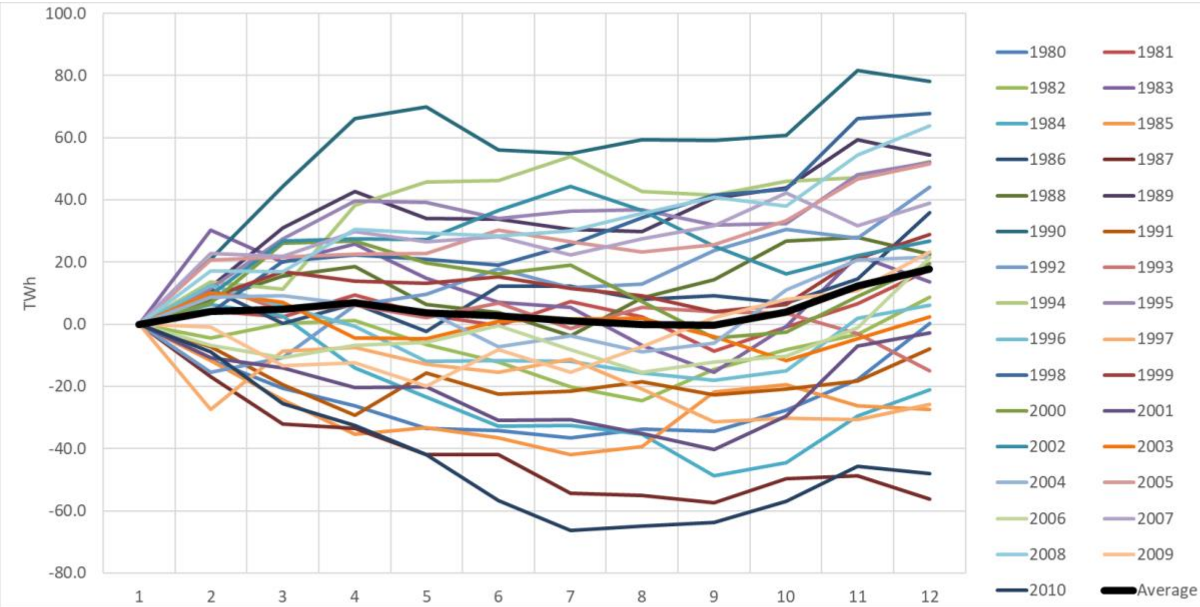
The curves of cumulative net difference (renewables-demand) for each month and the years 1980-2010 are shown in Figure 12 below. The simulation starts on January 1st each year; starting at a different time would not ultimately affect the cumulative difference over years and the consequent storage needs. It is not possible to clearly label the curves with a year; the point is to show that some years have surpluses and some deficits, and to show the average pattern of cumulative difference across all years.

Where the cumulative difference is negative at the year's end, there is excess demand in the year; in those years energy is needed 'in store 'at the beginning of the year to avoid the cumulative residual demand falling below zero. Where the cumulative difference is positive there is a surplus of generation over demand, some of which might be stored. For the two extreme cases:

i. The minimum of these curves is -66 TWh in month 7 in 2010; therefore 66 TWh of stored electrical output would be required at the beginning of the year to meet this maximum deficit / minimum surplus.
ii. The maximum of these curves is 82 TWh in month 11 in 1990; therefore 82 TWh of electrical input storage capacity would be required at the beginning of the year to absorb this maximum surplus.

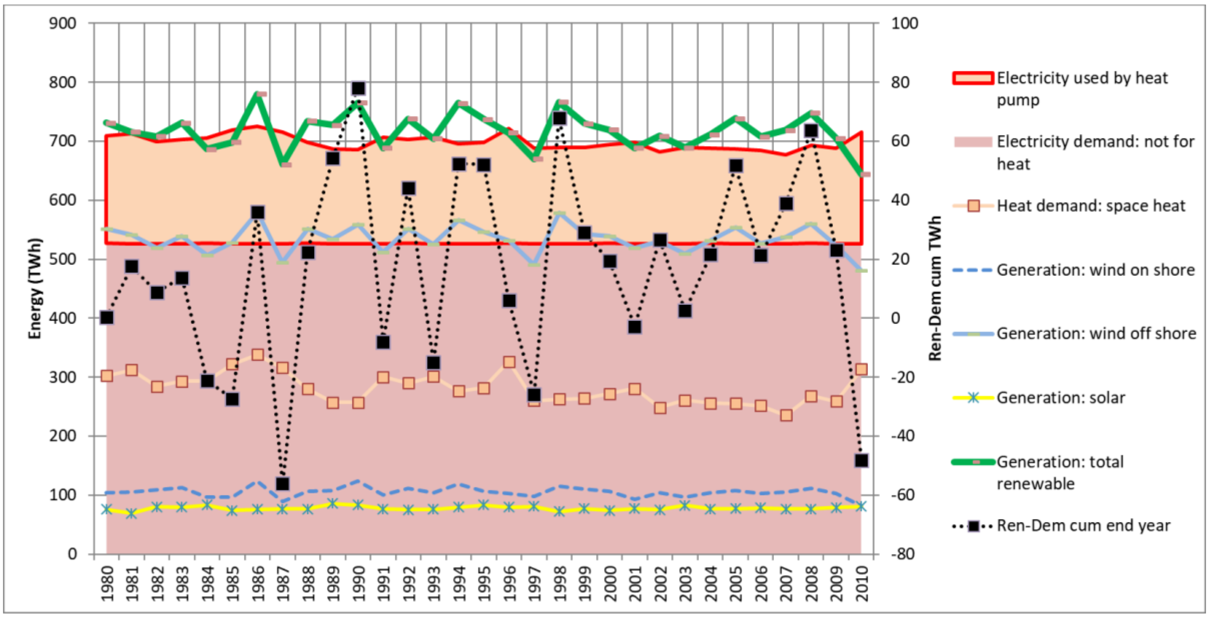
Because of the storage throughput inefficiency, there will be asymmetry between output and input which is not accounted for - cumulative difference is not the same as the actual storage technology capacity needs. The minimum calculated (i above) is the minimum stored energy at the beginning of the year needed to ensure demand is met, so this is critical. The maximum (ii above) is the storage required if no renewable spillage is to occur. The average monthly curve shows the average minimum to occur during August/September.

Figure 12 : Monthly cumulative renewables-demand - 1980 to 2010



The annual energy flows and cumulative (supply-demand) levels at the end of the year are shown in Figure 13. Wind provides the main year to year fluctuations in supply and offshore wind more than onshore wind. Space heating also varies as driven by changes in mean ambient temperature. It may be seen that a maximum cumulative difference ranges from about +/- 60 TWh, or +/- 10% of average annual demand. There is no immediately obvious correlation between sequential years in term of cumulative surplus.

Figure 13 : Annual results 1980 to 2010



The hourly difference (supply-demand) cumulated over 31 years, and the annual totals, are shown in Figure 14. There was no attempt to match overall supply and demand in each year. The supply system matches demand in 1980 and then responds to variations in wind, affecting supply and ambient temperature affecting demand, hour by hour and year by year. In this particular simulation, an initial energy 'storage' of 20 TWh is required in order that the cumulative surplus does not fall below zero across the whole period 1980-2010. The cumulative difference – excess supply over demand - increases particularly in the later years. This is because the average ambient temperature increases during this period, as noted in section 4, which decreases space heat demand and increases heat pump COP, and therefore reduces electricity used by the heat pumps. This results in a cumulative surplus over the period of 31 years of 600 TWh (with most of this arising 1990-2010), or 3% of average annual demand per year. However more detailed analysis is needed of the variations in demand and wind and solar across these years to detail why the cumulative surplus supply increases. It may be assumed that global warming will further reduce space heat needs and increase the (currently smaller) air conditioning demand: and if wind and solar generation is not affected appreciably, then storage need will likely be reduced in this simple system. Extending the modelling using MERRA data before and after the period 1980-2010 would make conclusions about the long-term variation in temperature, demand and renewable generation more robust.

Figure 14 : Cumulative supply-demand 1980-2010

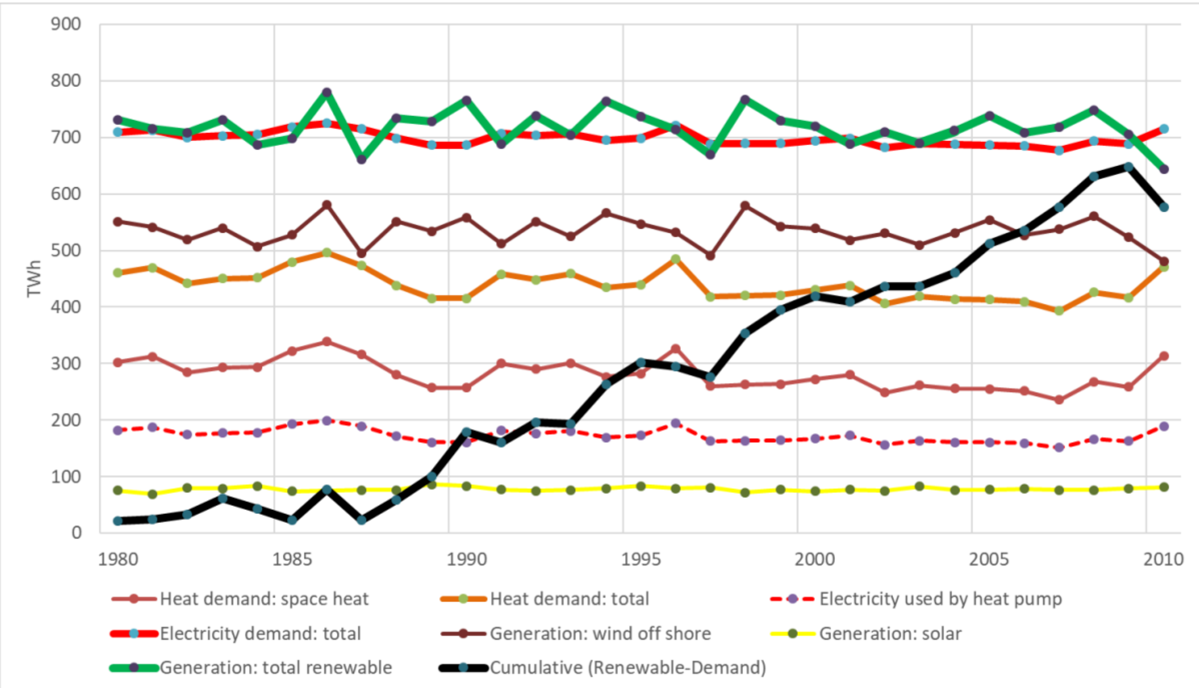
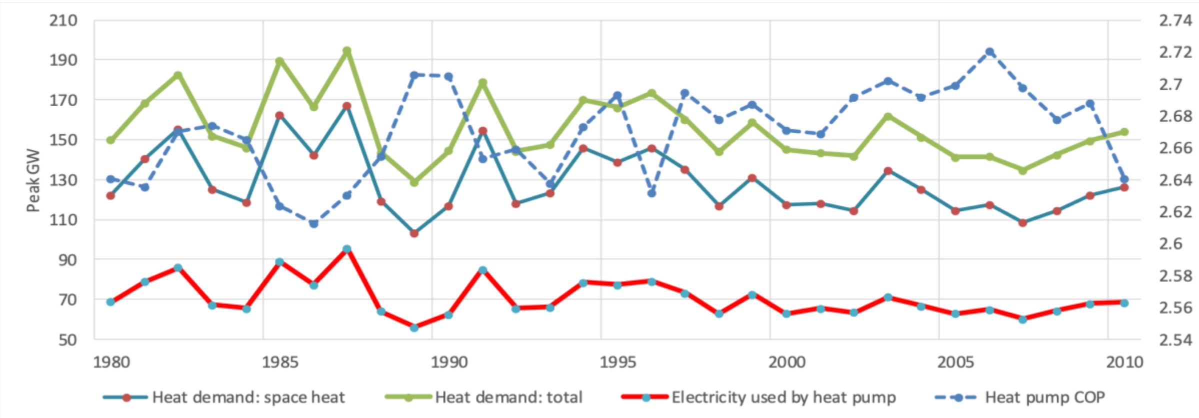


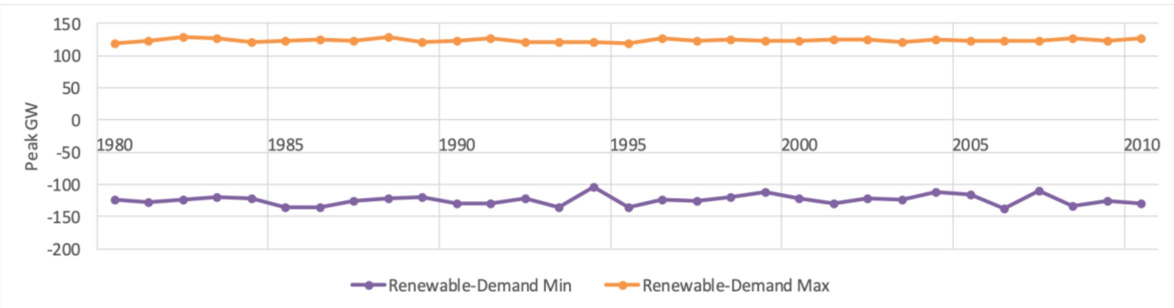
Figure 15 shows the peak heat demands and electricity supplied to heat pumps in each year 1980 to 2010. The peak flows in the system are important as they determine the installed power capacity requirements needed to ensure secure consumer services. For example, primary stores of biomass or gas input to generators of a capacity to meet peaks might be used when all other stores are exhausted. During this period, a reduction in the peak space heat and therefore total heat demand and heat pump electricity may be discerned: the average peaks in the period 2001-2010 are 12% less than in 1980-1989. It is also notable that the variation in peak from year to year gradually diminishes.

The second chart in Figure 15 shows the peak (in any hour of the year) surplus and maximum deficit (renewable – total electricity demand) in each year. These are generally in the range +125 GW peak surplus and -125 GW deficit. This gives a guide as to the maximum power capacities of storage input and output required. Note that stores of surplus, such as batteries or hydrogen, will not in general be the same as stores to meet deficit, such as biomass for input to CHP.

MERRA data for after 2010 are required to see if these trends continue.

Figure 15 : Peaks – heat, heat pump electricity, average COP, surplus and deficit





6. Variant scenarios: Increased renewable capacity

These variant scenarios explore the option to reduce storage need by increasing renewable generation. This will cause more renewable energy surplus which might be spilled or exported. Three variants of System 1, called System 2.1, 2.2 and 2.3, are developed where everything is the same except for wind and solar capacities: the Systems are shown in Table 2. There is no economic justification for the capacity mixes of System 2, or indeed System 1, and the optimal balance between generation, storage and interconnectors will ultimately mainly be determined by cost minimisation.

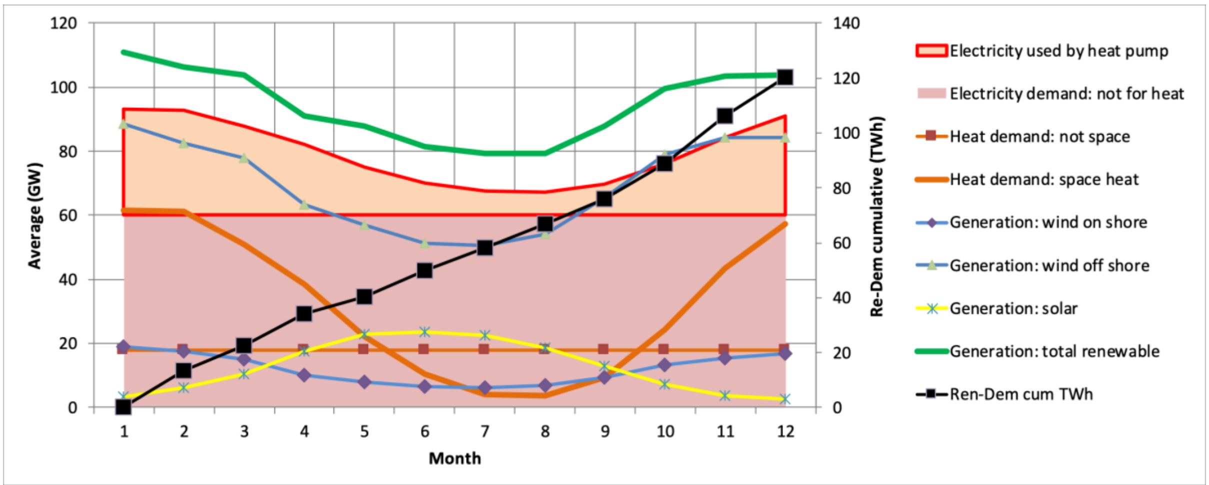
Table 2 : Systems 1 & 2 – renewable capacities (GW)

	System 1	System 2.1	System 2.2	System 2.3
Wind capacity: onshore	40	40	40	40
Wind capacity: offshore	120	130	140	160
Solar PV capacity	70	110	110	120

Some detail is first shown for the System 2.1 simulation, with a summary of System 1 and 2 given at the end of this addendum.

Average monthly results for 2.1 are shown in Figure 16. There is an average surplus of 120 TWh at the end of the year; this is 19% more than average annual demand.

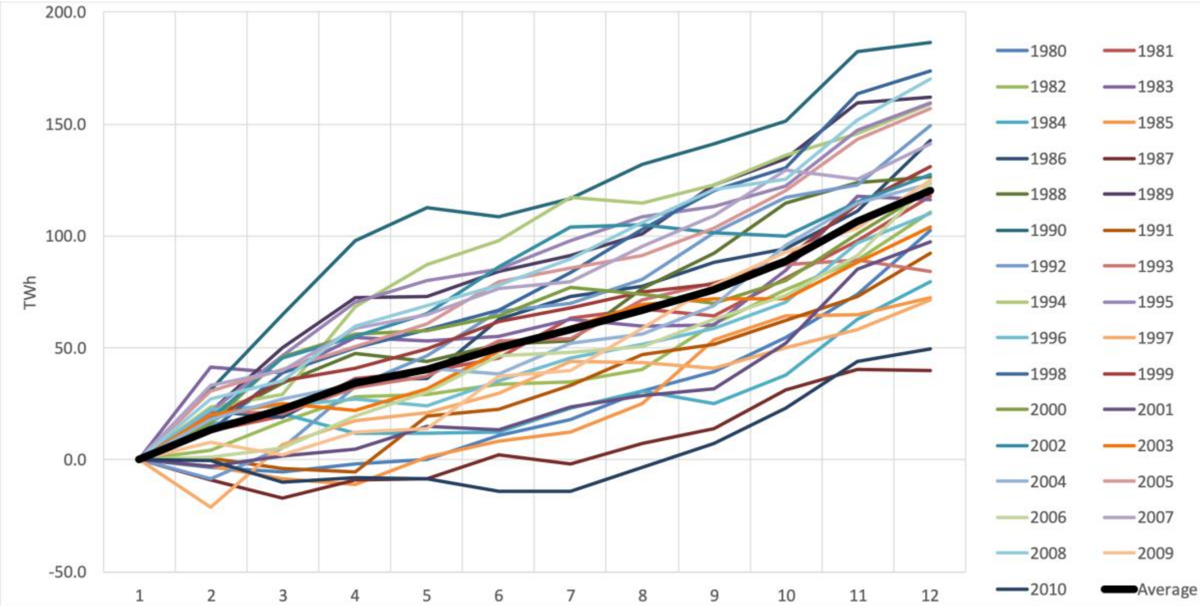
Figure 16 : Average monthly flows 1980-2010 (System 2.1)



The cumulative deficit (renewables-demand) for each month and year for System 2.1 is shown in Figure 17. The solar capacity has been increased by 57% as compared to offshore wind (8%) with the result that the maximum cumulative deficits are quite evenly spread over the first 6 months of the year: and are 21 TWh (month 2, 1997), 17 TWh (month 3, 1987) and 14 TWh (month 6, 2010). The deficits are more evenly spread across the year as compared to System 1.

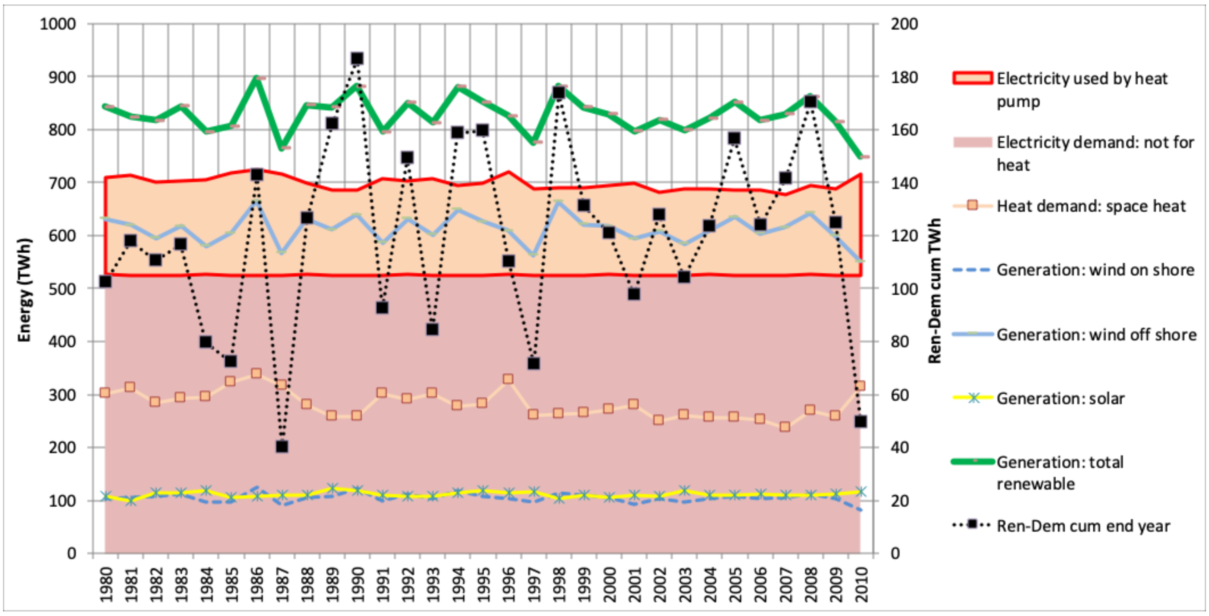
The maximum deficit of System 2.1 is 21 TWh in 1997 as compared to the System 1 maximum of 60 TWh: this is the minimum amount of energy needed 'in store 'at the beginning of the year. The minimum storage need is reduced by 40 TWh (65%) through increasing generation to give an average annual surplus of 120 TWh (19%). Comparing Systems 1 and 2.1, we see the trade-off between minimum storage need and renewable generation capacities.

Figure 17 : Monthly cumulative renewables-demand - 1980 to 2010 (System 2.1)



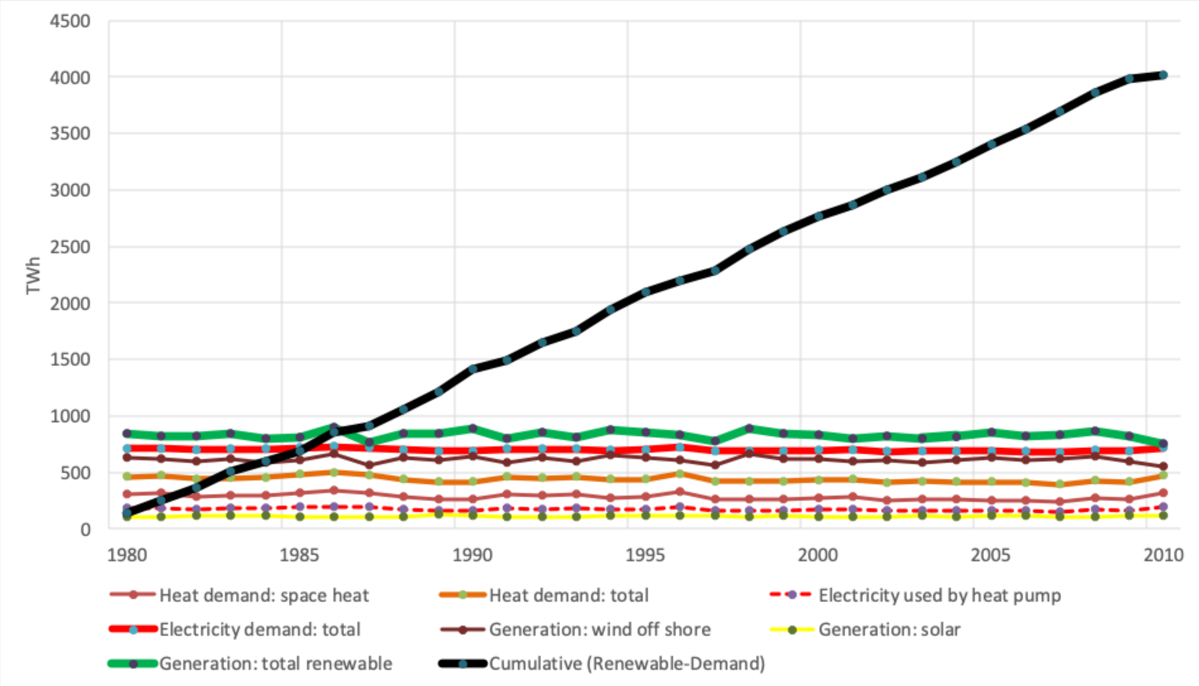
System 2.1 annual results are shown in Figure 18. The annual surplus of generation for every year is clear, but of course there are still deficits in some months of some years as shown in the previous Figure.

Figure 18 : Annual results 1980 to 2010 (System 2.1)



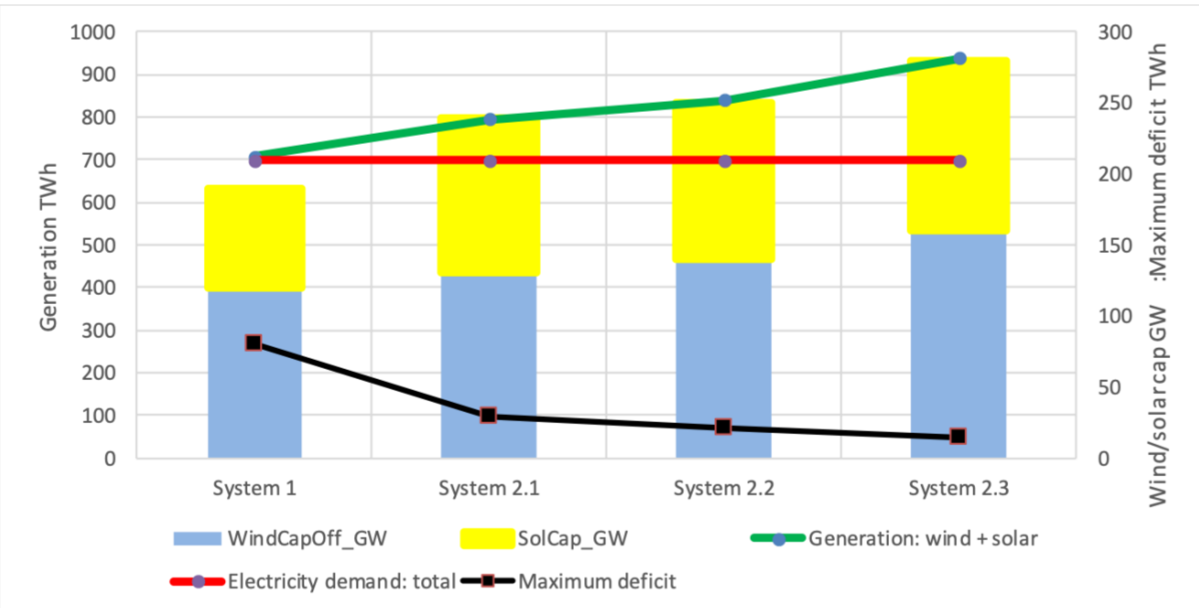
And there is a cumulative surplus of 4000 TWh over 31 years as shown in Figure 19.

Figure 19 : Cumulative supply-demand 1980-2010 (System 2.1)



The four Systems 1, 2.1, 2.2, and 2.3 were simulated over 31 years with summary results shown in Figure 20. The excess generation over System 1 rises: to 14% in System 2.1, 20% in 2.2, and 34% in 2.3. The maximum deficit decreases, but slower than the excess generation – there are decreasing marginal benefits in terms of storage need by increasing generation with the assumed mixes.

Figure 20 : Renewable generation and maximum deficit for System 1 and 2



A proportion of the excess generation might be stored (e.g. as hydrogen or ammonia) but absorbing excess engenders costs – for example for hydrogen electrolysers and storage and the more is absorbed the lower the capacity factors of storage systems. Ultimately adding to UK storage would be futile as the stored energy would never be used in the UK and therefore the excess would either be spilled or exported.

Export could be in the form of electricity or in the form of synfuels such as hydrogen or ammonia, but this may be less desirable as it is perhaps lower cost and higher efficiency to export surplus electricity and have the hydrogen or ammonia synthesis plant sited in other countries. Synthesis plant in central Europe might produce at a lower total cost than in peripheral countries. The surplus might also release some biomass for export, but this is unlikely because the current UK biomass is probably insufficient to meet aviation fuel demand, even with supplementary energy and electrolytic hydrogen.

The simple model has illustrated the interplay between two of the options - storage and renewable capacity - for variable demand and supply matching. In ESTIMO the model is of a more realistic system and it includes the third option of European interconnector trade which has been shown to have a major impact on storage need – see Gallo Cassarino et al (2018). In ESTIMO, the capital and operational costs of all components are calculated such that optimal least cost combinations of the basic three balancing options can start to be identified – see Gallo Cassarino and Barrett (2021).

7. Discussion

The discussion is of the simple system and simple model results, and of what a more realistic energy system would look like, and how it can be modelled.

7.1. Simple system and modelling in this report

This modelling of a simple all electric demand and renewable supply system shows that both in-year and year to year demand and renewable variation pose a significant challenge for matching supply and demand, and thence for storage or trading. The modelling shows the variable nature of meteorology over all periods and therefore of demands and wind and solar renewable generation. More elaborate modelling will not remove this fundamental variability. It should be noted that energy production from some other renewables such as hydro and biocrops can vary significantly from year to year because of meteorology, notably precipitation and ambient temperature.

The modelling showed that the cumulative surplus increased little in the years 1980-1985 but thereafter generally increased: this is because of the increase in ambient temperature lowering space heat demand and increasing heat pump COP. It also showed that peak heat demands reduce over the period 1980-2010. It would be useful to extend the meteorological data set to before 1980 and after 2010. It should be noted that increasing solar and wind capacities such that they generate significantly more than demand and therefore more energy is spilled will reduce storage need; so also will international trade through interconnection. The optimal balance of overcapacity, storage and interconnection will depend on the relative costs of these.

Given the simplified all renewable electric energy system and the assumed system definition inputs, the model indicates that a minimum about 60 TWh of cumulative difference ('storage'), or 10% of annual demand is needed at the start of the year to avoid a shortfall in the worst year. The maximum surplus of renewable generation in any hour across the years is about 125 GW, and coincidentally the maximum deficit is also about 125 GW. These gross results for cumulative energy and peak differences give approximate scope to the storage required. If the relative proportions of demands and renewables are not changed then the percentage of annual demand storage required will not change significantly because offshore wind and solar resources are very large and can be scaled up.

The cumulative differences calculated effectively reflect electricity storage with an efficiency of 100%. The actual technology capacity would have to account for the round-trip efficiency of input, standing losses and output from the store would need to be accounted for and addressed with the provision of additional capacity. For illustration: if the storage were biomass for input to a 50% efficient power station, then 60 / 0.5 = 120 TWh of biomass would be needed; if the biomass were input to district heating CHP with an overall efficiency of 80% (30% electrical plus 50% heat efficiency), assuming the heat and electricity outputs could be matched to demand, perhaps using district heat storage, then 60/0.8 = 75 TWh of biomass would be needed. For reference, assuming a calorific value of 17.5 GJ/t (Kofman, 2010), the wood pellet supply system to Drax power station includes 320 kt (1.6 TWh) of storage at the power station (DraxBiomass, 2020b) and 200 kt (1.0 TWh) at the Immingham dock (DraxBiomass, 2020a), to give a total 2.5 TWh of storage. This is of the order of 2%-4% of the total storage required in the simple system modelled here, though it is not suggested that this is the best use of biomass – it might be reserved for premium uses such as for aviation fuel synthesis.

The performance of some components will improve in the future and significantly impact storage needs. On the demand side, space heat depends on building efficiency and delivered electricity for that depends on the heat pump COP, especially at low temperatures: improvements to these would substantially impact on seasonal heat demand variation. The increasing size and offshore siting of wind turbines increases capacity factors. Over the period 2005 to 2018 aggregate offshore capacity factors have increased from about 30% to 40% (The Crown Estate, 2019).

Currently (2020) the average offshore UK installed wind turbine is typically 3-5 MW capacity, but the largest wind turbine installed in 2020 is 12 MW (GERenewableEnergy, 2020), located at Rotterdam, for which the capacity factor is projected to be 63%. SiemensGamesa are producing a 14 MW turbine which should be ready for the market in 2024 (SiemensGamesa, 2020). A study for the UK (DNV-GL, 2019) projects offshore capacity factors of 50-60% by 2030. Designs for wind turbines of up to 50 MW are being developed, as reported by gtm (gtm, 2020), so it may be that factors higher than 60% are realised over the coming decades. The offshore wind modelled in this work has a capacity factor of about 55% averaged over 31 years and so might reasonably represent future factors. In general, higher capacity factors will mean less storage, but the exact impact depends on how the generation is distributed across the year relative to demands.

This simple model might be further applied with different assumptions about demand and renewable mix. On the demand side, the assumptions of building heat loss characteristics driving heat demand and heat pump performance are particularly important as these together strongly impact annual heat demand and electric heat consumption, and its seasonality. However, the model used is too simple and restricted to take the analysis further and reach detailed robust conclusions. The main limitations are that vectors and storage other than electricity and international electricity trade are not included, and neither are costs.

7.2. More realistic systems and modelling

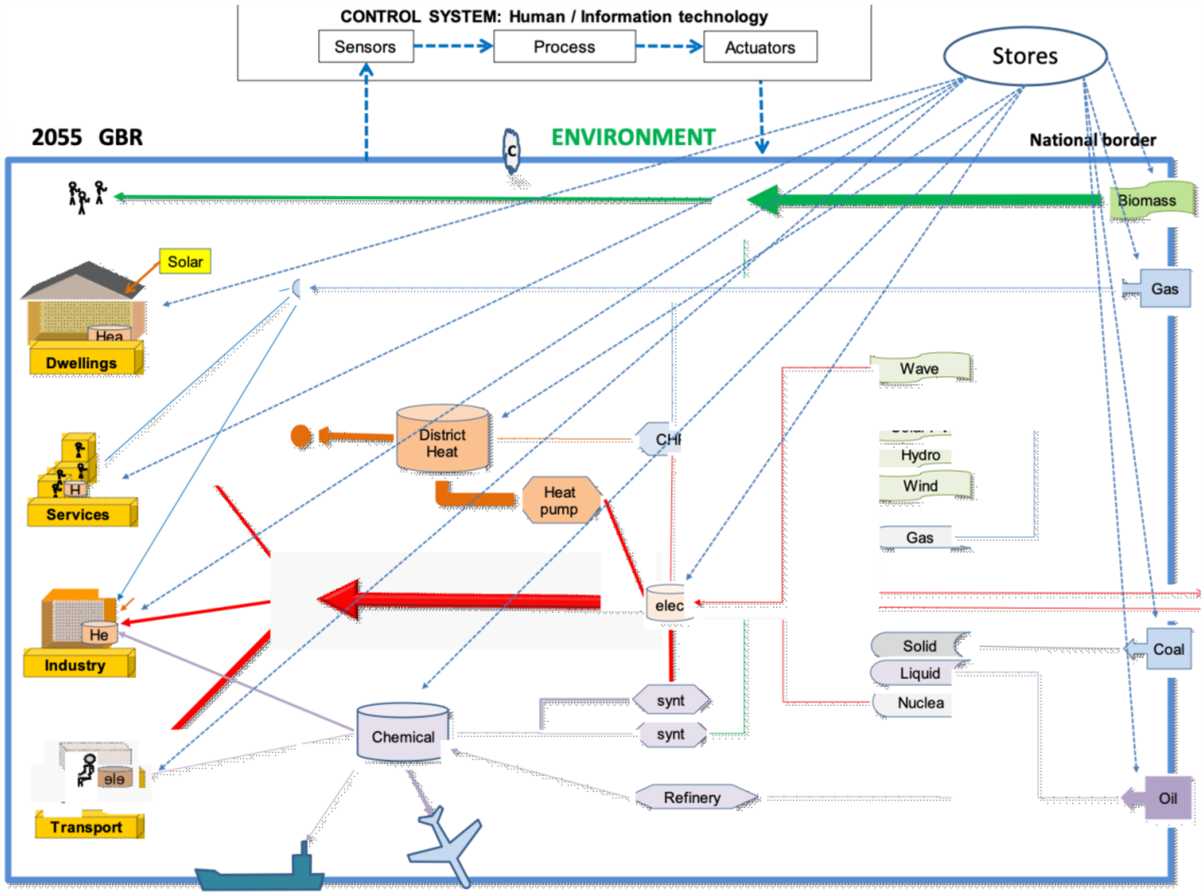
A diagram of a more realistic energy system is shown in Figure 21 as taken from a DynEMo (Dynamic Energy Model) simulation for 2055 (see below and (Barrett and Spataru, 2016)). This represents a national energy system. It shows some of the points (13 in all) where storage of different kinds (chemical, electricity, heat) can be connected in the system to different vectors: at consumers, in intermediate systems such as electricity, district heating and synthetic fuel production, or as primary energy. Modelling needs to account for a full set of sectors, service demands, intermediate systems (synthetic fuels, district heating, etc.) and multiple storage types (heat, electricity, chemical, etc.) and sizes connected at different points in the energy system. Renewable heat (solar, geothermal) and other renewable electricity (hydro, geothermal) and biomass sources should be included. Hydro and biocrops are also strongly affected by meteorology; hydro is subject to large inter-annual variations.

Also shown in Figure 21 is a schematic of the control system. The engineering performance of stores and other individual technologies can be modelled accurately in isolation. However, it is harder to devise dynamic whole system control strategies which change the inputs and outputs of all the various stores and consequent flows across the national and international system hour by hour across the seasons so as to efficiently utilise renewables and other system technologies and thereby minimise operational costs and emissions.

This system needs to be modelled in order to arrive at energy system operation combining the options of storage, transmission and renewable spillage, as set out in section 1, at low or least cost. This poses challenging questions, for example:

- If there is a surplus of renewable electricity, how should this be allocated to the different stores, such as to district or consumer heat pumps and stores, EV batteries, or hydrogen production?
- If there is a deficit, which stores should be used first – e.g. electricity from batteries or a biomass generator?
- Should some energy be retained in stores over long periods so as to meet maximum deficits during peak winter demands?
- How can meteorology short-term forecasts or long-term statistics be used for managing optimal operation over days or months?

Figure 21 : A more realistic energy system



The operation of this more realistic system has been simulated with the DynEMo model which includes control algorithms, as described in (Barrett and Spataru, 2013a), (Barrett and Spataru, 2013b) and (Barrett and Spataru, 2016). However, DynEMo is limited in two particular respects: a long-term meteorology data series is not used, and trade was not accounted for as this requires also concurrently simulating the countries or regions which the UK is connected to with transmission.

Building on DynEMo, these two deficiencies have been resolved with the ESTIMO (Energy Space Time Integrated Model Optimiser) model developed by Barrett and Gallo Cassarino. ESTIMO simultaneously simulates (hourly) each country or region within a trading bloc using MERRA data for each country. ESTIMO includes algorithms for storage management within a country and for trading surpluses and deficits between countries using storage where possible, within transmission constraints. Early analysis with ESTIMO (Gallo Cassarino, Sharp and Barrett, 2018) showed that electricity trade between the UK and other European countries might reduce European storage needs by about 30%.

Currently ESTIMO simultaneously simulates five regions: the UK, and regional aggregates of NW, NE, SW and SE Europe. ESTIMO has been applied to construct nine zero emission renewable systems with different electric and hydrogen heating shares showing, inter alia, the interdependence of required renewable, interconnector and storage capacities in providing system reliability; this is reported by Gallo Cassarino and Barrett (Gallo Cassarino and Barrett, 2021). The optimum balance between these capacities depends heavily on the relative costs of these. In the ESTIMO scenarios supported by ancillary optimisation, 40-50% of the renewable electricity is spilled, as this is lower cost than increasing storage.

ESTIMO was used to explore the impact of climate change on demands and certain renewable supplies and thus be used to design robust 100% renewable systems for the UK and Europe. It was found that climate change reduces space heat demand by about the same amount as it increases space cooling demand: this changes the seasonality of electricity demand and will alter the optimum balance between wind and solar generation.

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