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Short communication

On generation-integrated energy storage

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HIGHLIGHTS

- Current wisdom considers that energy storage and generation must be separate.
- Integrating energy storage with generation lowers capital costs.
- Integrating energy storage with generation reduces total energy losses.
- Existing policies militate against such integrated systems being developed.

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ABSTRACT

Generation-integrated energy storage (GIES) systems store energy at some point along the transformation between the primary energy form and electricity. Instances exist already in natural hydro power, biomass generation, wave power, and concentrated solar power. GIES systems have been proposed for wind, nuclear power and they arise naturally in photocatalysis systems that are in development. GIES systems can compare very favourably in both performance and total cost against equivalent non-integrated systems comprising both generation and storage. Despite this, they have not hitherto been recognised as a discrete class of systems. Consequently policy decisions affecting development or demonstration projects and policy approaches concerning low-carbon generation are not fully informed. This paper highlights that policy structures exist militating against the development and introduction of GIES systems-probably to the detriment of overall system good.

1. Introduction

Fossil fuelled generation is very controllable. As electricity systems decarbonise, the challenge of balancing supply and demand intensifies. Newbery (2010) highlights the problem in connection with wind generation but it applies to nuclear and most renewable generation (see Denholm and Hand (2011)). Energy storage is one of the primary measures to address this. Within this area, most attention focuses on solutions drawing electrical energy from the grid and returning it. A different class of technologies warrants attention-generation-integrated energy storage (GIES) systems.

All grid-scale energy storage techniques store energy in a form other than electrical energy. These include pumped-hydro, pumped heat, flywheels, compressed air, vacuum or electrochemical storage. Transforming energy from electricity to a storable form and back again carries two strong disadvantages: (i) it requires equipment to effect the transformations and (ii) it invariably loses some further energy[1]. GIES systems avoid some transformations when energy passes through storage because storage is implemented before the conversion to electricity. Energy

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[1] Strictly speaking, it is *exergy* that is lost rather than *energy*. We deliberately concede some thermodynamic precision for the sake of brevity.

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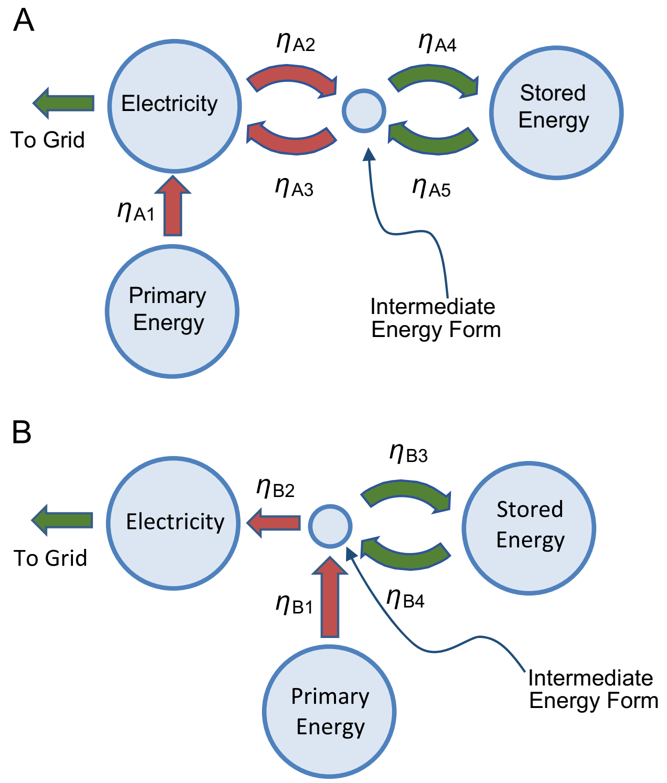

Fig. 1. Generation systems with storage: (A) Non-GIES system with standalone storage and (B) a GIES system.
Red arrows represent *energy transformations*. Green arrows represent *energy movements*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

flow from the primary energy source is never reversed and flow to the grid is not (usually) reversed either.

Existing instances of GIES systems include most natural hydro power plant and selected concentrated solar power plant (Dunn, 2010; Bergan and Greiner, 2014). They have been mooted for wind power (Ingersoll, 2008; Salter and Rea, 1984; Lee, 2012; Garvey et al., 2015; Garvey, 2010) and GIES schemes have been proposed for nuclear generation, e.g. Ren et al. (2014) and Denholm et al. (2012). Photochemical splitting of water to produce hydrogen (Ismail and Bahnemann, 2014) also constitutes a GIES technology if the hydrogen is then used to generate.

Fig. 1 contrasts a Non-GIES system (comprising generation and standalone storage) and an equivalent GIES system. In the former, energy passes through one or more transformations to become electricity and any energy passed through storage undergoes two further transformations and two moves. In the GIES system, all electrical energy extracted has undergone two transformations. Energy put through storage is moved twice but not transformed further. Examples of energy moves include air passing through ducts (Garvey, 2010), water being raised in pipes (Whittaker and Folley, 2012) and heat travelling across heat exchangers (Lee, 2012; Garvey et al., 2015). Energy movements incur some losses but these are normally much smaller than the losses due to transformation. For example, passing air at 100 bar down a pipe with 2% pressure drop in the pipe loses only 0.44% of the exergy whereas expanding that air isothermally to produce work will invariably dispense with $>10\%$. Transferring heat at 900 K across a heat-exchanger with 95% effectiveness causes the loss of only 1.64% of the exergy[2] whereas converting that same heat into work in any real heat engine will destroy over 25% of the exergy. Converting electrical power to hydraulic power in present-day pumped-hydro units loses around 10% of the energy processed but the actual losses due to resistance in the tubes are $<0.5\%$. Evidently the marginal losses incurred when energy is passed through storage will be far lower with a GIES system than with a Non-GIES system. The costs of equipment or provisions simply to move energy are much lower than equipment costs to transform the same energy – a 10 MW heat exchanger costs a small fraction of what would be required to buy a 10 MW heat engine of similar exergetic efficiency (if such an engine was even achievable at all).

The message emerging is a familiar one in systems engineering: a system that must perform two functions may be designed either as a simple aggregation of two separate components or in some integrated way. The latter is not necessarily better in any one system design case but imposing a constraint that the system must comprise two discrete subsystems with prescribed functions is likely to result in a sub-optimal solution. There are countless examples illustrating this widely-recognised truth.

Sections 2 and 3 of this paper outline why future electricity systems comprising generation and energy storage could have significantly lower total costs and higher performance if some or all of the energy storage was to be implemented within GIES subsystems. We do not seek to prove the assertion or claim to have done so. It suffices, therefore, to include some cost estimates and comparisons without extensive external referencing that would distract from the main point of this paper: that even if GIES systems do offer strong cost and performance advantages over Non-GIES electricity systems including energy storage, present policy structures would still favour the latter and stifle GIES developments.

2. Methods

Fig. 1 associates an efficiency value with each energy transformation or movement for both GIES and Non-GIES systems. In each case, these individual efficiencies combine to form two important but different system efficiencies. These two system efficiencies are defined below and Table 1 provides expressions for them.

$$\eta_X := \frac{\text{electrical energy output from the system if noenergy passed through storage}}{\text{total primary energy input to system}} \tag{1}$$

$$\eta_S := \frac{\text{electrical energy output from the system if all energy passed through storage}}{\text{electrical energy output from the system if no energy passed through storage}} \tag{2}$$

The overall *throughput efficiency*, η_T, of any energy generating system with coupled energy storage is defined as

$$\eta_T := \frac{\text{total electrical energy output from the system}}{\text{total primary energy input to system}} \tag{3}$$

Table 1
Expressions for the *transmission* and *storage* efficiencies.

	Non-GIES	GIES
η_X	η_{A1}	$\eta_{B1} \times \eta_{B2}$
η_S	$\eta_{A2} \times \eta_{A3} \times \eta_{A4} \times \eta_{A5}$	$\eta_{B3} \times \eta_{B4}$

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[2] Ambient temperature is assumed to be 280 K here.

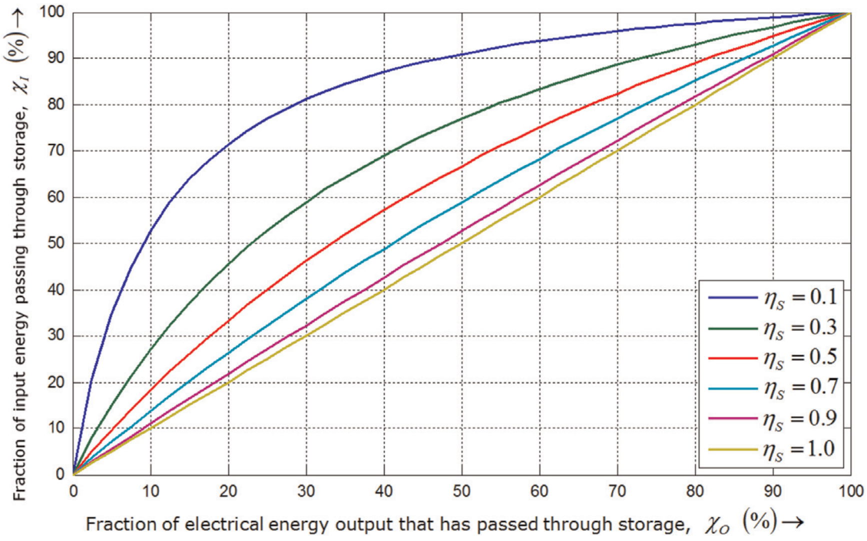

Fig. 2. Relationship between χ_O (%) and χ_I (%).

For a system having *transmission efficiency* η_X and *storage efficiency* η_S, *throughput efficiency* η_T must always be within the bracket $(\eta_S \times \eta_X) \le \eta_T \le \eta_X$.

The throughput efficiency depends crucially on what proportion of total energy passes through storage. Two different ways to express this proportion are explained in the following subsection.

2.1. How much energy will pass through storage in future

Energy storage is not the only measure available to reconcile electricity supply with demand. Demand side management and increasing interconnectivity can also contribute. All three certainly have some role in the future. Despite the completion of several studies (e.g. Strbac et al., 2012; McKenna and Thomson, 2014; Taylor et al., 2013), uncertainties on socio-economic factors and relative future costs of the technologies impede any accurate prediction of what mixture will emerge. Only energy storage has the potential to be a complete and fully-controllable solution to the problem of reconciling supply and demand. Demand side management depends on user willingness to modify consumption in response to price or some other stimulus. The effectiveness of interconnection at any one time depends on the supply-demand differential having near-zero mean across the interconnected region at that time. It is thus safe to assume that energy storage will play a large role.

Onshore wind farms typically have *capacity factor*[3] ~26% (the *RenewableUK* website cites 25.74 in July 2015). Hourly data for UK electricity consumption and wind resource for 2001 were studied by Barton et al. (2013) and Barnacle et al. (2013). These data show that had the country been powered completely by onshore wind turbines with large energy stores capable of delivering exactly the required total energy, 30.3% of all energy consumed would have passed through storage. Photovoltaic (PV) systems currently achieve *capacity factors* of ~10% to 20% depending on location. The same data for the UK system in 2001 show that had all UK power come from PV with storage, 57.1% of all energy consumed would have passed through storage. Evidently, if future electricity systems are powered largely from inflexible sources, substantial fractions of all electrical energy consumed may pass through storage.

We define two new dimensionless quantities χ_O and χ_I as follows:

$$\chi_O := \frac{\text{electrical energy output that has passed through storage}}{\text{total electrical energy output}} \tag{4}$$

$$\chi_I := \frac{\text{primary energy input that will pass through storage}}{\text{total primary energy input}}. \tag{5}$$

Quantities χ_O and χ_I would be equal if $\eta_S = 100\%$ or if $\chi_O = 0$ or $\chi_O = 1$. In all other cases χ_I exceeds χ_O. The appendix shows that

$$\chi_I = \frac{\chi_O}{\eta_S + \chi_O(1 - \eta_S)} \tag{6}$$

and the results section illustrates this relationship.

The proportion χ_O is established by the profiles of demand and primary energy input resource. Overall system throughput efficiency, η_T, is determined from χ_I according to:

$$\eta_T = \eta_X \times ((1 - \chi_I) + \chi_I \times \eta_S) = \frac{\eta_X \times \eta_S}{(\eta_S + (1 - \eta_S) \times \chi_O)} \tag{7}$$

Throughput efficiency is close to transmission efficiency, η_X, if $\eta_S \approx 1$ or if $\chi_O << 1$.

A fundamental motivation for this paper is that in many future electrical power (sub)systems, significant fractions of electricity consumed will have passed through storage. In such cases, the arguments for adopting an integrated system are especially strong.

2.2. Cost analysis

Fig. 2 presents the relationship between χ_O and χ_I for several different values of storage efficiency, η_S. Note that if η_S is low, χ_I may be significantly greater than χ_O.

GIES systems can deliver large energy storage capacities into future power systems at low marginal costs. To understand this, we must recognise and value that GIES systems provide both generation and storage.

For a given generation type, we can assume that the cost of generation is proportional to the output power. We term this the *transmission cost* C_X (£/kW) although strictly it addresses the cost of both transforming power and moving it a small distance. *Transmission cost* does not include costs of any element associated directly with energy storage. GIES systems tend to have fractionally higher *transmission cost* than their generation-only

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[3] For any renewable energy *Capacity Factor* is the ratio between average power output and the peak power output when the resource is strong.

counterparts due to the (possible) requirement for a more complex power transmission/conversion system. There are further costs for power conversion/movement into storage, C_{SI} (£/kW) and for power conversion/movement out of storage, C_{SO} (£/kW). Combined, these two costs are often similar to C_X or higher. For illustration, the power conversion and transmission system for a conventional wind turbines might typically account for ~25% of total cost (c.f. p37 of Krohn et al. (2009)) putting this at ~£200/kW for onshore machines in 2014. Open-cycle gas-fired generation plant typically cost upwards of £300/kW and one such plant rated at 10 MW comprises most but not all of the main components that would be required for the power conversion equipment in a 10 MW-rated compressed air energy storage installation. The plant required for pumped thermal energy storage is necessarily more expensive because thermal pumping involves a high ratio between the total exergy converted and the net exergy moved. A notional value of £300/kW each way for power conversion equipment is above the estimate suggested in Wagner (2012) which suggests £292/kW for two-way conversion (excluding certain items of "balance-of-plant") but clearly in the correct order of magnitude. GIES systems have capital costs associated with moving energy into and out of storage but these will normally be much lower than the costs associated with the power-transformation equipment required for equivalent Non-GIES systems.

We do not attempt a comprehensive examination of achievable costs for GIES and Non-GIES systems. Some evidence is given in the results section suggesting that GIES systems are likely to have significantly lower capital costs than Non-GIES equivalents.

Finally, there are costs associated with energy storage capacity. Every energy store has some associated design *residency-time*[4,5], T_S, defining the energy storage capacity[6] in terms of the overall rated (output) power of the system. The marginal costs of energy storage capacity, C_{SE} (£/kW h), are comparable for GIES and Non-GIES systems if the energy is stored in the same form in both cases.

2.3. Setting GIES system parameters

The designer of a GIES system must set three different power ratios. Power input from the primary energy source (efficiency η_{B1} in Fig. 1B) is taken as the reference rating acting as the denominator for each of the three ratios:

γ_{SI} : determining the power rating for putting energy into storage(efficiency η_{B3} characterises this energy movement)

γ_{SO} : determining the Power rating for recovering energy from storage (efficiency η_{B4} characterises this energy movement)

γ_G : determining the electricity generation power rating (efficiency η_{B2} characterises this energy movement)

Setting γ_{SI} is trivial. It is invariably set so that all primary power could pass into storage at any one time. For most GIES systems, the same hardware would be used for moving into and out of storage (heat-exchangers, water pipes and compressed air ducts are all "reversible"). In all such cases $\gamma_{SI}=\gamma_{SO}$. The value of γ_{SO} chosen depends on γ_G. In most practical cases we would set γ_{SO} very slightly larger than γ_G to account for losses in the movement of energy between storage and generation.

Initially it seems natural to consider setting $\gamma_G = 1$ but this warrants deeper thought. If a GIES whose primary energy input was intermittent was implemented offshore or in some other environment where marginal costs of transmission from GIES output to the grid/demand-centre could be extremely high compared with other costs, it would be logical to consider using the energy storage to achieve a flat output profile. In such cases we might set γ_G equal to the capacity factor – ~0.3 for an onshore wind farm or ~0.15 for PV.

With $\gamma_G=1$ for a GIES with intermittent primary power source (i.e. wind/wave/tide/sun) or $\gamma_G > > 1$ for a GIES whose primary power source is naturally uniform (i.e. nuclear fission), output power can be profiled significantly to match demand – especially where the integrated energy store is itself large – i.e. with $T_S=50$ h. Such systems could provide much of the total supply-demand reconciliation function for the UK or similar regions. The illustration of the following section shows that value of χ_O for these systems could be very high and this would tend to deliver excellent value from a given investment as the previous section explained.

3. Results

3.1. Cost comparison for GIES/Non-GIES systems

Table 2 provides some data for the purposes of illustrating a comparison calculation. These data are based on best present estimates of what might be achievable for a well-engineered wind farm with associated energy store based on pumped thermal technology and what might be achievable for a wind-power GIES also using thermal storage as described by Garvey (2014) and Garvey et al. (2015). If the system is engineered to have energy residency time $T_S=80$ h and if equipment is sized in the simplest way, the total capital costs of the conventional and GIES systems are £2.15 M/MW and £1.72 M/MW respectively. More sophisticated approaches to the sizing of equipment are certainly warranted but the contrast remains large and in favour of the GIES systems. Since no large-scale system has yet been implemented that integrates energy storage with wind power, the cost estimates are necessarily uncertain. We do not claim that a GIES system based around wind generation will necessarily have lower total cost than any Non-GIES system comprising wind generation and storage with the same performance but this is likely.

Throughput efficiency also affects an economic comparison. Assume, for illustration, that a Non-GIES wind power system is characterised by $\eta_{1A} = 92\%$ and $\eta_{2A} = \eta_{3A} = 84\%$ (see Garvey et al. (2015)). This leads to $\eta_X = 92\%$ and $\eta_S = 70.5\%$ for that system. Following Garvey et al. (2015), we take the GIES system to be characterised by $\eta_{1B} = \eta_{2B} = 93\%$ and $\eta_{3B} = \eta_{4B} = 94\%$ to calculate $\eta_X = 86.5\%$ and $\eta_S = 88.5\%$ for the GIES system. Fig. 3 shows how total throughput efficiency, η_T, varies with the fraction of output energy that has passed through storage for the two systems. The Non-GIES system has higher throughput efficiency, η_T, if very little energy passes through storage. However, if most of the energy emerging from the system has passed through storage, the GIES system achieves a throughput efficiency up to 17.7% higher than that of its Non-GIES counterpart.

Table 2
Illustrative possible cost levels for Non-GIES and GIES systems.

Cost Component	Conventional Generation+Standalone Energy Storage	Generation-Integrated Energy Storage
Primary Harvester C_X	£750 k/MW	£820 k/MW
Storage Input Power C_{SI}	£300 k/MW	£50 k/MW
Storage Output Power C_{SO}	£300 k/MW	£50 k/MW
Energy Storage Capacity C_{SE}	£40 k/MW h	£40 k/MW h

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[4] Described as *storage duration* by Strbac et al. (2012).

[5] Most energy stores also have some time-constant indicating the timescale over which energy leaks from the system. This is normally much longer than design *residency-time*.

[6] Input and output efficiencies for the storage play a role here also but only slight.

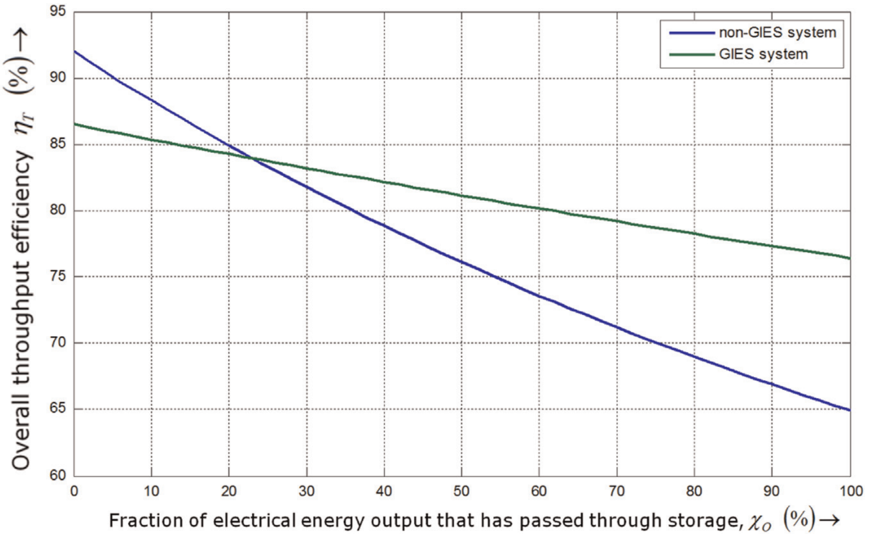

Fig. 3. Throughput efficiency for non-GIES and GIES systems.

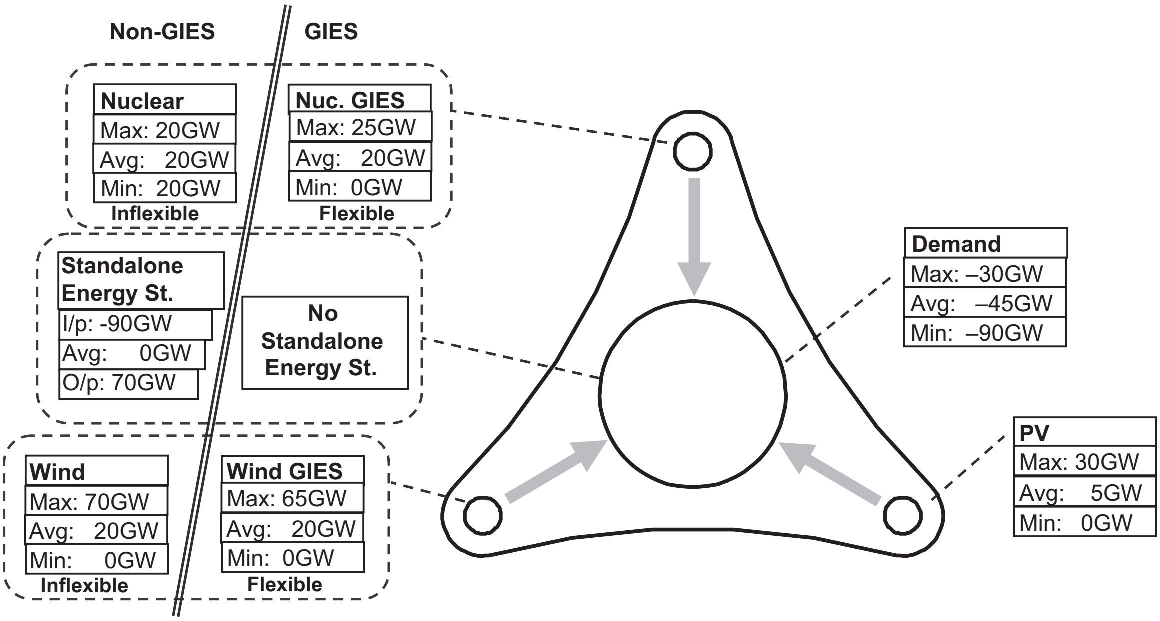

Fig. 4. A notional zero-carbon electricity system: 2 workable configurations.

3.2. *A simple system illustration*

Fig. 4 depicts a very simple island system with three zero-carbon generation sources: wind, PV and nuclear. The maximum, minimum and mean power ratings of these three generation sources and of the demand (without any demand-side response) are summarised in Fig. 4 together with two extremes of possible configuration: (a) a system relying fully on standalone energy storage to balance electricity supply and demand and (b) a system exploiting GIES implementations of wind and nuclear to provide all requisite flexibility. Demand and power flow into the energy storage is considered to be negative generation for the purposes of the figure. For simplicity, the losses due to energy storage are ignored initially in this illustration. We comment on these at the end of the section.

With option (a), all flexibility is provided by standalone energy storage. With the input and output ratings being 90 GW and 70GW respectively, we might expect that the cost of power-conversion equipment for such a standalone energy store would be in the realm of ((70 GW+90 GW)×£300/kW[7])=£48bn.

Taking the cost of energy storage capacity to be £40/kW h and supposing that 1 TW h (equivalent to 25 h at 40 GW) was required, the energy store itself might cost £40bn.

With option (b), the flexibility is provided completely from GIES. The capital costs of the nuclear, wind and PV generation facilities might be estimated as (20 GW × £4 bn/GW), (70 GW × £0.8 bn/GW) and (30 GW × £2 bn/GW) respectively – summing to £196bn. Table 2 indicated that marginal costs for integrating storage with wind generation might be 22% (excluding the energy storage itself). If the same applied to nuclear generation, a rough estimate for the combined costs of upgrading the wind and nuclear facilities to GIES might be (22% × £136bn)=£ 30bn.

Comparing options (a) and (b) shows the marginal costs of energy storage to be £88bn and £70bn respectively – 45% and 35%

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[7] This number is based broadly on pumped thermal energy storage-see Section 2.2.

of primary generation costs. Given that the cost estimates are necessarily very crude, an apparent cost reduction of 20% might not seem compelling. The contrast increases if we assess the losses associated with passing energy through storage. If, say, 50% of all electrical energy consumed had passed through storage, the net throughput efficiencies (from Fig. 3) might differ by 6.5% in favour of the GIES system. To compensate for this difference in losses, the capacity of primary generation in the Non-GIES case would have to be greater by 6.5% and this would carry an associated cost of ~£13bn. This changes the cost comparison to £101bn vs £70bn. Since the marginal costs of integrating energy storage with nuclear and wind generation are still very unclear, the only reliable message from this simple illustration is that true marginal system costs of installing energy storage may be substantially smaller for GIES systems compared with their Non-GIES counterparts.

4. Discussion

There is increasing acceptance that energy storage will play a major role in future electricity systems to provide at least a partial replacement for the flexibility naturally present in fossil-fuelled generating stations. Demand side management and interconnection will also play some roles. For the purposes of this paper, it is necessary only to suppose that these will not form complete solutions obviating the requirement for any energy storage. The remarkable increase in support for energy storage research and development projects in numerous countries over recent years endorses this supposition.

The early sections of this paper provide evidence that (a) GIES systems represent an important class of energy storage system not already recognised explicitly and (b) there are indications, at the very least, that GIES systems can have significantly lower capital costs and lower marginal losses than their Non-GIES equivalents. These cost and performance advantages would ultimately be experienced by the energy consumer.

Policy will play a crucial role in determining whether/how GIES systems are developed in the near future. Three distinct features of present UK energy policy militate against these systems being attractive for commercial investment:

(1) The fact that incentives provided for renewable energy generation are based on the number of kW h(e) delivered into the system penalise GIES systems because losses associated with passing energy through storage necessarily occur “behind the meter” and thereby subtract from the rewards available to the operator.
(2) Within the UK Electricity Market Reform (EMR), all energy storage (not only that present in GIES systems) is rewarded only as a capacity asset – competing with gas-turbine peaking plant. Its ability to generate when required is valued but no value is attached to the other service that energy storage provides to the grid – the ability to reduce net surplus generation by consuming energy usefully.
(3) Under the UK EMR, no one facility is allowed to claim rewards for both providing low carbon generation and flexibility. Thus a GIES system could not recover the partial reward for services that other forms of energy storage can access presently.

A rational future incentives policy supporting further integration of low-carbon generation into electricity generation should reflect that generated electrical power has greatest value when demand is high (especially demand local to the generation). This is especially important if renewable energy sources retain present priority dispatch status among generators. Instances of negative electricity prices already occur (Nicolosi, 2010; Paraschiv et al., 2014). At such times, at least some renewable energy has reduced (arguably zero) value and it is obviously sensible to differentiate between the incentives that would be secured by an inflexible generator and one that can also offer flexibility.

A revised incentives policy might consider rewarding each MW h(e) of low-carbon energy generation with some multiple of (an appropriate assessment of) the energy value at the time of delivery in addition to using a fixed value per MW h. The total reward to the operator would then be

$$\text{Income}(t) = \int_0^t (a + b.\ v(\tau)).\ P(\tau).\ d\tau \tag{8}$$

where *Income*(t) represents cumulative income to the operator over the period $[0, t]$, a denotes a fixed value per MW h(e), $v(\tau)$ denotes (some assessment of) the actual value per MW h(e) at time τ and b denotes a simple multiplier. Obviously, $P(\tau)$ represents the actual power being delivered into the grid at time τ. Setting $a = 0$ and $b = 1$ would return the income collected by any standard generating plant (not low-carbon).

Prior to the UK's EMR, renewable generation was rewarded with *Renewable Obligations Certificates* (ROCs). The ROCs effectively set a value upon a and had $b = 1$. The value of a was determined exactly after each one-year period when it was clear which utilities had met their renewables obligation but a reliable guideline value was available in the form of the buy-out price (£43.30 for the year ending April 1, 2015). Different forms of low-carbon generation would attract different numbers of ROCs per MW h(e) but in all cases receiving one or more ROCs per MW h(e), a exceeded $(b.\ \overline{v(\tau)})$. With $b = 1$ in all cases under the ROCs, there was at least some motivation for an operator to deliver power when its value was high.

Under the present (June, 2015) implementation of EMR, renewable generation is rewarded with *Contracts for Difference* (CfDs). The key difference between the ROCs and the CfDs is that the latter offer more certainty to the investor by guaranteeing a pre-determined value per MW h(e). The intention behind the CfDs is that system operators will accept lower total income in return for increased certainty of that income. In effect, the CfDs set $b = 0$ – removing all motivation for an operator of the renewable generation plant to deliver power when its value is high.

Noting that the systems of both ROCs and CfDs conform to instances of Eq. (8), it is clear that the balance of rewards can be adjusted by changing the ratio $a{:}\ (b.\ \overline{v(\tau)})$. The possible existence of GIES systems motivates a serious examination of this. Evidently, investors place some value on certainty and changing the ratio $a{:}\ (b.\ \overline{v(\tau)})$ from its present 1:0 towards 0:1 would increase uncertainty for those investors and would be likely to have the effect of (slightly) increasing the total cost to the energy consumer for generation of a given quantity of low-carbon MW h(e). However, what appears not to be accounted-for at all in the EMR rationale is that such a change towards rewarding low-carbon generation in proportion to instantaneous power value might reduce overall system costs quite substantially – possibly making a dramatic reduction in very substantial payments that might otherwise be required to provide sufficient system flexibility to reconcile supply and demand. This possible change in reward structure could deliver value even with conventional (Non-GIES) approaches to energy storage but it has especially strong relevance when GIES possibilities are recognised. From the foregoing (and also Toke (2011)), there is a strong case for some modelling to be done to explore the net effects of changes in the reward structures for low-carbon generation. Such modelling is far beyond the scope of this paper.

5. Conclusions and policy implications

Energy storage becomes increasingly important as electricity systems decarbonise. Generation-integrated energy storage (GIES) systems form an important class of systems not previously recognised. GIES systems can be superior in both cost and performance to a combination of conventional pure (low-carbon) generation systems with standalone energy storage systems. GIES systems perform well when much of the energy output from a system incorporating both generation and storage passes through the storage. It is accepted that in some circumstances, economies of scale might so improve the case for specific standalone energy storage systems that the costs of a Non-GIES was lower than the cost of its nearest GIES equivalent but in most instances, this will not be the case. The paper illustrates a possible future zero-carbon generation system including nuclear, wind generation and PV components. A contrast is made between such a system where all grid flexibility is delivered by standalone energy storage and one where the same flexibility is delivered from GIES implementations of the nuclear and wind generation units.

Present policy structure in the UK is a significant hindrance to the evolution of GIES systems. The fact that this class of system is not explicitly recognised obviously precludes that any development or demonstration funding can be directed at it. Even if such systems were developed privately without support, the present structures of incentive schemes based exclusively on reward per unit of electrical energy delivered into the grid militates strongly against their adoption since, in effect, a net negative value is then attached to the ability provided to pass energy through storage prior to the generation of electricity.

Two other aspects of current UK energy policy also obstruct GIES developments: (a) the treatment of all energy storage purely as a *capacity* resource (pitting it against gas-fired peaking plant) and (b) the explicit preclusion of any one generating unit obtaining rewards for both low carbon generation and flexibility.

There is a strong argument for further policy revision if affordable and secure low-carbon generation systems are to be delivered in future. Specifically, changing the reward structure for low-carbon generation such that a high proportion of the reward reaped was dependant on delivering electrical energy into the system at times of high value is a proposition that has obvious potential and relatively low possible disadvantage. There is also a strong argument for some detailed modelling to be directed specifically at such reward structures existing within electricity systems containing energy storage where various fractions of the energy storage are implemented in GIES configurations.

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Appendix A. Derivation of the relationship between χ_i and χ_o

Define the following quantities:

$$A_I := \text{Input energy that will not pass through storage} \tag{A.1}$$

$$A_O := \text{Output energy that did not pass through storage} \tag{A.2}$$

$$B_I := \text{Input energy that will pass through storage} \tag{A.3}$$

$$B_O := \text{Output energy that did pass through storage} \tag{A.4}$$

Obviously all of these quantities are non-negative. From the definitions of the *transmission efficiency* η_X and *storage efficiency* η_S, we have

$$A_O = \eta_X A_I, \tag{A.5}$$

$$B_O = \eta_X \eta_S B_I, \tag{A.6}$$

The definitions of χ_I and χ_O yield

$$\chi_I := \frac{B_I}{A_I + B_I}, \tag{A.7}$$

$$\chi_O := \frac{B_O}{A_O + B_O} \tag{A.8}$$

Combining the latter equation with the previous equations for A_O and B_O provides

$$\chi_O := \frac{\eta_X \eta_S B_I}{\eta_X (A_I + \eta_S B_I)} = \frac{\eta_S B_I}{(A_I + \eta_S B_I)} = \frac{\eta_S\left(\frac{B_I}{A_I + B_I}\right)}{\left(\left(\frac{A_I}{A_I + B_I}\right) + \eta_S\left(\frac{B_I}{A_I + B_I}\right)\right)} = \frac{\eta_S \chi_I}{((1 - \chi_I) + \eta_S \chi_I)} \tag{A.9}$$

It is then trivial to multiply both sides of the above by $((1 - \chi_I) + \eta_S \chi_I)$ and gather terms in order to discover the required relationship

$$\chi_I = \frac{\chi_O}{\eta_S + \chi_O (1 - \eta_S)} \tag{A.10}$$

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