Private and social benefits from storage — relationships and tensions

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Abstract

Electricity storage is percieved by some as an esential component of a low carbon future system. Others dismiss electricity storage as too costly and refer to alternatives, such as flexible generation, flexible demand and increased network interconnection. To establish the value of storage it is therefore important to take a whole-systems view with consideration of all alternatives to storage. Whilst such an approach can inform the value of storage, the distribution of costs and benefits amongst stakeholders is cruicial in determining how and if storage enters the market.

This paper puts forward an analytical framework for the evaluation of benefits arising from storage. The framework is applied based on stakeholder information gathered during a workshop and through personal interviews.

It can be shown that the perceived benefits of storage are poorly aligned between different stakeholder groups. This could lead to a market failure in delivering storage services to the system, unless market or policy instruments can be found to reward social benefits to investors in storage.

Note for the discussant:
This is a draft working paper, which I hope to develop into a thesis chapter. Please treat it as a document that could undergo fundamental changes (i.e. sweeping comments welcome!)

Contents

1 Introduction

Previous work has shown the conditions under which electricity storage can become commercially viable in the UK (Grünewald, et al. 2011). The revenue streams in that study are limited to arbitrage in the wholesale market — one of the forms of income generation available within the current regulatory framework. In this paper I will argue that this approach provides a lower bound of the value of storage. To gain a better insight into the value of storage and its potential for uptake, a wider view of the the potential benefits has to be taken. The broader the scope of enquiry becomes, the more stakeholder groups are involved, and tensions between these groups must be considered as part of the assessment. An analytical framework covering the wider system and societal impacts of storage is therefore provided and employed here.

Section 2 introduces the framework of assessing storage by mapping the private, system and social benefits of storage and argues that the alignment of these benefit clusters is crucial for their realisation.

A macro-economic view of the role of storage in providing welfare is taken in Section 3 which represents the effect of producer and consumer surplus on overall welfare.

Section 4 considers a range of specific benefits, gathered with the help of stakeholder engagement. The nature and relative importance of these benefits to different stakeholder groups provides input to the analytical framework.

The framework is applied in Section 5. Approaches to valuing the private, system and consumer benefits will be discussed and their implications translated for use in this framework.

2 An analytical framework for storage value distribution

When viewed as a disruptive technology to the current socio-technical landscape, storage has the potential to affect a range of actors in both positive and negative ways. This will affect their attitude towards how any wider benefits should be rewarded and how much additional reward they deem necessary to encourage investment, or even become investors themselves.

The aim of understanding the investor position requires a) an understanding of who the likely candidates for investing are; b) how they relate to the existing benefit distribution; and c) how the benefits external to the investors private benefits can be rewarded to overcome any potential market failure in delivering a Pareto-efficient investment in storage, by minimisingnot only in terms of storage capacity, but also regarding the type of technology and its operating strategy.

The process of gathering and evaluating benefits follows the following steps:

- stakeholder engagement to identify benefits
- stakeholder participation in clustering, valuing and critically reviewing suggested benefits
- mapping of benefits against key stakeholder groups
- identify tensions arising from benefit distribution
- review tensions with selected stakeholders in semi-structured interviews

Due to the diverse nature of benefits, the monetary value of benefits can not be explicitly captured in all cases. Whilst system savings may be quantifaible with the approriate modelling framework, for some benefits quantification can be be difficult and controversial. In order to ensure that as wide a range of benefits as possible is considered, the focus here is on the relative merit and its perception by stakeholders. More quantitative approaches can inform the process by providing upper and lower bounds for specific benefit groups.

The mapping step is intended to highlight areas of overlap between different actor groups. These groups can be aggregated at a high level (e.g. society, policy makers and investors), or equally at a more dis-aggregated level (e.g. distribution network operator, local authority and consumers). The greater the overlap of 'interests', the stronger the drivers for uptake, whereas dispersed benefits lead to a weak environment for uptake and may necessitate policy intervention, so long as the sum of benefits warrants such measures. An illustration of the conceptual framework is shown in Figure 1. Each actor has its own set of benefits. Areas of overlap indicate that benefits accrue for more than one actor. If the cost bearer (Investor) does not have sufficient overlap with the benefits of ather actors, he is unlikely to realise these benefits for them. It is thus in the interest of those actor groups that some re-distribution of benefits takes place, or that the investor is otherwise incentivised to invest.

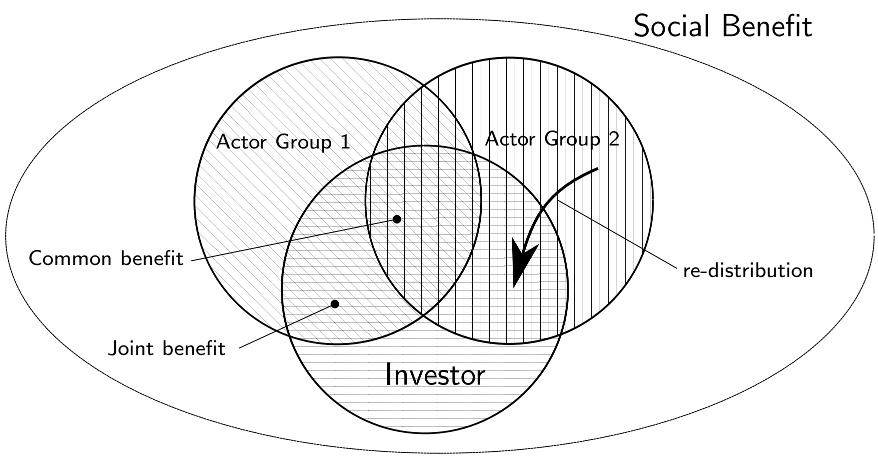

Figure 1: Conceptual illustration of benefit mapping. Areas of overlap represent areas of joint interest. A benefit in this area is realised by at least one actor group and rewarded for at least one other actor, usually in the form of an exchange

3 Social benefits

Social benefits are the broadest unit of enquiry employed in this framework. They encompass all benefits, monetary or otherwise, that accrue from the presence of storage. All other beneficiaries are subsets of the social benefit. These subsets may exhibit areas of overlap (two or more actors benefiting from a non-rival value stream as shown in Figure 1) or indeed compete (one actors benefit is another actors loss). In the sum, however, all subset benefits will add up to the total social benefit.

Figure 2 shows the welfare loss that arises from external social benefits not being realised by private investors. Instead of the Pareto-efficient quantity Q^*, only quantity Q of storage is installed leading to a welfare loss. Internalising the social benefits into the private benefits of storage investors, such that these would invest closer to quantity Q^*, is a policy challenge, which is complicated by the fact that storage technologies encompas a wide range of tenical and operational degrees of freedom. Making storage commercially viable per se does not necessarily result in the social benefits being realised. An understanding of the constituent parts of the

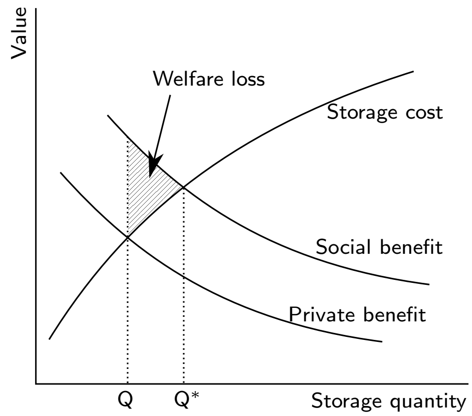

Figure 2: Welfare loss as a result of social benefits not being realised by private investors in storage. An 'ideal' mechanism to transfer social benefits towards investors could theoretically raise the installed storage quantity from Q to Q^* and thereby capture the full social benefit.

social benefits is therefore needed.

Ultimately, it has to be the policy makers aim to maximise social welfare. In neo-classical economic terms the market will deliver an economically efficient system, minimising waste and thus leading to a Pareto-efficient solution. This does however assume that all social benefits are internalised, i.e. that market participants are rewarded (through producer surplus) to deliver products and services up to the point were the marginal producer cost is equal to the marginal social benefit. In the following, I will explore the relationship between producers and consumers in delivering welfare gains, based on changes to electricity price profiles, before looking more closely at the wider constituent parts of consumer and producer surplus in Section 4.

3.1 The welfare impact of demand elasticity and storage

The move towards a low carbon electricity system is expected — at least in the interim — to result in higher electricity prices. Cause of this increase is the capital cost intensive nature of low carbon technologies, as well as operational factors, such as the expected drop in load factor for some conventional plants.

Storage has been suggested to potentially reduce the operational costs of the overall energy system. However, a robust analytical framework and sufficiently detailed modelling to establish the value contribution of storage is still missing. (Cooper, et al. 2011, ERP 2011, Royal Accademy of Engineering (RAEng) 2011)

Time resolved modelling has shown that the private benefits to investors under current regulatory arrangement may not be sufficient to incentivise investment in storage and that strategic support may be necessary (Grünewald et al. 2011). Such support, be it through changes to the regulatory framework or direct support schemes, must be justified by the total social benefit provided by the presence of storage.

Analytical tools are currently being developed and refined to establish the impact of storage on the energy system and the techno-economic conditions to be met, if storage is to compete with alternative solutions, such as flexible generation and network reinforcement. Demand flexibility is also often cited as an alternative to storage, competing for the same 'market'. In this section I explore the effect of flexible demand on producer and consumer surplus to address the following questions:

1. Do system cost estimations assuming inelastic demand capture the full value of storage?
2. How does storage affect total social welfare?

3.2 Analytical approach: consumer and producer surplus

Although the effects of storage on the energy system are complex and depend on a great number of assumptions, for this discussion I take a simplified macro-economic view of welfare as the sum of consumer and producer surplus. Consumer surplus accrues when the market price is below the consumers 'willingness to pay', whilst the producer experiences surplus when the market price is above his marginal production costs (see also (Brent 2007)).

Studies by Frontier and E-Bridge have taken a similar approach to assess the welfare impact of interconnects (Frontier 2009, Bandulet, et al. 2010). Since interconnects and storage have similar underlying characteristics, in that they arbitrage energy in space and time respectively, a similar welfare approach will be applied to storage. I explore how the total social welfare is affected by changing assumptions about the elasticity of demand and the cost of production, as they may result from the presence of storage on the system.

3.3 Welfare changes resulting from consumer benefit and production cost

3.3.1 Base case of inelastic demand

Even though literature and especially policy makers increasingly acknowledge the potential for demand side response (DSR), modelling still predominantly builds on inelastic demand with a single value of lost load (VoLL). This assumption not only simplifies the complexity of the models - in that demand can be treated as a time series of loads that 'has to be met' - it further reduces the complexity of interpreting the results: lower overall costs equals better value for for all.

This thinking is graphically represented in Figure 3. Demand is inelastic, meaning regardless of the electricity price (π) a given amount of Energy (E_0) is demanded and delivered. Only if the production curve rose to meet E_0 at VoLL does demand reduce. Since consumers are assumed to be indifferent between paying the VoLL and receiving energy services, the demand drops to zero at this price.

The producer side is stacked in order of marginal costs. Assets with the lowest cost will dispatched first, until the required load is met. A market price is established at π_0. The electricity price floor is dictated by the short run marginal costs of producing electricity, with a ceiling provided by competitive bidding in the market.

It is important to note that Figure 3 is not time resolved. In practice producers will experience different short run marginal costs, depending on the level of demand at the time and the state of the system. Currently the consumer is not exposed to changes in short run prices and is billed based on average costs over long periods of time. The variability of the short run costs is expected to increase in future and it is conceivable that these variations are passed on to consumers through time of use (TOU) or other real time pricing (RTP) systems.

In the example in Figure 3, the consumers experience a surplus (CSP), as they are assumed to be willing to pay the VoLL for each unit of energy. Their surplus is therefore the rectangle with the area $(VoLL - \pi) \times E_0$. The producer surplus (PSP) is the triangular area between the marginal cost of production (MPC) and the market price (π).

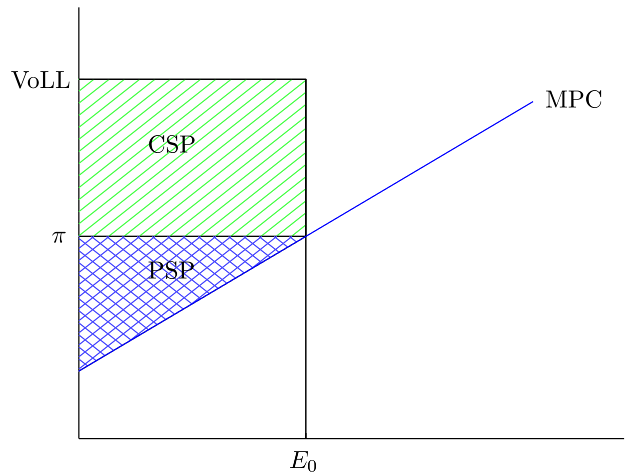

Figure 3: Consumer and producer surplus (CSP/PSP) with inelastic demand of quantity E_0 for a marginal production cost curve MPC. The consumer surplus is given by the assumption of 'willingness to pay' the value of lost load (VoLL) above the market price π for every unit energy up to E_0. For the producer the surplus is the cross-hatched area, where the price π is higher than the marginal cost of production.

3.3.2 Reduced cost of production

Should a policy measure or other technological development reduce the cost of production from MPC to MPC^*, then additional welfare is created, as shown in Figure 4. The new found surplus can be distributed between producers and consumers. Their relative share depends on the new market price, which could be anywhere between π and π^*, depending on the relative market power of producers and consumers. If the price dropped to π^*, then all additional surplus falls to consumers, and conversely, should the price stay at π the producers keep the benefit to themselves. Here I try to show under what conditions there is a social benefit. Then the equity question of 'who benefits' is addressed as part of the analytical framework in Section 5 and 6.

3.3.3 Elasticity of demand

A major assumption in Figure 4 is the inelasticity of demand. Over longer time-scales demand may indeed be fairly inelastic. For shorter periods of time, such as a few hours or less, however, there may be some flexibility, say by shifting the use of wet appliances or other forms of embedded storage. This leads to a flatter marginal consumer benefit (MCB) curve.

Figure 5 takes account of a sloped MCB curve. As a result of the reduced MPC curve, the price drops to π^* and the energy consumption increases to E_0^*. Compared to the inelastic case in Figure 4, the increase in producer and consumer surplus is further increased, by the cross hatched area. This benefit can only be captured when the analysis includes the elasticity of demand.

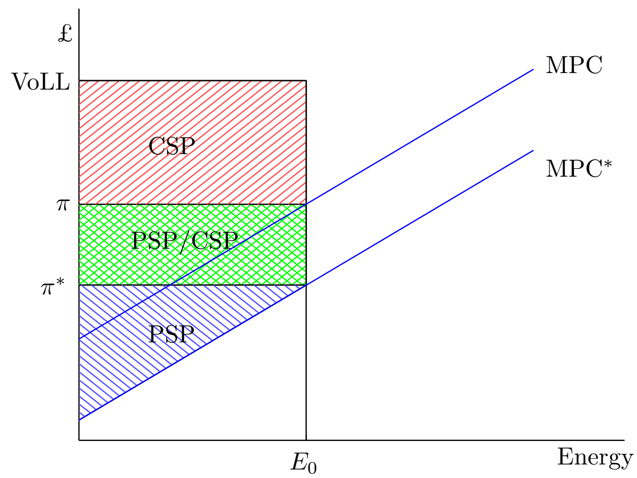

Figure 4: Increase in producer and consumer surplus (PSP/CSP) as modelled with inelastic demand. Reduced marginal production cost (MPC^{*}) lead to additional surplus (cross-hatched area). The allocation of this surplus between consumers and producers depends on the new price, which could be anywhere between π and π^{*}, depending on market power. The energy delivered remains unchanged at E_0.

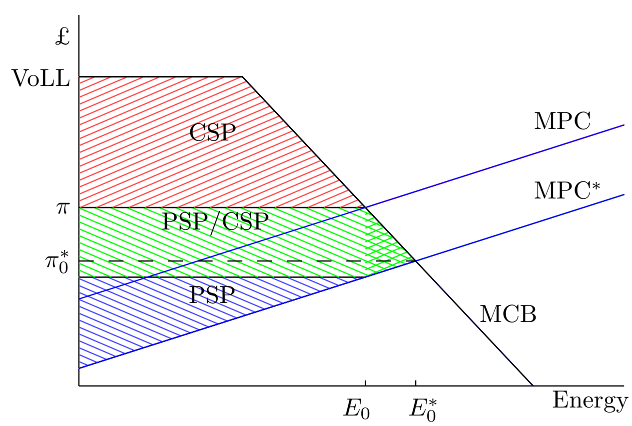

Figure 5: Additional welfare increase from elastic demand. If prices fall from π to π_0^{*} and consumption increases. The surplus that results from the elasticity in demand is shown as the cross-hatched area.

3.3.4 Storage flattening marginal production cost

For efficiency measures and many other technical improvements, the above approach may be sufficient, as these measures lead to an overall reduction of production cost. The effect of storage on the cost curve is however slightly different. Storage provides arbitrage of energy over time, by buying energy at times of low prices and selling it when the price is high. It thereby flattens the price duration curve: peak prices become reduced, whilst low electricity price periods become more expensive.

Instead of lowering MPC throughout, storage flattens it, which is represented in Figure 6 as a rotation from MPC to MPC*. The pivot point is a price/energy point, which demand can lie above or below depending on the state of the system. The demand curves for two distinct periods of the day are shown.During high demand periods (MCB_1) the willingness to pay for energy is greater, shifting the MCB curve to the right. Here the presence of storage delivers additional surplus by lowering prices (and increasing consumption).

On the other side, a low demand period with a 'left-shifed' consumer benefit curve (MCB_2) leads to an equilibrium point to the left of the turning point of the MPC^* curve. This means that the prices to consumers are now higher, than they would have been originally. The area enclosed by $\pi_2 E_2$ and $\pi_2^* E_2^*$ in this case is not additional surplus, but a loss of it, due to increased prices and reduced consumption.

Consumer benefit can therefore not be assumed to be uniformly distributed amongst consumers. Those with a flat load profile stand to gain less than consumers with inflexible demand during peak hours.

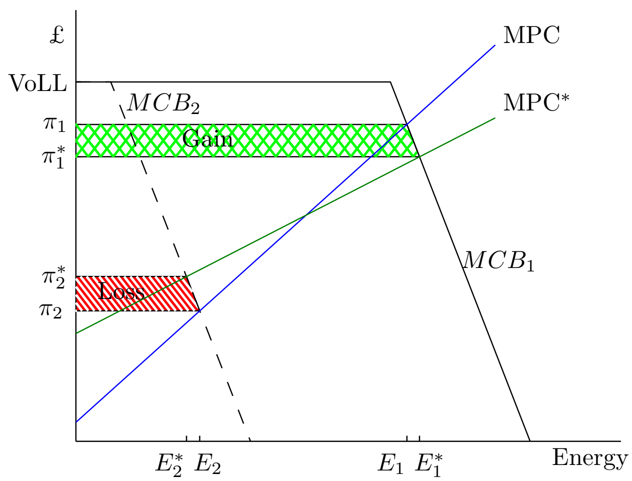

Figure 6: Welfare gains and losses from the presence of storage. The marginal production cost flattens from MPC to MPC^* through the presence of storage. The marginal consumer benefit is higher during peak periods (MCB_1) than at low demand periods (MCB_2). The reduction in peak prices increases welfare by the cross-hatched area, whilst the hatched area represents a welfare loss, caused by increased prices during low demand periods.

4 Valuing private, system and consumer benefits

In general terms, two approaches have been taken to evaluate the value of storage. The first is concerned with the value of storage to private investors under the current regulatory framework.

Revenue for storage stems primarily from volatilises in electricity prices, or existing arrangement for ancillary and other reserve services. It has been argued that such models can capture some, but not all of the benefits storage brings to the energy system.

> "[...] the multiplicity of storage solutions must be recognised. A holistic approach is essential to aggregate the diverse benets of storage." (Cooper et al. 2011)

This has encouraged the second approach. Efforts to model storage in the system context reveal values that are not necessarily realised by investors in storage, but benefit the overall system. The most comprehensive studies of this type to date has been developed for the Electric Power Research Institute in the U.S. (EPRI 2010) and more recently for the Carbon Trust in the UK (Sun & Grünewald 2011). The EPRI study assumes given values for different types of services, wheras the Carbon Trust study optimises the overall system— generating and network assets, as well as operation—for minimal system cost. The model thus seeks the 'ideal' operating strategy and technology choice for storage to minimise these system costs.

The former approach of investment focus provides a lower bound for the value of storage, whereas the latter is an upper bound — at least as far as tangible costs are concerned.

Only if investors invested in the same type of technologies and followed the exact charge and discharge pattern set out by the system model, would the transfer of all benefits quantified in the system model from the 'energy system' to the storage operator be justified. Any deviation in the use of storage would not result in the same reduction in plant capacity, network capacity or operational savings.

This leads to the crucial question of how the potential benefits of storage can be realised through incentives that lead at least to a partial capturing of the social benefits illustrated in Figure 2. The system benefit is a subset of the social benefits. Not included, or only poorly represented, in the system benefits approach are consumer values, such as security of supply, and the impact distributed storage could have on energy practices by altering the way in which consumers engage and value the their time of use patterns. Figure 7 shows where benefits from storage currently accrue. It is noticeable that the storage investor is currently rewarded for only two of the system benefits through explicity market arrangements: ancillary services and arbitrage. It is of course possible for an investor in storage to negotiate bi-laterally with other actors in the energy system to be rewarded for any of the other benefits or, conversely, for actors within the energy system to commission storage services explicitly. This type of arrangement is already taking place with exisiting storage, for instance by providing short term operating reserve (STOR) and other reserve services. However, as discussed in Section 5, the non-rival and non-excludable nature of some of these benefits could lead to market failure in rewarding these services. Unless they can be made available to the investor through re-distribution, or because the investor is better aligned with these benefits than shown in Figure 7. Such alighnment could be achived through veritical integration within the energy system, or if the investor "shares" some of the consumer benefits.

4.1 Private benefits

Private benefits are revenues after tax, resulting from an investment, in this case an investment in storage.

Under the current regulatory framework an investor in storage can generate revenue from

- Arbitrage services (buying low, selling high);
- Reserve services; and
- Ancillary services.

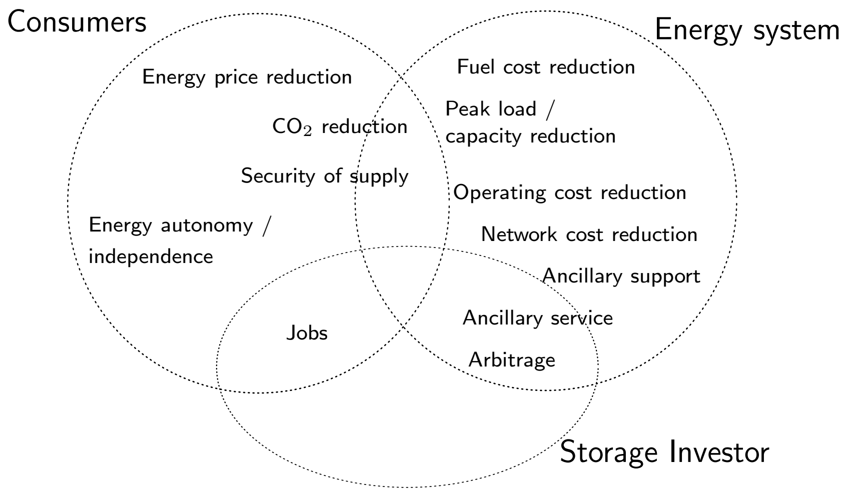

Figure 7: Where do the benefits of storage accrue? Application of actor mapping for consumers, the energy system and storage investors. The overlapping regions (joint and common interests) are limited for storage investors that are not vertically integrated with the energy system or share consumer interests.

The above can be modelled with the help of time resolved market price data, to establish the net present value for different technologies. This has been done for arbitrage services ((Grünewald et al. 2011)) and balancing services ((Black & Strbac 2006)).

When integrated with other business units other benefits that are not explicitly rewarded in the market can be realised internally. A wind farm operator would, for instance, directly benefit from the ability to shift surplus energy into a more valuable period. The more vertically integrated an actor is, the more of the potential benefits he may be able to accrue. Taking this concept to its extreme, if a single actor represented the entire market, he would realise exactly the total system benefit. It is thus the dis-aggregation of actors in the system that brings about the challenge of ensuring that private benefits are well aligned with system benefits, and ultimately social benefits.

4.2 System benefits

The system benefits are the sum of all benefits to the electricity system as a result of introducing storage to this system. This should include 3 broad categories from the benefit groups discussed in more detail in Section 5:

- Generation capacity cost
- Network cost
- Operating cost

The estimation of the savings for the system require a holistic system model, which is capable of optimising the system in the face of many competing trade-offs amongst these costs. An example of such a conflict is the role of storage in adding value to 'wrong time' wind energy and the reduction of network costs. Such a case has been suggested by Goran Strbac (Strbac

2011b) as follows: A future distributed storage system in Scotland may be operated to absorb Scotland's abundant wind resource at times when the transmission capacity with England is exhausted. If this happens at times of already high demand, then the distribution network has to carry higher loads (consumer load plus storage load). In this case storage may bring about benefits to the overall system through reduced curtailment of wind, but at the expense of additional network cost.

Conversely, distributed storage in England may be operated with the greatest system benefit, if it reduces peak load and therefore limits the need for distribution network reinforcement.

One approach to model the value of storage to the energy system is to include it as a technology option at no cost to the system and compare the total system investment (annuity) cost and operating costs before and after. The resulting cost reduction is the value of storage to the system, provided that the alternatives (network reinforcement, interconnects, flexible generation and flexible demand) have been available to the solver.

> "The value of storage is the cost of the cheapest alternative."
>
> *(Strbac 2011b)*

This approach has been implemented by the Energy Futures Lab in the UK (Energy Futures Lab 2011). For given scenarios the value in £/kW for different quantities of storage can be established. These values differ depending on the efficiency of storage and whether it is installed on the transmission network (bulk) or on the distribution network.

The value constitutes the sum of benefit to all participants. The distribution of this value amongst different actors can differ as the example of Scotland and England above have already shown. It is therefore possible to state that these amounts are the value that a investor in storage *should* receive from the 'system'. It is, however, not necessarily clear who is willing to pay for them.

The system model also allows to extract the impact of storage on CO_2 emissions. Although these are not a primary driver for the value of storage, these will be included as non-monetary benefits in Section 4.4.

4.3 Consumer benefits

The current 'passive' perception of consumers, within a 'predict and provide' approach to demand, leads to a simplified concept of the value of storage to consumers, as shown in Section 3.

The de-coupling of wholesale electricity price volatility from retail prices and the absense of retail signals on the value of capacity, means that most system benefits of storage—except when passed on as overall reduction in electricity prices—are not realised by consumers, and therefore unlikely to be driven by them.

There are however some other, less tangible, benefits, that accrue for consumers and may lead them to 'value' storage. These are discussed in the following section.

4.4 Non-monetary and indirect benefits

Although not all of the benefits are traded in markets, most of them can be quantified and monetised. This does to some extent include externalities, such as CO_2 reductions, which can be estimated within whole-system-models (see Section 4.2). Artificial market arrangement, such as emission trading schemes, provide (at least in theory) a mechanism to reward storage, should CO_2 saving be directly attributable to storage.

A secondary benefit from storage is job creation in the development and production of storage technologies, with further potential for export markets. Studies to quantify the value of job creation have been conducted for other 'sustainable technologies' and a similar approach could be taken for storage, but only once the scale of likely adoption scenarios is better understood.

The impact, which might be the most difficult to quantify, is the role storage might play in influencing practices. Especially distributed storage may lead to greater awareness of the time-value of energy to consumers. Energy independence, which comes with ownership of storage, could further be perceived as valuable.

5 Perception of value — A stakeholder consultation

5.1 Stakeholder review of benefits

The number of benefits to the overall energy system poses an equity challenge of how these benefits can be rewarded by the beneficiaries and passed on to the storage owner, such that the appropriate quantity of storage is delivered to the system.

Tensions and conflicts amongst stakeholders are highly likely in the negotiation of any such ‘redistribution’. The more stakeholders are involved, the greater the conflicting demands. The workshop facilitates the process by creating conditions in which the participants can “cocreatively meet their individual and collective needs” (Holman & Devane 2007).

To develop an approach that focuses on common good values, stakeholders from across the energy system were invited to participate in a two-day workshop. The aim of the workshop was to establish and evaluate perceived benefits and barriers facing storage. This section focuses on the benefits and how these were viewed by the group as a whole and some stakeholder sub-groups in particular.

The intention, as well as to gather the current perceptions, was develop an “increase shared understanding and dissemination of shared strategy/direction”.

> “What’s needed for effective, sustainable change are sessions in which people collectively explore each other’s assumptions, seek and expand common ground, shape a desired future, and jointly take ownership of the solutions to the issue at hand.”
> *(Holman & Devane 2007)*

As part of the workshop, stakeholders were asked to submit suggestions for what they perceived to be benefits arising from the presence of storage. At the time of submitting benefits, participants had received general scene setting presentations and engaged in a round table discussion of some of the major challenges facing storage. No guidance was given about the type, scale or ownership model for this storage. Neither was any particular scenario put forward. The stakeholders were intended to provide ideas unconstrained. Conversation with other stakeholders was permited and encouraged, but ultimately every participant would submit their own suggestions, tagged to their stakeholder group.

More detail about the workshop process and participant groups is available in the factual report (Cooper et al. 2011).

5.2 Characterisation of benefits

A total of sixteen types of benefits were identified within the submissions, which fall into the following seven broad categories (in order of submissions in each category):

- System operation
- System cost
- Consumer benefits
- Security / resilience
- Renewables integration

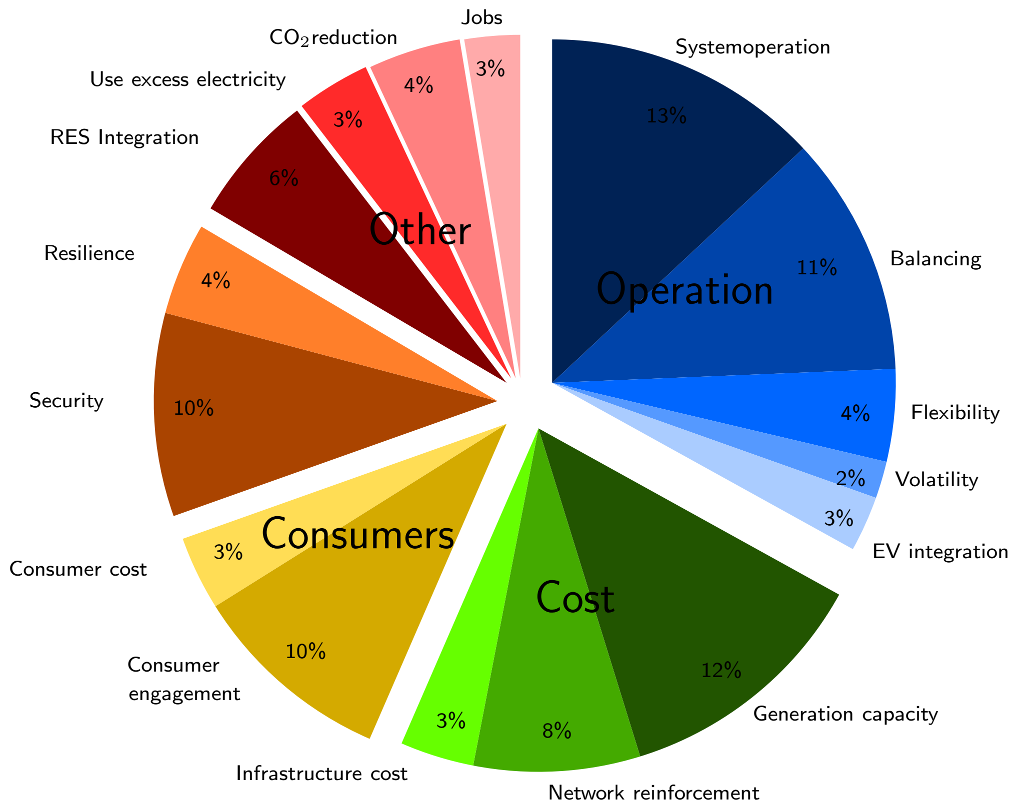

Figure 8: Breakdown of benefits suggested across stakeholders groups

- CO_2 reduction
- Job creation

A total of 117 submission were made and their breakdown into the different categories is shown in Figure 8.

In the following, the categories will be explored to establish the nature of this benefit and to what extent the benefit is in fact an externality under the current regulatory framework.

5.2.1 System operation

This category received the largest share of submission (33%) and spans several sub-categories benefits, such as:

- System balancing;
- System flexibility;
- Reduction in price volatility;
- Utilisation of assets;
- Operational efficiency of the system; and
- Operating costs.

These values are all realised within the energy system, but potentially by different actors. The following explores how these benefits are currently dealt with within the energy system.

System Balancing Balancing services are currently rewarded under the balancing and settlement code (Elexon 2001). Other ancillary services, such as reserve and response, are procured by the system operator. The provision of frequency response services is an obligation under the Grid Code, however the services are remunerated, both for availability whilst instructed to be in response mode (paid per hour), and for the energy delivered to and from the system during that time (paid per MWh). (National Grid 2011)

Some plants are more suited to providing frequency response than others. A nuclear power station, although obliged to offer such a service, would be an unlikely candidate to be selected to provide it, given that the system operator awards the service competitively. If storage entered this market, the competition for such services increases and should theoretically lead to lower premiums. The system operator would in any case benefit from having additional choice in the provision of frequency response.

The provision of response from non-generating assets is also possible under the "Frequency Control by Demand Management" (FCDM) service. The conditions to provide this service include 24 hour availability, a response time of 2 seconds, an aggregated load of 3 MW for at least 30 minutes, and suitable integration with the system to meter and monitor the operation. The service provider offers availability for specific settlement periods in the week ahead. If the offer is accepted, an Availability Fee (£/MW/h) is paid out.

For large scale storage sites, such as Dinorwig, this service constitutes an important part of their revenue stream (Boon 2010). Smaller distributed units may find it harder to qualify for such revenue streams. They need to aggregate in order to meet the above conditions. The main obstacle may lie with the requirement to interact with the system. Scheduling availability, requires planning and a willingness to sacrifice on the availability of other services from this storage site. This trade off can be more effectively estimated and calculated by commercial operations.

System Flexibility Compared to 'System Balancing', System Flexibility is a property of the system, rather than a service to the system. It can be said that increased flexibility will ease system balancing. The absence of flexibility leads to more costly balancing measures, or in extreme cases lead to disruptions in service.

Introducing additional flexibility is best explored as a scenario. In this scenario flexibility is placed into the current energy system. It is assumed that this flexibility is the by-product of other measures and therefore incurs no additional costs to the system. The type of flexibility provided is a subset of the existing flexibility provision, meaning it can provide some features as a full equivalent or even better than the existing system, but some properties are inferior. The impact of different assumptions, such as availability and location, will be explored qualitatively below.

In general terms, the addition of flexibility would have the following implications: the service provision for flexibility becomes more competitive and the prices for such services on the whole drop. Although flexible generation is more valuable to the system than inflexible or uncontrolled generation, this property is not necessarily always rewarded fully in the market. It is true that in the balancing market and even under bilateral contracts those providers, who can reliably forecast and adjust their availability, are able to realise higher prices for their energy. At the same time, however, other sources of energy that are not able to provide such services are rewarded through subsidies, such as FiT's and ROC's. Such support schemes allow inflexible generation to bid into the market at lower prices, with two effects:

- displace otherwise competitive flexible generation (reducing load factors for such plants); and
- tip the price duration curve into a steeper profile, with lowest and highest prices becoming more extreme.

The rise in peak prices opens up new and alternative solutions to enter the market.

Price volatility Price volatility is a market response, which results from a lack of generating flexibility. Increasing volatility, even if the mean price remains the same, encourages the presence of more flexible plants with a subsequent long term reduction in baseload plant. Flexible plants tend to have higher marginal costs of production, which ultimately does lead to higher electricity prices overall.

There are other reasons, why volatility can lead to increased electricity prices. Forecasting revenue streams for a plant operating in a volatile market is more difficult and the risk to investors translates in the a higher cost of finance, which ultimately get passed on into electricity prices.

Even within existing bilateral contracts, high price fluctuations will encourage participant to trade in the balancing market as well. For instance a unit committed within a bilateral contract could be bought on the balancing market at a lower price at certain times and thus reduce the physical volumes delivered from the supplying party.

Electricity markets are already the most volatile markets, in part due to lack of storage.

The beneficiaries of price volatility are plants that are flexible enough to follow the fluctuations. This flexibility requires both physical and economic characteristics. The physical ability of a plant to operated flexibly is given by its ramp up and ramp down rates. For thermal plants these could be constrained by their thermal and mechanical inertia, as well as wear and tear considerations that results from fast load changes. Furthermore plants may operate less efficiently or even unstable below certain part loads. These factors play into the economic considerations when deciding whether to load follow or not. The additional cost of maintenance is one such factor. Most importantly, however, is the short run marginal costs of a plant. If these are low, the responsiveness to price signals is weaker. For such plants the physical ability to load follow does not necessarily mean that they would do so.

Flexibility may be required upward (i.e. to increase output or reduce load) or downward. The ability of actors to provide one or both of these services differs. For a generator to provide upward flexibility it must run at part load. If it also is to provide downward flexibility the part load has to be above the minimum stable generation (MSG).

Keeping plants operating at part load can only be economically justified, if the reward for ramping up exceeds the lost revenue from reduced output. For plants with high marginal cost this condition is met at lower price volatility and they are therefore the first to benefit.

Analogous to plants ramping up, is curtailment of demand in a controlled fashion, as for instance under the FCDM (see System Balancing above). Here the commercial consideration is that as soon as the electricity price exceeds the utility value of electricity a consumer would opt to reduce their load.

Utilisation of assets This benefit applies especially to mid-merit plants, variable generation, and network infrastructure.

Mid-merit generation, because it is positioned in the merit order behind low-carbon and base-load generation, is faced with reduced load factors, and thus, higher levelised energy costs. Strbac et al. estimate the load factor for mid-merit plants to drop from currently 55% to below 25% in some low carbon scenarios (Strbac 2011a). Retiring these plants is not possible without reducing security of supply. If, however, storage was to provide some of this capacity, the least economic plant can be retired and the load factor for the remaining fleet increases.

Variable generation, although dispatched in preference to most other plant with higher short run marginal cost, may encounter periods of market saturation or congestion, in which dispatch is not possible. Storage provides an option to shift this energy in time to a period when the energy can be 'used'.

Related to the issue of congestion is the capacity of the network. Network capacity that is sized to avoid curtailment at all cost, would lead to poor utilisation of the network capacity. Historically, National Grid sized transmission lines to cater for the sum of all name-plate capacities connected to it. For variable generation with load factors as low as 30% this approach leads to excess capacity and poor utilisation.

Similarly, peak loads are short lived. Unlike on the generation side, curtailment of demand is typically not an option (politically divisive) and network assets have to be sized to cope with these infrequent events. In both cases—peak generation and peak load—storage can shift energy such that a smaller network capacity is sufficient. Less network capacity means that the remaining capacity is better utilised.

Better utilisation of their assets should in theory be welcomed by the operators of such plants. However, the utilisation only improves because storage enters the market as a competitor, forcing out the least profitable plant. Once this plant is removed from the market the remaining plant of very similar characteristics enjoy higher load factors. Plant owners may not know themselves in advance which side of this divide they fall, and if in doubt err on the conservative side of preferring no change to the status quo, to a disruption which could bring about better as well as worse commercial prospects (risk adverse behaviour).

Operational efficiency of the system The system efficiency gain can stem from two different sources. Firstly, avoided curtailment of variable sources of energy is a direct efficiency gain, in that it captures and later uses energy that would otherwise have been lost. Secondly, the system efficiency can be improved by operating it closer to optimum conditions. For instance a thermal power station has an operating point at which it converts thermal energy into electrical energy most efficiently. Ramping up or down, or operating at part load, reduces the plant efficiency. With the appropriate operating strategy, storage could improve the efficiency of thermal plants. Related to this type of efficiency gain is another system improvement, if storage is operated to reduce the amount of plant held as spinning reserve. Due to the stochastic uncertainty over future demand, wind generation, and the possibility of sudden plant outages, a certain amount of reserve capacity must be held in a 'ready' state by the system operator. Because these plants have a minimum output at which the can operate in a stable condition, the presence of spinning reserve tends to displace other plant, which may not be able to respond to load changes as fast, but operated more efficiently.

These efficiency gains must be seen in context with the round-trip efficiency of storage itself, which can reduce, or in some instance even negate, the efficiency gains. As long as storage is charged from 'excess wind', the efficiency balance is positive. But charging storage with energy from thermal plants may not justify the round trip loss in all cases.

As a benefit, the causality between efficiency gains and the presence of storage can be difficult to establish in a day-to-day system context. All actors can potentially be beneficiaries.

Operating costs Operating costs are directly related to efficiency, where fuel costs are concerned. Furthermore operating costs can reduce as a result of reduction of more operationally and maintenance intensive plant.

The cost reduction is in any case a welfare gain. The equity question of whether this cost reduction leads to greater producer or consumer surplus, depends on the market arrangements, as mentioned in Section 3.3.2. If electricity prices remain the same producers benefit. Alternatively, consumers could benefits from lower bills.

5.2.2 System cost

Areas that contribute to the reduction of system investment costs (as opposed to the operating costs above) include:

Generation capacity Storage could lead to a reduction in plant capacity requirement for secure electricity provision at all times. This could include a reduction in peaking and reserve plant capacity, if storage is operated to reduce peak load. It could also reduce the amount of renewables required in highly renewables dependent pathways, by matching the time of generation with time of demand (or network availability), and thereby improving the capacity factor of renewable generation.

Changes to the investment landscape are long term in nature and will in many cases only be realised years after the installation of storage. Two forms of introduction to the market should therefore be distinguished

1. Driving existing plant out of the market (disruptive introduction)
2. Avoiding future investment (evolutionary introduction)

The former is expected to lead to greater resistance from incumbents, as existing assets are reduced in value, whilst the latter can lead to slow or even unsuccessful uptake, due to techlology lock-in.

Reducing the total capacity of renewables required to meet a given target does not necessarily equate to a reduction in the market for renewables. It could however lead to a redistribution of their relative value. Technologies with the lowest capacity factors (such as PV) stand to gain the most from the ability to shift wrong time energy into useful energy.

Whether the renewables market as a whole is reduced in value is again an equity question. The following simple *Gedankenspiel* illustrates the possible tensions. In the base case scenario an ambitious carbon target can only be met with a large capacity of renewables. The total system cost (investment and operation) is C_{sys}, the total amount of energy delivered from renewables is E_{RE}, but since the penetration is very high, during periods of high wind and low demand, the amount $E_{surplus}$ has to be curtailed (where $E_{RE} + E_{surplus}$ is the total renewable potential). In this example, it is assumed that the investment in storage is offset by less investment in renewables, such that the overall system cost unchanged ($C^*_{sys} = C_{sys}$). The amount of energy delivered from renewables is also unchanged ($E^*_{RE} = E_{RE}$), meaning more energy is delivered per kW installed, because less has to be curtailed ($E^*_{surplus} < E_{surplus}$). The breakdown of previously curtailed renewables into reduced RE resource, reduced curtailment and storage losses is illustrated in Figure 9.

In aggregate the 'wind+storage' cost/benefit case is identical to the 'wind+curtailment' case when only considering these two actors. More energy can be sold from less installed renewabe capacity. As the total amount of energy delivered to customers remains unchanged, the price realised by the renewables operator will on average be lower, but ultimately lead to the same commercial result.

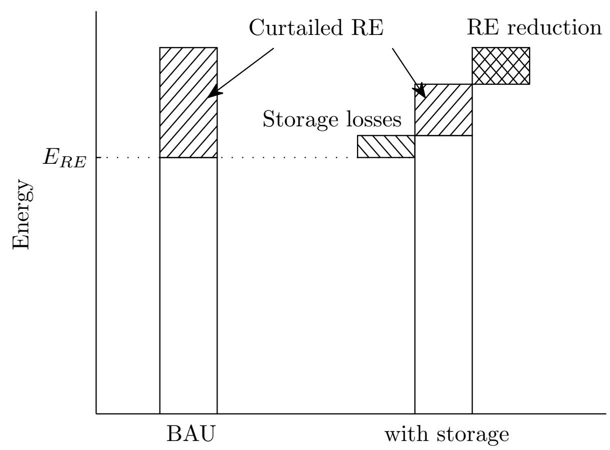

Figure 9: Conceptual impact of storage on a high renewables scenario. The total amount of energy available from renewables is reduced by the cross hatched area (less installed capacity). However, the presence of storage reduces the amount of curtailment with respect to the business as usual (BAU) case. After storage losses are taken into account the total amount of energy delivered for energy services (E_{RE}) remains unchanged.

Network reinforcement The envisaged electrification of transport and heat could have significant implications on transmission, but especially distribution networks. Nick Winser from Natioal Grid expects the distribution network to have to scale up by a factor of 3.5 by 2050 with respect to the 2010 network. In comparison, he estimates the transmission networks requires a 1.7× increase over the same period (Winser 2011). Since the last few kilometers of the distribution network are estimated to contribute about 85% of the total network cost, this has potentially serious cost implications. (Strbac 2011a)

As mentioned in Section 4.2, the presence of storage can lead to a reduction in network capacity, as well as—in special circumstances—an increase. Since both the transmission and distribution networks are operated as 'regulated monopolies', a change in network requirements does not change the competitive relationship of network operators. Under current regulation network operators are not permited to own 'generating assets', and storage is classified as such an asset. Network operators are, however, considering contracting out 'storage services' to get around this limitation. This could create a value stream from 'avoided network reinforcement' to storage investors.

Stakeholders did raise the possibility to use temporary storage, not to avoid network reinforcement, but to 'buy time', before such reinforcements can take place.

5.2.3 Consumer benefits

Consumers can benefit through cost reductions as a result of overall system cost reductions, provided these are passed on to consumers. These cost reductions increase consumer surplus, either in the form of money saved for other expenditure, or, as suggested by the 'rebound effect', by increasing energy consumption (or both).

Aside from cost benefits, storage can have an impact on consumer behaviour and practices. Stakeholders, especially amongst utilities and policy makers suggested that distributed storage in particular can provide consumers with a greater degree of autonomy and choice in the way they source electricity. This in turn could lead to greater awareness and behavioural changes. Such 'double dividends' have also been suggested for μ-generation and were studied by (Keirstead 2006). He observed demand reduction as well as load shifting responses as a result of installing photo-voltaic systems. Storage could have a similar impact. However, photo-voltaics systems are supported through feed-in-tariffs (FiT) and other grants, which do not apply to storage. On the contrary, some stakeholders claim that the nature of FiTs discourages storage, because they reward electricity regardless of the time of generation.

> [...] instead of an incentive tariff for producing, why not an incentive for using low carbon energy?
>
> *Workshop participant*

5.2.4 Security and resilience

The ability of storage to increase system resilience and robustness was perceived most strongly amongst storage developers and operators. It was suggested that storage could avoid supply disruptions during extreme events or desasters.

Rewarding this type of benefit is difficult in a system context, becasue the absence of disruptions is non-rival and largely non-attributable either under the current arrangements. Participants did suggest, however, that a market could be created if consumers were given the choice to opt for more expensive reliable supply, or instead accept supply disruptions as part of a cheaper contract.

5.2.5 Renewables integration

No explicity operators of wind farms were present at the workshop. Nonetheless, the importance of integrating large shares of renewable energy into the system cost effectively was acknoleged by participants and storage was seen to play an important role in this process.

High penetration of renewables could potentially lead to integration costs estimated at £70–90bn (Strbac 2011a). The contribution of storage towards reducing this cost is complex and requires a holistic modelling approach, if it is to be attributed to storage.

5.2.6 CO_2 reduction

The CO_2 reduction potential of storage tends to be given little attention. The Chief Scientific Advisor to DECC, David MacKay, does not expect the case for storage to be made on the strength of its carbon reduction potential [1]

Amongst the worshop participants, the policy makers mentioned CO_2 reductions more than others. Consensus existed that system models would be required to establish the scale of potential CO_2 savings.

The practical attribution of CO_2 savings to storage operation is non-trivial. Whilst it may be possible to estimate the marginal emissions factor of energy during charging, and perhaps even capture the avoided emissions as a result of displacing other plant during discharging, the operational impact, for instance as a result of a reduction in provision of spinning reserve, are difficult to quantify reliably.

5.2.7 Job creation

Not surprisingly, job creation as a benefit is perceived most strongly by storage developers and operators themselves. It was raised that storage also offers a potential export market world wide, if the UK was to establish itself as a world leader in this sector.

The scale and value of the business opportunity for the UK is not clear at present, but should be considered by policy makers.

6 Distribution of perceived importance of benefits amongst stakeholder groups

After reviewing the origin and nature of the benefits qualitatively, based on stakeholder engagement, in the previous section, the framework is now applied quantitatively to the association of benefits with stakeholder groups. It would be desirable to dis-aggregate the data into as many stakeholder sub-groups as possible. However, groups with less than 3 members have been merged into larger groups to preserve the anonymity of individual contributions.

The distribution of perceived benefits has been based on the number of submitted benefit suggestions (n) for each benefit type i by stakeholder group j. The relative importance of a given benefit to this stakeholder $P_{i,j}$ is calculated as

$$P_{i,j} = n_{i.j} \frac{\sum_i \sum_j n_{i.j}}{\sum_i n_{i.j} \sum_j n_{i.j}} \tag{1}$$

where values greater than one indicate that this benefit is more significant to this stakeholder than it is to the others groups. A graphical representation of the distribution of P values is shown in Figure 10. The categories are arranged in order of the number of submissions they received.

Three clusters become apparent. One cluster for utility representatives encompasses both cost and operational aspects. These have been perceived during the discussions to yield potentially high value (or cost if not mitigated).

A second cluster, with the strongest relative preference ($P = 4.8$), falls to policy makers and regulators, to whom cost to consumers and CO_2 reduction are especially important.

Thirdly, storage developers and operators are prominent in the 'miscellaneous' category. This is significant. Not only does it show a lack of overlap in priorities between storage related

[1] This comment was made in response to the question why the DECC2050 calculator did not attribute any CO_2 savings to storage. (MacKay 2011)

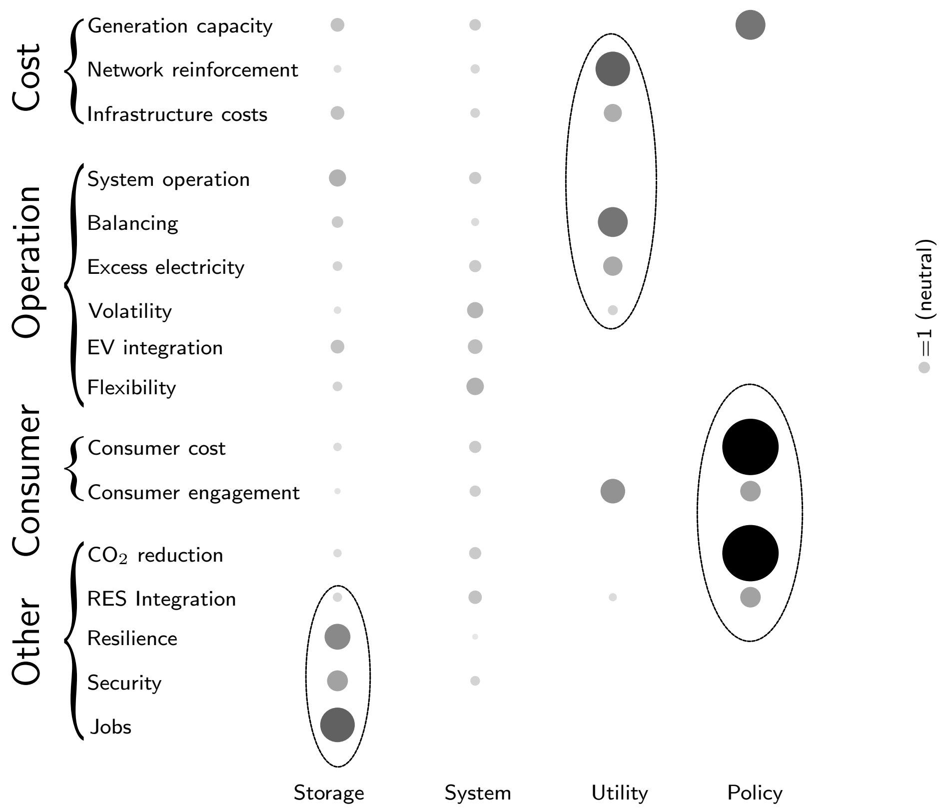

Figure 10: Relative importance of benefits to stakeholder groups. The size of circles is scaled by their relative importortance squared (P^2)

actors and the other groups, but it also highlights that this group sees most value in areas that did not attract many submissions overall. ‘Jobs’, ‘security’ and ‘resilience’ combined do only account for 17% of sumbissions (see pie chart in Figure 8).

Not surprisingly, the group who classified themselves as having a ‘systems perspective’ or being otherwise ‘independent’, do not show up as having a preference for any particular group of benefits.

7 Conclusion

An analytical framework for the evaluation of the distribution of benefits arising from storage has been introduced and employed, based on a review of storage benefits gathered during a stakeholder workshop. The review of benefits covered their origin, relative importance to stakeholders and particular interest groups, as well as potential issues in valuing and rewarding benefits for the providers of storage services.

By comparing the increase in welfare for inelastic and elastic demand, this paper has shown that modelling with assumed inflexible demand can underestimate the welfare benefit of measures, which result in reduced cost of production (both investment and operational costs).

The framework was applied to storage investors, consumers, and the energy system as a whole. It exposed a misalgnment of benefits between these stakeholders groups. Several benefits were found not to be rewarded within the current market structure. This could lead to a market failure in the uptake of storage and a resulting welfare loss.

Policy and market mechanisms to internalise some of the external benefits of storage and should be explored based on this framework. Ongoing consultation with stakeholders is envisaged to further develop these and inform the need and merit of such measures.

* * *

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