Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 42 (2013) 670 – 679
Energy Procedia

The Mediterranean Green Energy Forum 2013, MGEF-13

Storage in energy systems

Mark Barrett[a]*, Catalina Spataru[a]

[a]University College London, Energy Institute, 14 Upper Woburn Place, London WC1H 0NN, UK

Abstract

The potential role of any energy system component, including storage, can only be assessed within a whole system context. The whole system of demands, supplies and stores must be modelled over timescales from minutes to months in order to accurately calculate energy flows, costs and emissions. In this paper, a hypothetical future national energy system with high efficiency and large components of renewables and storage has been posited. Modelling includes 'smart' algorithms to control the stores and other system components as demands and renewable supplies vary over different time periods. Here, a sequential allocation (SA) algorithm has been applied and it is seen that it performs well in that stores reschedule energy flows to make good use of renewable energy. The performance of stores and their inputs, such as heat from a heat pump, can be highly non-linear and the challenge remains to better simulate and optimise the configuration of the energy system including storage at the same time as optimising dynamic system control.

Selection and peer-review under responsibility of KES International

Keywords:energy storage, policy, whole energy systems model

1. Introduction

The UK has objectives of an 80% carbon dioxide reduction by 2050 over 1990 [4] and 15% renewable energy by 2020, a large fraction of which will be renewable electricity from wind [7, 8]. In addition, an important objective is enhancing energy security. Meeting these objectives requires significant, rapid changes to demand, supply, storage and transmission. Most UK energy is currently supplied from large natural or artificial stores of fossil and nuclear fuels and the output from these can be regulated so as to meet energy demands as they vary across the day and the year. To meet energy security and environmental objectives, it is necessary to increase energy supplies from renewable sources which vary

---

* Corresponding author. Tel.: : +44 (0)20-3108-5983.
E-mail address: mark.barrett@ucl.ac.uk.

Selection and peer-review under responsibility of KES International
doi:10.1016/j.egypro.2013.11.069

uncontrollably, such as wind and solar. To match these renewable supplies to energy service demands hour by hour, there are two technology options which may be deployed: a) storage to alter the timing of energy flows and b) transmission to even out demands and supplies with spatial diversity. The potential of these, or indeed any connected energy component, can only be assessed within a whole system context as most connected components directly or indirectly affect the energy flows through every other. Storage is used to alter the timing of service and energy flows in a system. It includes the storage of:

i. Service, such as operating a dishwasher at night and storing the clean dishes for the morning
ii. Secondary energy, such as heat, cool, hydrogen or electricity
iii. Primary energy, such as renewable biomass or hydro, or fossil energy such as gas or coal

Hereafter, the paper will be confined to types ii and iii only.

2. Storage technologies

There is a range of technologies storing energy in different forms, including chemical (gas, liquid, solid), potential energy (pumped storage), sensible heat, kinetic, electrochemical; and these stores can have a range of energy input and output forms. From a system perspective, stores are more often labelled by the type of energy they input and output (e.g. pumped storage is an electricity store) rather than the form in which the energy is stored, as this latter is invisible to the system.

Examples of storage include:

- thermal storage embedded in end use technologies such as buildings and refrigerators where storage output has no control
- thermal stores (sensible heat - water tank, ceramic; phase change- molten salts)
- electricity storage (chemical – batteries; pumped storage – gravity; kinetic - flywheels)
- chemical storage ((hydrogen, ammonia, methane)

These may be applied in different locations and at different scales. Summaries of some storage technologies may be found in various papers (some examples can be found in [9], [10], [11], [12], [13]). From a systems modelling perspective, a store may be technically characterized by the forms of energy input and output, the capacity of the store (kWh), the input and output maximum power (kW), the efficiencies of input and output to give the storage throughput efficiency, and the standing losses (e.g. the heat losses from a heat store). Other features, such as the volumetric (kWh/m3) and mass energy density (kWh/kg) of storage, can critically affect potential application, especially in the transport sector. The technical performance of storage and its charging and discharging processes generally vary dynamically. For example: the heat loss of a sensible heat store (e.g. a hot water tank) increases with temperature; the efficiency of charging and discharging an EV battery varies with power, voltage and storage level; heat storage is a means for storing the heat output from a heat pump when utilizing low cost or low carbon electricity, however, as the temperature of the store increases the efficiency of the heat pump decreases and therefore more electricity is required to supply a given amount of heat – even though it may be at lower cost and carbon. The performance of stores such as batteries can deteriorate with use. Stores also have capital and running costs, and environmental impacts because of physical size, or engendered by their energy losses, and so on.

3. Model and energy system

A dynamic energy model (DynEMo) ([1]; [3]) has been used to simulate and aid the design of the system with optimization, including energy storage. DynEMo calculates the flows of energy over periods of minutes to years. DynEMo models stores as aggregates – e.g. the millions of domestic heat stores are modelled as a single store. In reality, there will be a diversity of storage levels in stores which means that the potential input capacity (MW) to the aggregate will not be either zero or maximum, but will gradually reduce as the aggregate fills to its maximum level. In this paper we will consider a posited future UK energy system (see Fig. 1 for principal components) in which there are high levels of energy efficiency, a shift from gas and oil to energy delivered as electricity and heat, and primary supply dominated by wind, solar and biomass. The system has seven 'electrically connected' controllable aggregate stores which store electrically produced energy such as electricity itself or heat (all of which are sensible heat stores): three heat stores located in the domestic, services and industrial sectors; batteries in electric vehicles (cars and vans); heat storage in district heating with inputs from electric heat pumps when there is surplus renewable output, or from CHP otherwise; a chemical store for synthetic transport fuels (ammonia, hydrogen); and an electricity system store (pumped storage). In addition, there is uncontrolled thermal storage in solar pre-heat water tanks and in the fabric of buildings; the thermal storage in dwellings is explicitly modelled so as to reproduce the heating up and cooling down of the fabric. Altogether nine aggregate stores are modelled. Other stores could be included in the future: for example, cool (low temperature heat) can be stored in water or ice to use later for cooling a building.

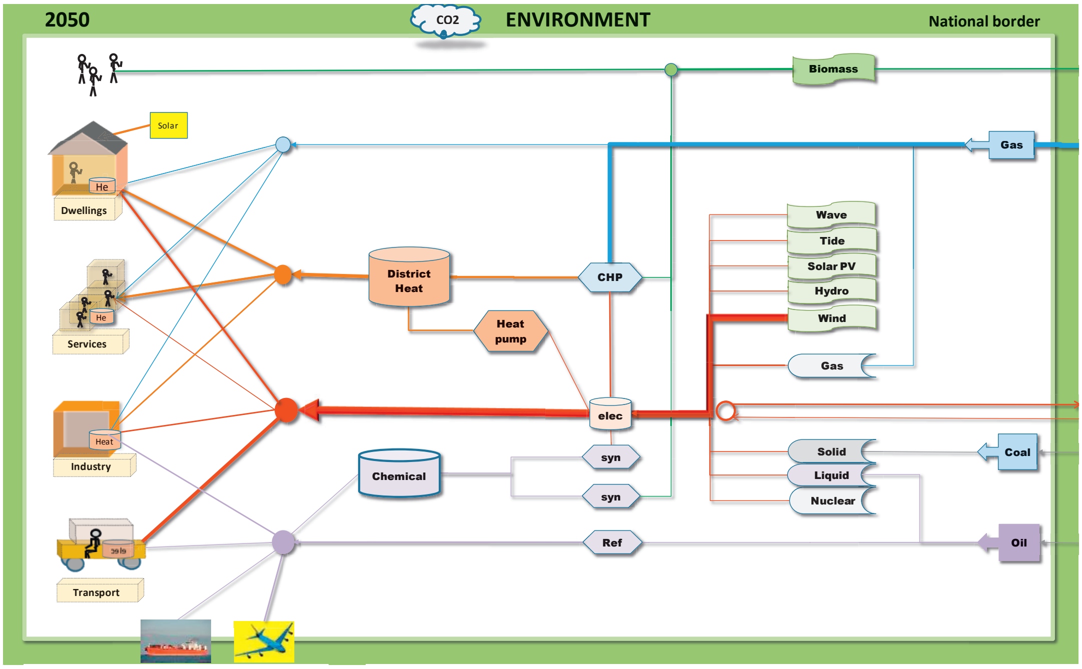
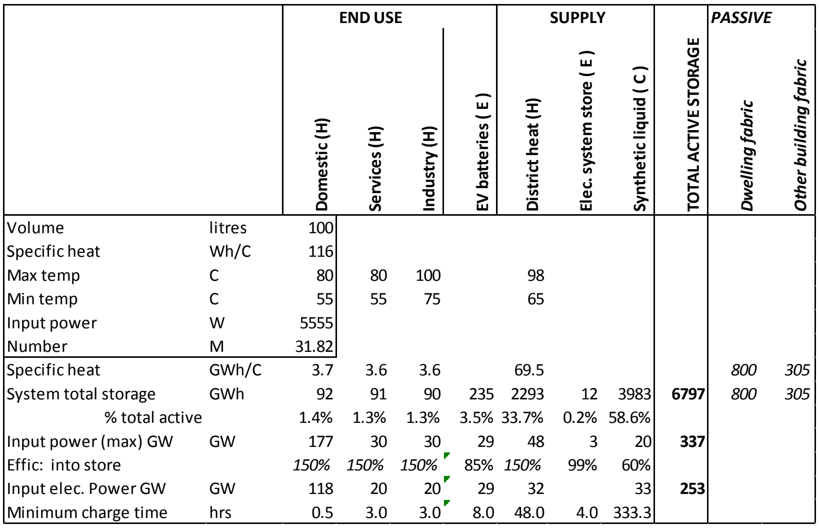


Fig. 1. A schematic diagram of the energy system model

Table 1 gives the aggregate capacities of the stores assumed in the future system. The total storage capacity of the controllable stores is 6.8 TWh with a maximum electricity input of 253 GW. The electricity system store (pumped storage) is the smallest electrically connected store. Note that UK dwellings currently have (very approximately) 10 GW / 30 GWh off peak electric storage heating and 20 GW / 20 GWh in electrically connected immersion heated hot water tanks – altogether larger than the 2 GW/10 GWh capacity of UK pumped storage. Additionally there is about 1 TWh of heat storage in building fabric for a 1 ^{o}C temperature change, estimated from a building stock mass of about 4.7 Gt and specific heat of 0.8 J/g/K. The connectivity and effective capacity of end use storage can vary with time.

Electric vehicle batteries may only be connected when the vehicle is stationary at a charging point, and thus the total connectivity of the aggregate EV battery varies across the day with minimum connection at times of high vehicle use. Heat stores are emptied more during periods of high activity in the end use sectors; and for space heating or cooling, the demand and store output varies with diurnal and seasonal variations in weather. DynEMo accounts for these variations in demand and storage connectivity.

Table 1. Electrically connected storage capacities



		END USE				**SUPPLY**				***PASSIVE***	
		Domestic (H)	**Services (H)**	**Industry (H)**	**EV batteries (E)**	**District heat (H)**	**Elec. system store (E)**	**Synthetic liquid (C)**	**TOTAL ACTIVE STORAGE**	***Dwelling fabric***	***Other building fabric***
Volume	litres	100									
Specific heat	Wh/C	116									
Max temp	C	80	80	100		98					
Min temp	C	55	55	75		65					
Input power	W	5555									
Number	M	31.82									
Specific heat	GWh/C	3.7	3.6	3.6		69.5				*800*	*305*
System total storage	GWh	92	91	90	235	2293	12	3983	**6797**	*800*	*305*
% total active		1.4%	1.3%	1.3%	3.5%	33.7%	0.2%	58.6%			
Input power (max) GW	GW	177	30	30	29	48	3	20	**337**		
Effic: into store		*150%*	*150%*	*150%*	85%	*150%*	99%	60%			
Input elec. Power GW	GW	118	20	20	29	32		33	**253**		
Minimum charge time	hrs	0.5	3.0	3.0	8.0	48.0	4.0	333.3			

4. Storage economics, operation and control

All stores result in the loss of energy, and have capital and running costs. Therefore stores are only worthwhile if they result in greater reductions in costs elsewhere in the system so as to reduce the total capital and operational costs of a system; or if they are required to meet objectives, such as a renewable energy target. Storage can reduce total system costs in various ways: it can store excess renewable or other short run marginal cost supply for times when this supply is in deficit; it can reduce peak flows and thereby reduce capital investment in system component (generation, transmission etc.) capacities; it can reduce the use of higher cost marginal supplies - generally, in electricity systems, the unit cost of supply (£/MWh) increases with supply power (MW); and it can reduce the variability of demand which is costly for some supply, most notably electricity generation.

Once installed, energy stores should be operated so as to minimise the short run avoidable costs of the energy system over some period whist meeting constraints such as pollution emission. For an individual store, this means rescheduling energy flow Q (MWh) with a store of throughput efficiency e (output/input) from period 1 to 2 with unit energy costs p_1 and p_2 (£/MWh) respectively where $p_1 > p_2/e$ results in Qe being stored at time 2. Assuming no operational costs, the cost saving $C_{s1=>2}$ (£) incurred in moving energy Q (MWh) is:

$$C_{s1=>2} = Q\,(p_1 - p_2/e) \qquad £ \qquad (1)$$

To calculate the annual cost saving C_{sa}, $C_{s1=>2}$ must be summed for each energy rescheduling in the year. In general, rescheduling energy will decrease p_1 and increase p_2 so these need to be recalculated if the model is iterative rather than simultaneous. Furthermore, p_1 and p_2 will result from all the electrically connected stores operating simultaneously as well as all the other connected components of the energy system; and so they all must be calculated for the same time period. Again, if done iteratively, these generally have to be recalculated after each rescheduling. The net present value of the store can be found by annuitizing its capital cost and subtracting the summed annual discounted cost savings C_{sa} and any other capital cost savings (e.g. in reduced transmission capacity). Ultimately, the net present value of the whole system should be calculated.

It is difficult to devise control algorithms which can manage all stores and other components in an energy system. The control problem may be illustrated as follows. Assume a large quantity of low cost wind power is expected in a few hours' time, but it is insufficient in terms of power and energy to meet all needs and fill all stores. Consumers and suppliers will want to wait to use this low cost energy to meet demands and fill stores, but there is not enough power for all. What control strategy will result in the competitively equitable, least cost, maximally cost effective use of this wind power? Using current price signals or auctioning may not work well; there should be some account of the future demands, supplies, and current storage levels, otherwise the system may be inefficient and possibly chaotic.

Operational control algorithms have to cover all system components, not just stores: for example the switching of heat input to district heating from electric heat pumps when there is a surplus of renewable electricity, to an input from CHP when there is a deficit. Electricity becomes a proportionally larger vector in most high renewable, low carbon scenarios and electricity is expensive and inefficient to store as compared to chemical fossil fuels or biomass, or heat: therefore the operational algorithms developed in this work focus on the management of electrically connect components from generation through to services. Finding robust and efficient algorithms and constructing social markets for their practical implementation is a major challenge. The heterogeneity, complexity and non–linearity of the energy system and the large number and scale of operational time periods is such that the control algorithms so far developed for DynEMo are based on heuristic formulae and rules, rather than employing explicit optimisation.

As noted above, buildings are estimated to store about 1 TWh of heat per degree Centigrade temperature change in the fabric. The heat input to the fabric may be controlled using the timing and internal temperature settings of building heating and cooling systems. For example, by heating in the night, a dwelling may be kept at a minimum, unoccupied 'set-back' temperature higher (say 17 ^{o}C) than it would naturally cool to in the night (say 15 ^{o}C). This would reduce the amount of heating required to raise the dwelling temperature to comfort level (say 20 ^{o}C) in time for the morning's active occupancy. This strategy increases the total heat demand of the dwelling as the average fabric and internal air temperatures are increased and thereby the temperature difference between the building and its surrounds; but it allows some modification of the heat power profile so as to produce benefits such as reduced peak load, increased renewable energy utilisation or increased average heat pump efficiency. However, the heat output of fabric storage is uncontrolled and this can lead to problems of overheating possibly several hours after heat input to the fabric. Given an increased use of electricity for heating, this use of passive storage could become very significant, either for end use systems such as individual dwelling heat pumps, or for public systems such as district heating – some 50-100 GW of electrical power may be involved depending on system configuration and state. DynEMo simulates the passive building storage dynamics using a range of time-clock and temperature controls in dwellings, but these controls are fixed for a simulation and are not currently included in the national system control algorithms; this is harder to do for uncontrollable output storage that impacts directly on consumers than for purpose built energy storage. A possible approach is to increase the unoccupied set back temperature when there is surplus uncontrolled renewable supply, but the question is – by how much? These remarks concerning heating can equally apply to cooling, but in the 'opposite' sense – e.g. the building would be cooled during unoccupied periods and the cool stored in the fabric.

In DynEMo, two approaches to developing national system control algorithms for storage have been developed to date. Common to both approaches is a power function whereby the input to a store is increased as it becomes nearly empty even if there is no renewable surplus, otherwise there is the possibility that a large fraction of storage becomes empty at the same time thereby incurring an unavoidable surge in energy flow.

The first algorithms developed have a global system signal (GSS), analogous to a cost signal, quantifying the excess of renewable supply over demand over some period in the future – say, the next 6 hours. The GSS makes all stores increase input simultaneously (unless full) when there is a renewable surplus. Variants of GSS with different parameter values (e.g. the demand-supply forecast period) were tested; some of these work well but take no account of the different characteristics of the store – such as its capacity to average demand ratio which may range from around an hour (e.g. a domestic hot water tank) to several months (e.g. a chemical fuel store), or the potentially for multi-fuelling inputs such as in the case of dual input heat pump or CHP to district heating.

Consequently, a second, sequential allocation (SA) algorithm was developed which better accounts for store characteristics, but does not use projected surpluses or deficits. In this algorithm, an uncontrollable supply surplus is sequentially allocated to stores according to store size and the availability of multi-fuelling: in the system modelled, the order is domestic heat stores, electric vehicles, services and industry heat stores, district heat stores and synthetic fuels. If all demands are met and stores or input capacities are full, any remaining surplus is exported or spilled. In more detail, the algorithm is:

i. Sum uncontrollable demands (*EleDemUnc*). These include appliances, equipment and lighting – demands which cannot easily be stored and have to use electricity.
ii. Sum uncontrollable renewables (*EleRenUnc*). These include wind, solar, tidal flow and wave.
iii. Find net uncontrollable supply (*EleNetRenUnc = EleRenUnc - EleDemUnc*). If *EleNetRenUnc* > 0 then supply electricity to each sector and end use in turn if the sector store is not full and spare input capacity (MW) is available - domestic heating, electric vehicles, services heating and industrial heating. If a store is nearly empty, then it will be charged even if there is no surplus.
    a. Calculate additional electricity demand *Da* for input to store
    b. Find new *EleNetRenUnc = EleNetRenUnc –Da*
    c. If *EleNetRenUnc >0* do next sector – go to iii
iv. Do iii for:
    a. District heating.
        1. Calculate minimum heat required to keep store above minimum temperature.
        2. Use surplus electricity to drive electric heat pumps.
        3. Heat load remaining after iv.a.2 supplied from CHP fuelled by biomass or gas.
    b. Synthetic fuels. Use surplus electricity to synthesise hydrogen and ammonia.
    c. Export. Export remaining surplus up to capacity of trade link.

5. System simulation

The DynEMo model simulates (at 15 minute time steps in this case) the performance of the putative energy system with the stores shown in Table 1, using the SA algorithm. For illustration, results for three days for months 1, 4 and 7 are shown as if they were contiguous days. DynEMo can simulate the system performance over longer periods. Random weather is used; of course different weather will change some energy demands and supplies significantly. First, the total end use energy demands are shown: space heat (SpHeat), space cooling (SpCool), hot water heating (HWHeat), process heat (ProHt), process chemical (ProChem), lighting (Light), electrical equipment (EqEle) and motive power (Mot). The major peak is space heating to heat up the building fabric after a cold night. This is a major system design issue when moving from easily stored gas to electric or district heating.

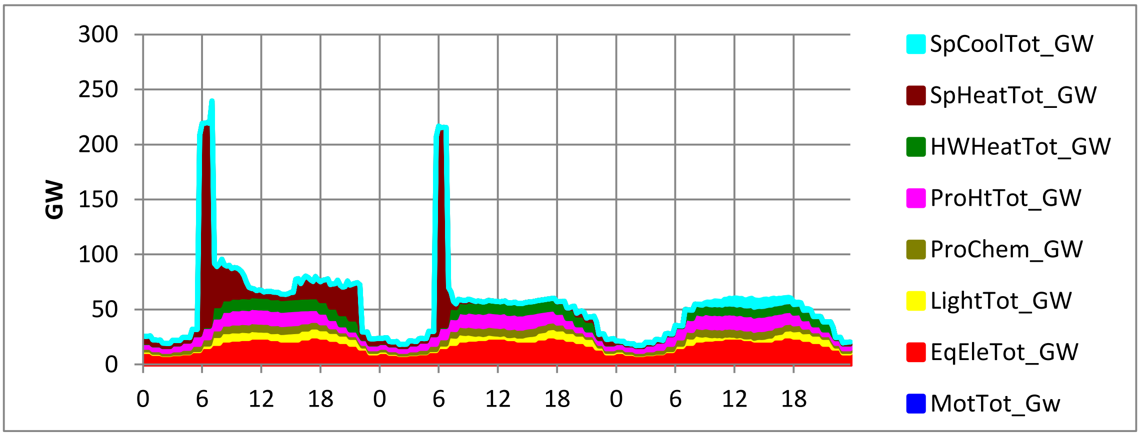


Fig. 2. Useful energy demands

Fig. 3 shows the renewable electricity production from renewable sources – uncontrollable wave, solar PV, wind (on and off shore), tide, and controllable hydro and CHP. Note the dominance of wind and the increased solar PV output in the summer.

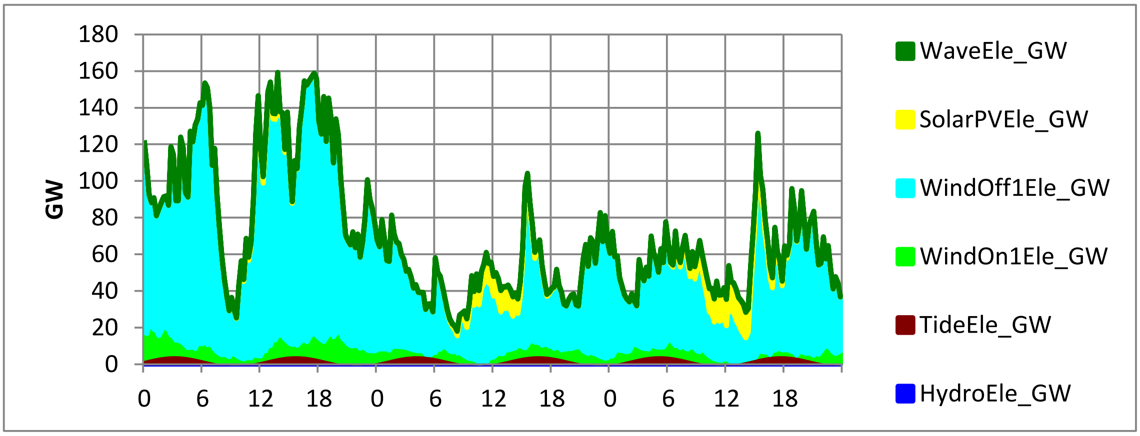


Fig. 3. Uncontrollable renewable electricity production

The seven controllable stores are used to match demand to uncontrollable renewable electricity production using the SA algorithm. We see uncontrollable renewables (EleRenUnc) and demand (EleDelUnc), the electricity inputs to user stores (Domestic-DEleForHeatTot, Industrial-IEleForHeat, Services-SEleForheat, EV batteries-TEVBattIn): and public stores (district heating-DHHPEleIn and synthetic fuels-LiqSynEleInp).

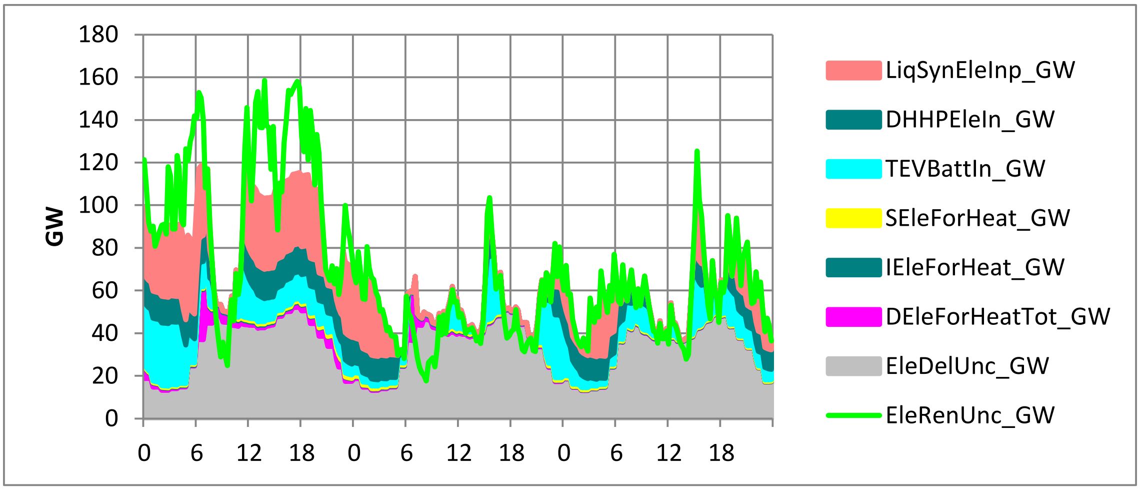


Fig. 4. Storage modified demands

The variation in the seven storage levels as renewable generation and surplus change, is shown next. We see the proportionate change in the large stores is small over this period, but that the smaller end use heat store levels vary widely. The typical cycle times of end use heat stores might be hours; for district heat a day or two; and for synthetic fuel stores weeks or months. We also see how small the electricity system store (EleSysStore) is.

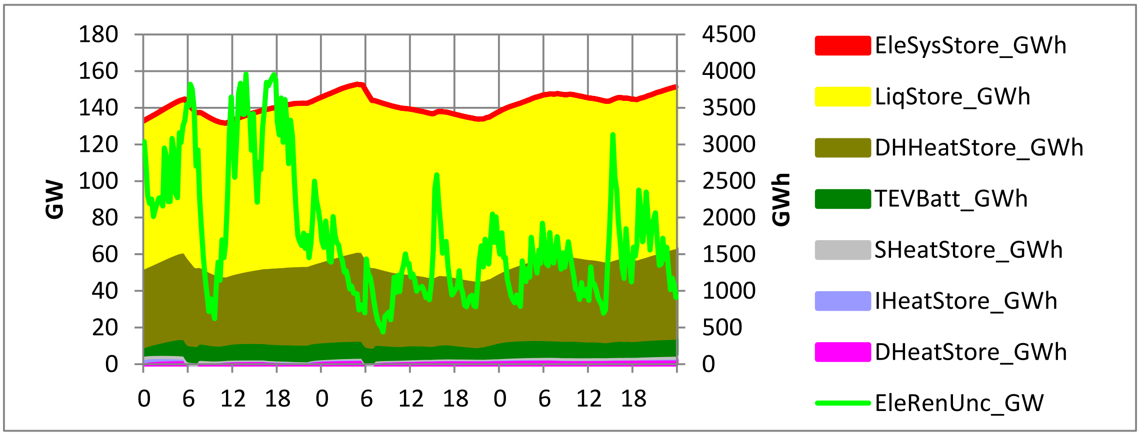


Fig. 5. System energy storage levels

Then the overall electricity system balancing is shown. We have the total supply requirement from all sources (EleSuppReq), after storage except for electricity system storage. We see, in addition to renewable generation, output from dispatchable gas (GasEle) and coal (SolEle) generators. In addition to stores, further balancing is done with electricity system storage inputs and outputs (EleSysStoreIn, EleSysStoreOut) and trade (TradeEle). If there is still not sufficient supply dispatchable gas (GasEle) and coal (SolEle) is deployed. We see around 6:00 and 18:00 on the winter day there is a surplus which is exported (negative), and around hour 9:00 on the day of month 4 there is a deficit and so gas and coal generation is used. This shows the minor role of electricity system storage in the posited system.

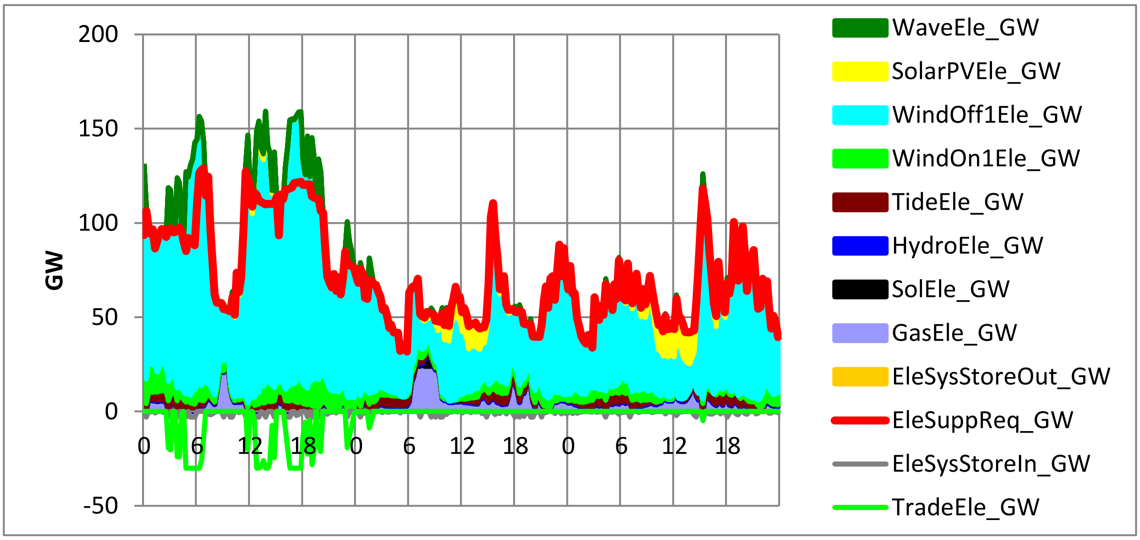


Fig. 6. Overall system demand, supply and trade

6. Discussion and conclusions

In energy systems with large fractions of uncontrollable, varying renewable energy supply, storage will be required on a large scale to reduce system costs. Electricity may be a major vector for distributing renewable energy, but electrical energy is more expensive to store than products of electricity such as heat or synthetic fuels and so the system mooted here has large capacities of these stores.

One control algorithm – the sequential allocation (SA) algorithm – has been applied here and it is seen that flows are rescheduled to make good use of available renewable electricity over fairly short periods. The development and application of possibly better algorithms to control the stores and other system components, as demands and renewable supplies vary, is a major challenge. The control strategy needs to optimise over period from minutes (e.g. for small domestic stores) to days (e.g. district heat stores) to months (e.g. large synthetic fuel stores); and the control algorithms should be extended to building heating and cooling regimes. Renewable outputs can be quite accurately predicted over periods of a day or so, but over months projections are necessarily probabilistic – e.g. of wind power over the next three months. A greater challenge is to optimise the configuration of the energy system including storage at the same time as optimising the dynamic system control – the optimum configuration and control are co-dependent. DynEMo includes configuration optimisation of some storage and other components, but it does not optimise control.

Finally, the system control algorithms will have to be implemented in practice. This will require the development of energy markets for consumers, suppliers and store operators that combine social arrangements such as contracts and technological systems such as automatic controllers of stores that account for demand and supply variations.

The key conclusions of this paper are:

- Electrically connected energy storage can facilitate the electrification of services and large-scale deployment of variable renewable generation.

- Energy storage needs to be modelled within a whole energy system model, considering options across different time and energy scales.
- Heat and chemical storage may have greater capacities than electricity storage.

Future work will include the improved simulation of the system, enhanced control algorithms and the extended application of optimisation to both configuration and control algorithms to better understand the potential role of energy storage within systems with varied demands, renewables and conventional supply.

Acknowledgements

The authors wish to acknowledge the support of the EPSRC and EdF France who funded some of this work as part of a wider research project called PEB (People, Energy and Buildings: Distribution, Diversity and Dynamics (PEB:D3)).

References

[1] Barrett, M. A Dynamic Physical Energy Model of the United Kingdom, PhD thesis, Open University, 1981 http://societyenergyenvironment.net/Energy/Dynamic%20model/MBarrett%20DYPHEMO%20ERG%20044.pdf

[2] Barrett, M., & Spataru, C.. Optimizing Building Energy Systems and Controls for Energy and Environment Policy. In Anne Håkansson, Mattias Höjer, Robert J. Howlett, and Lakhmi C. Jain (Eds.) (Ed.), *Smart Innovation, Systems and Technologies, Sustainability in Energy and Buildings* 2013, pp. 413-425. Berlin Heidelberg: Springer-Verlag, ISBN 9783642366444

[3] Barrett, M., Spataru, C. Dynamic Energy Model Documentation, June 2011, UCL paper.

[4] Climate Change Act, 2008, Section 1. http://www.legislation.gov.uk/ukpga/2008/27/section/1

[5] Chan, C.W., Ling-Chin, J. and Roskilly, A.P. A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilisation. *Applied Thermal Engineering* 2013, 50(1), pp. 1257–1273.

[6] Cot-Gores, J., Castell, A. and Cabeza, L.F. Thermochemical energy storage and conversion: A-state-of-the-art review of the experimental research under practical conditions. *Renewable and Sustainable Energy Reviews* 2012, 16(7), pp. 5207–5224.

[7] DTI Meeting the Energy Challenge, A White Paper on Energy, 2007.

[8] European Commission, 31 final Communication from the commission to the European Parliament and the Council, Renewable Energy: Progressing towards the 2020 target COM, 2011

[9] Hongois, S., Kuznik, F., Stevens, P. and Roux, J.-J. Development and characterisation of a new MgSO4−zeolite composite for long-term thermal energy storage. *Solar Energy Materials and Solar Cells* 2011, 95(7), pp. 1831–1837.

[10] Kucharski, T.J., Tian, Y., Akbulatov, S. and Boulatov, R. Chemical solutions for the closed-cycle storage of solar energy. *Energy & Environmental Science* 2011, 4(11), p. 4449.

[11] Li, C. and Wang, R.Z. Building integrated energy storage opportunities in China. *Renewable and Sustainable Energy Reviews* 2012, 16(8), pp. 6191–6211.

[12] Moth-Poulsen, K., Ćoso, D., Börjesson, K., Vinokurov, N., Meier, S.K., Majumdar, A., Vollhardt, K.P.C. and Segalman, R.A. Molecular solar thermal (MOST) energy storage and release system. *Energy & Environmental Science* 2012, 5(9), p. 8534.

[13] N'Tsoukpoe, K.E., Liu, H., Le Pierrès, N. and Luo, L. A review on long-term sorption solar energy storage. *Renewable and Sustainable Energy Reviews* 2009; 13(9), pp. 2385–2396.