

THE ROLE OF
ELECTRICITY STORAGE
IN
LOW CARBON ENERGY SYSTEMS

*TECHNO-ECONOMIC DRIVERS AND
TRANSITIONAL BARRIERS*

PHILIPP GRÜNEWALD

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*IMPERIAL COLLEGE LONDON
CENTRE FOR ENERGY POLICY AND TECHNOLOGY
FACULTY OF NATURAL SCIENCES*

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Declaration

I herewith certify that all material in this dissertation which is not my own work has been duly acknowledged. Selected results from this dissertation have been published during the course of this work and are referenced and listed on page 11 with further outputs on page 233.

Philipp Grünewald

ABSTRACT

UK Government policy sets out ambitious aims to decarbonise the energy system. This requires fundamental changes to the existing energy infrastructure and electricity from low carbon sources is expected to play a major role in this transition.

Electricity storage is widely believed to be able to support the integration of low carbon technologies. So far, the installation of wind power in the UK has not led to any significant deployment of additional storage capacity. Investors still regard electricity storage as too expensive. As more low carbon technologies are deployed, the need for storage may increase. How do these developments affect the role for electricity storage in future UK energy systems?

This thesis addresses this question by combining technical, economic and social approaches. A techno-economic model has been developed to examine the commercial opportunities for electricity storage in future scenarios. A socio-technical perspective of technological transition complements this approach. Stakeholders have informed the analysis on the uptake of storage through a workshop and interviews.

The results point towards a significant increase in the gross value of electricity storage, even at modest efficiencies, especially within highly renewables based scenarios. However, the concept of storing electricity is poorly aligned with existing institutions and regulatory structures. Despite the potential increase in value, electricity storage may fail to be adopted in the best societal interest. Path dependency may lead to the deployment of established alternative solutions, or favour storage technologies with unnecessarily high performance.

This thesis concludes that if electricity storage is to play an effective role as part of a low carbon transition, long term developments would need to be considered as part of a strategic policy framework. These may need to address commercial as well as institutional barriers to deployment.

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to my family

Publications

The following publications, in which the candidate was the lead author, have resulted from this dissertation in the academic literature. Further dissemination is listed on page 233.

Grünewald, P., 2010. *Techno-Economics of Distributed Generation and Storage of Solar Hydrogen*. Conference paper and presentation. 18th World Hydrogen Energy Conference. 16–21 May 2010. Essen, Germany.

Grünewald, P., 2011. *Consumer capacity charging: the effect of ‘not paying for energy’ on an active demandside*. Energy and People: futures, complexity and challenges conference. 20–21 September. Lady Margaret Hall, Oxford [Online] Available from: www.academia.edu/1215036 [Accessed: 12th December 2012].

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Glossary

a	Discount factor [years]
α	Exponential price uplift factor
bl	Base load capacity
C_E	Energy related capital costs [£/kWh]
C_g	Installed generating capacity [GW]
C_P	Power related capital costs [£/kW]
D	Electricity demand [GW]
d	Storage duration [hours]
e	Emissions factors [t_{CO_2} /GWh]
E_{in}	Energy to charge storage [MWh]
E_{out}	Energy delivered from storage [MWh]
$E_{str}(t)$	Storage state of charge [GWh]
E_{str}	Rated energy storage capacity [GWh]
η_{in}	Charge efficiency [%]
η_{out}	Discharge efficiency [%]
η_{self}	Self discharge rate [%/day]
η_{CO_2}	CO ₂ reduction potential [%] [%]
η_{sys}	Round trip efficiency [%]
$f_{(t)}$	Power flow in (>0) or out of storage (<0) [MW]
g	Generating capacity index by merit order
κ	Proportional price uplift factor

L	Engineering life [years]
mm	Mid merit capacity
n	Economic life [years]
$P_g(t)$	Generation from capacity class g [GW]
$P_{str}(t)$	Rate of charge (+) or discharge (-) [GW]
P_{str}	Rated power of storage capacity [GW]
$\dot{P}$	Ramp rate [kW/h]
$\Pi(t)$	Wholesale electricity price [£/MWh]
π_{CM}	Strategic reserve price (same as π_{SR}) [£/MWh]
$\dot{\pi}$	Short run marginal cost [£/MWh]
π_{SP}	Capacity mechanism strike price [£/MWh]
π_{SR}	Capacity mechanism strategic reserve price [£/MWh]
pk	Peaking capacity
r	Discount rate [%]
$S_{(t)}$	Energy held in storage [GWh]
τ	Storage duration ($E_{str}:P_{str}$) [hours]
$U_g(t)$	Uplift factor [1]
$\dot{V}_{str}$	Marginal gross value of storage [£/kW/year]
V_{str}	Gross value of storage [£/kW/year]
z^*	Boundary of confidence interval

Acronyms

AC	Alternate current
BADC	British Atmospheric Data Centre
BETTA	British Electricity Trading Transmission Arrangements
BEV	Battery electric vehicle
BM	Balancing market
BSC	Balancing and settlement code
CAES	Compressed air energy storage
CapEx	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon Capture and Storage
CEGB	Central Electricity Generating Board
CEP	Centre for Environmental Policy, Imperial College
CHP	Combined heat and power
CI	Customer interruptions
CM	Capacity mechanism
CML	Customer minutes lost
CO ₂	Carbon dioxide
DC	Direct current
DECC	Department of Energy and Climate Change
DN	Distribution network
DNO	Distribution network operator
DoD	Depth of discharge
DOE	U.S. Department of Energy
DSM	Demand side management

DSR	Demand side response
DUKES	Digest of UK Energy Statistics
EES	Electrical energy storage
EMR	Electricity market reform
EN&S	Electricity networks & storage
EPRI	Electricity Power Research Institute
ERP	Energy Research Partnership
ESMI	ETI Energy System Modelling Environment
ETI	Energy Technologies Institute
EU	European Union
EV	Electric vehicle
FF	Fossil fuel
GB	Great Britain (referring to mainland England, Scotland and Wales network)
GHG	Greenhouse gas
GW	gigawatt [10^9 W]
GWh	gigawatt hour [10^9 Wh]
h	hour(s)
H ₂	Hydrogen
I/C	Interconnector
ICEPT	Imperial Centre for Energy Policy and Technology
IEA	International Energy Agency
J	Joules (SI derived unit)
kW	kilowatt [10^3 W]
kWh	kilowatt hour [10^3 Wh]
LCNF	Ofgem's low carbon network fund
LENS	Ofgem's Long-term Electricity Network Scenarios
Li-Ion	Lithium-Ion
LTS	Large technical system
MARKAL	IEA MARKet ALlocation model
mcm	Million cubic meters
MLP	Multi-level perspective

MW	megawatt [10^6W]
MWh	megawatt hour [10^6Wh]
NaS	Sodium Sulphur Batteries
NETA	New Electricity Trading Arrangements
NGO	Non-governmental organisation
NINES	SSE Northern Isles New Energy Solutions
NPV	Net present value
Ofgem	Office of Gas and Electricity Markets
OpEx	Operational expenditure
PH	Pumped hydro
ROC	Renewable Obligation Certificate
SMES	Superconducting magnet energy storage
SO	System operator
ST	Socio-technical
STOR	Short term operating reserve
TINA	Technology Innovation Needs Assessment
TN	Transmission network
TNO	Transmission network operator
TRL	Technology readiness level
TT	Technological transition
TVA	Tennessee Valley Authority
TWh	terawatt hour [10^{12}Wh]
UK	United Kingdom
UKERC	UK Energy Research Centre
W	Watt (SI derived unit)
WASP	Wien Automatic System Planning model
Wh	watt hour [3600 J]

Introduction

ENERGY SYSTEMS WILL undergo fundamental changes over coming decades, if present ambitions to decarbonise supplies and to ease fossil fuel dependency are to be achieved. The UK has set itself challenging targets to decarbonise the energy system until 2050 (Climate Change Act, 2008) and low carbon electricity generation is expected to play a major role in achieving these objectives (Skea et al., 2011; DECC, 2009). The transition towards such a future energy system requires policy makers to consider three competing objectives of ensuring that energy can be provided sustainably, affordably and securely (HM Government, 2011).

Displacing conventional fossil fuel based thermal generation affects the balance of these objectives and will have knock on effects for system integration more widely. Thermal generation can respond flexibly to system demands and fossil fuels provide a convenient, abundant and low cost form of storage.

Low carbon technologies, on the other hand, tend to have intermittent or poorly controllable temporal profiles. These sources effectively displace energy output from conventional generation. However, due to their variability, they are less effective at displacing generating capacity. To ensure security of supply, some capacity has to be held in reserve. For low penetrations of renewables (with less than 20% of energy provided by renewables) the additional costs of system integration remain modest (Gross et al., 2006). Higher levels of penetration could, however, result in load factors for conventional plant of less than 10% (from presently over 50%). This would lead to a substantial increase in the cost per unit of energy from such plants if these are to remain in operation (Cox, 2009; Barton et al., 2013).

The increasingly costly conventional approach of providing flexible generation and of curtailing excess generation is only one of four options available for future systems to balance supply and demand. One alternative is to enhance networks, which can help to connect areas with spare capacity to distant regions at periods of high demand. The larger, and less contained such a network is, the more opportunities for spatial arbitrage exist. Temporal arbitrage is, however, not possible with networks alone. The third option is a departure from the present ‘predict and provide’ paradigm, by engaging the

demand side to participate and respond to system stresses by reducing or shifting loads. And lastly, there is electricity storage.

For some, electricity storage is the ‘holy grail’ of our sustainable energy future (Ellis, 2012). Many of the challenges of integrating renewables into the energy system would be solved if electricity could be stored. Technically this is of course possible, but critics claim that electricity storage is ‘too expensive’ (APS, 2007).

The case for storage has been made repeatedly over the years. Yet, in the UK no significant electricity storage capacity has been commissioned on the national grid over the past three decades, since the days of centralised, publicly owned and vertically integrated businesses. Might the prospect of more wind generation in the UK constitute a turning point for electricity storage in liberalised markets?

The arguments put forward by proponents of storage tends to be qualitative. Storage is seen as an ‘intuitively good idea’ and it is widely accepted that storage has ‘a role to play’ (Ekins et al., 2009). Subsequently there are calls on policy makers to provide support (Thorpe, 2012).

For policy makers to decide on support for storage, two questions arise: 1) Does the presence of storage provide added value to the energy system in excess of its costs, and 2) are there reasons why the market would not deliver this value unaided? At least one official has remarked that, especially on the second question, policy makers are ‘hurting for objective evidence’ (ESN, 2011).

Present market arrangements were not designed with electricity storage in mind. It is therefore unclear whether present market structures will bring forward storage in the first place, and whether such capacity would be aligned with the wider long term system interest.

Part of the problem, as this thesis will argue, is that storage is a complex component of the energy system and has evaded many of the models informing future scenarios and policy. High temporal resolution is required to capture the balancing requirements, which storage is likely to contribute to. Furthermore, a range of stakeholders are affected by the operation of storage. Operating strategies that favour some, may incur additional costs for others or challenge established practices. Such trade offs are not always captured in optimisation models.

In the absence of easily comprehensible evidence for the value of storage—or the cost penalty of its absence—indecision may lead to a missed opportunity and potentially higher long term system integration costs.

Electricity storage may thus constitute both a commercial proposition to investors as well as offering ‘common good’ characteristics for future energy systems as a whole. Both aspects will be considered in this thesis. The commercial value considerations give an indication of likely investment behaviour going forward, whereas the ‘common good’ perspective allows this thesis to identify wider benefits, barriers and tensions between different interest groups and to offer tentative policy suggestions.

1.1 Focus of this study

This thesis focusses on long term ‘needs’ for storage and contrasts these with possible routes for market uptake in the context of structural and regulatory barriers and possible path dependencies. The long term focus allows this thesis to identify trends, which may not be apparent from the analysis of short term and incremental developments.

Geographically the analysis is confined to the GB network, but insights may be transferable to other regions. The GB region¹ is interesting from a storage perspective due to its potentially large wind resource, limited interconnection with neighbouring networks (as a result of its island location), and because of its legally binding commitment to reduce GHG emissions.

By taking a holistic approach, exploring the benefits to various stakeholders in the UK, a range of benefits of storage will be considered. Of particular interest is the impact of the wider benefits on the choice of storage configuration and scale. This holistic approach is made possible through a combination of disciplines, including techno-economic modelling, transition theory and stakeholder engagement.

The analysis remains largely technology agnostic. The focus is on generic characteristics of storage, rather than specific properties of particular technologies. This allows this thesis to assess the merit of innovations in characteristics that may not be present in today’s portfolio of technologies.

The modelling underlying this work is intended to remain conceptual. It explores the commercial potential for trading within the electricity market. Exchange of energy between sectors is also a possibility, especially with hydrogen as a vector, creating links with transport and industry. Cross-sectoral interactions are not included in this study. Their potential importance will be discussed and could form part of further work.

1.2 Research questions

The critical review of the literature on electricity storage in the UK in Chapter 2 will establish a gap in the literature, which this thesis seeks to address by posing the following overarching research question:

What influences the role of electricity storage in future low carbon energy systems?

This main question will be broken down and answered in three parts.

1. What are the techno-economic conditions for the commercial viability of electricity storage on the GB network?
2. How do the wider societal benefits affect the case for electricity storage?

¹This study refers to the GB region as the electricity network of mainland England, Scotland and Wales.

3. Which factors might shape the uptake, configuration and operation of storage?

Chapter 2 will return to these questions after critically reviewing the literature on electricity storage and its role in future energy systems. This analysis will identify gaps in the literature on this subject and refine the above questions in order to address these gaps.

1.3 Aims and objectives

The aim of this thesis is to address a gap in the literature on the long term whole system role of storage in low carbon futures. It sets out to identify the key commercial drivers for storage and to explore the sensitivity of its value to changes in key parameters, assumptions and scenarios.

Factors that lead to or inhibit technology uptake are included in the scope of analysis. Commercial incentives, as well as wider drivers and barriers to uptake, which may not be adequately represented in the commercial perspective are addressed.

System wide costs and benefits arising from the presence of storage, such as positive or negative ‘externalities’, are to be gathered subjectively for different stakeholder groups to draw out potential tensions and conflicts of interest. From these, and in conjunction with the commercial drivers, this thesis aims to identify potential barriers to deployment for storage and instruments which may help to overcome such barriers.

The following objectives were set to meet these aims:

1. Identify present gaps in the literature on uptake of storage technologies and any shortcomings in modelling approaches.
2. Develop a method to represent the key techno-economic factors to simulate storage within selected future scenarios.
3. Apply the model to explore key drivers and sensitivities affecting the commercial proposition of storage.
4. Develop and apply an analytical framework to expand the unit of enquiry to include the role of key actors through a socio-technical perspective.
5. Incorporate feedback between the techno-economic and the socio-technical work streams to inform their impact on technology uptake.

1.4 Thesis structure

This thesis is grouped into eight chapters. Following this introduction, the background in Chapter 2 is discussed by means of a critical review of the literature, focussing on literature on storage representation in electricity system models and on transition theory in relation to large technical systems.

The inter-disciplinary analytical framework of this study is introduced in Chapter 3. This sets out three threads employed in this thesis to address each of the research questions. Firstly, the techno-economic model and its representation of storage is outlined. Secondly, the methods of the stakeholder engagement process are explained. And thirdly, the applications of transition theory is introduced. These three methods will be drawn upon to develop an analytical framework, which provides the structure of the analysis of the possible uptake of electricity storage in future systems.

Aspects of this framework are first evaluated in Chapter 4 as part of a review of historic adoptions of electricity storage. This chapter tests the applicability of the analytical framework to inform future uptake of storage when viewed as a technological transition. Limitations of the approach and necessary adaptations are discussed.

Chapters 5–7 apply the components of the framework in turn. The commercial drivers within future scenarios are simulated in Chapter 5. The techno-economic model simulates conditions under which storage might become commercially viable within an electricity wholesale market. This chapter further explores the uncertainties and sensitivities relating to the choice of scenario, parameter assumptions and stochastic variables.

The socio-technical transitions perspective requires a more broadly focussed lens. Chapter 6 therefore builds upon the commercial insights of Chapter 5 and complements them with results from stakeholder engagement work. This allows for perceived benefits and barriers to uptake to be identified and discussed in the context of some of the techno-economic results.

Chapter 7 focusses on the potential uptake of storage, drawing on tensions identified between commercial drivers and stakeholder views. It revisits the techno-economic model to explore the merit of some to the support suggested by stakeholders and their impact on the commercial attractiveness of storage.

Chapter 8 concludes this thesis by reviewing the approach taken in this study and drawing out the main conclusions relating to the research questions. It further discusses areas that could not be addressed and identifies new areas that emerged during this research and are deemed in need of further research.

Energy storage in the UK: present stores, technology options and future scenarios

IN THIS CHAPTER the background to the research questions is provided through a critical review of the literature on energy storage, with particular focus on studies attempting to (directly or indirectly) estimate future contributions of electricity storage in the UK context.

Section 2.1 begins with a review of the state of storage in the UK today. The majority of storage provision presently stems from fossil fuels and this review will therefore acknowledge the role of coal, oil and gas as means of storage, before narrowing the focus of analysis to the primary subject of enquiry—electricity storage. The potential increase in electricity generation from low carbon sources may displace some of the existing fossil fuel based generation and necessitate additional electricity stores. This section outlines some of the electricity storage options considered in the literature. This section concludes that a technology focus is insufficient to assess the future role of storage and that the system context should be considered. The review therefore turns to possible future developments and their treatment in scenario studies. The focus of this review is on the methods applied in different studies and their shortcomings in representing storage. Two forms of models are distinguished: system models (Section 2.2) and engineering models (Section 2.3). Each has their strengths for particular aspects of analysis. For the purposes of this study they do, however, leave a conceptual gap. Section 2.4 concludes this chapter by discussing this gap and three contributions by which this study intends to address it.

2.1 Present storage options

Energy systems require storage of some form or another. This section reviews the present means by which energy is stored in the UK and discusses how different storage forms and

technologies compare. Cases where even relatively cheap fossil fuel stores are not necessarily brought forward by markets to provide desirable levels of reserve lead Section 2.1.2 to conclude that present markets may not recognise the societal value of storage capacity.

2.1.1 Energy storage in the UK today

In their review of present stores in the electricity system, Wilson et al. (2010) make an important distinction between two different forms of energy storage in the UK today: rechargeable stores and non-rechargeable stores. They define the former as a store that can be charged using electricity. The latter store is provided in the UK predominantly by fossil fuels and small amounts of biomass. Although these stores cannot be ‘recharged’ with electricity, they, too, can undergo cycles of depletion and replenishment.

Table 2.1 gives an overview of the present storage capacity for the fossil fuels and shows the durations over which these stores would typically last. Long storage durations of close to 80 days can be provided by the gas storage site at Rough. This store feeds a larger number of smaller stores, closer to the points of demand shown in Figure 2.1. In gas networks the line pack can provide some storage itself (Qadrdan et al., 2010).

For electricity storage similar roles may need to be considered. Large scale bulk storage located remotely on the transmission system could fulfil similar functions to the Rough gas store and provide long duration stores, whereas smaller stores closer to the point of demand on the low voltage network might support fluctuation over shorter timescales.

To date, rechargeable electricity storage shown in Table 2.2, by contrast, only provides small quantities of storage capacity by comparison. The four main sites, all of which are pumped hydro, amount to less than 30 GWh of capacity, compared to potentially over 100 TWh of fossil fuel storage capacity. Furthermore, the most recently commissioned site dates back three decades to a time prior to liberalisation and privatisation. Neither the New Electricity Trading Arrangements (NETA) nor the British Electricity Trading Arrangements (BETTA) have brought about any significant electricity storage capacity investment.

In addition to coal and gas storage in the electricity sector, the UK also holds some oil stores primarily for the transport sector. The stored capacity of fuels for transport has been streamlined towards a ‘just in time’ delivery principle, with more capacity held in the vehicle fleet itself, than the supply line. The vulnerability of the system becomes exposed during sudden surges in demand, such as witnessed in the lead up to a feared industrial dispute in 2011 (DECC, 2012a).

Despite the relative cheapness of storing crude oil, it was deemed necessary to legislate the provision of strategic reserves for European community member states, to guard against ‘serious disturbances’ to the economic activity of the community due to ‘any difficulties, even temporary’. (EEC, 1968)

This directive was issued in 1969, notably before the 1973-74 oil crisis, and stipulates a reserve of at least 65 days average daily internal consumption in the preceding calendar year. A later European Union (EU) directive increased the reserve level to 90 days (EU, 2006). The International Energy Agency (IEA) also mandates strategic reserves of 90

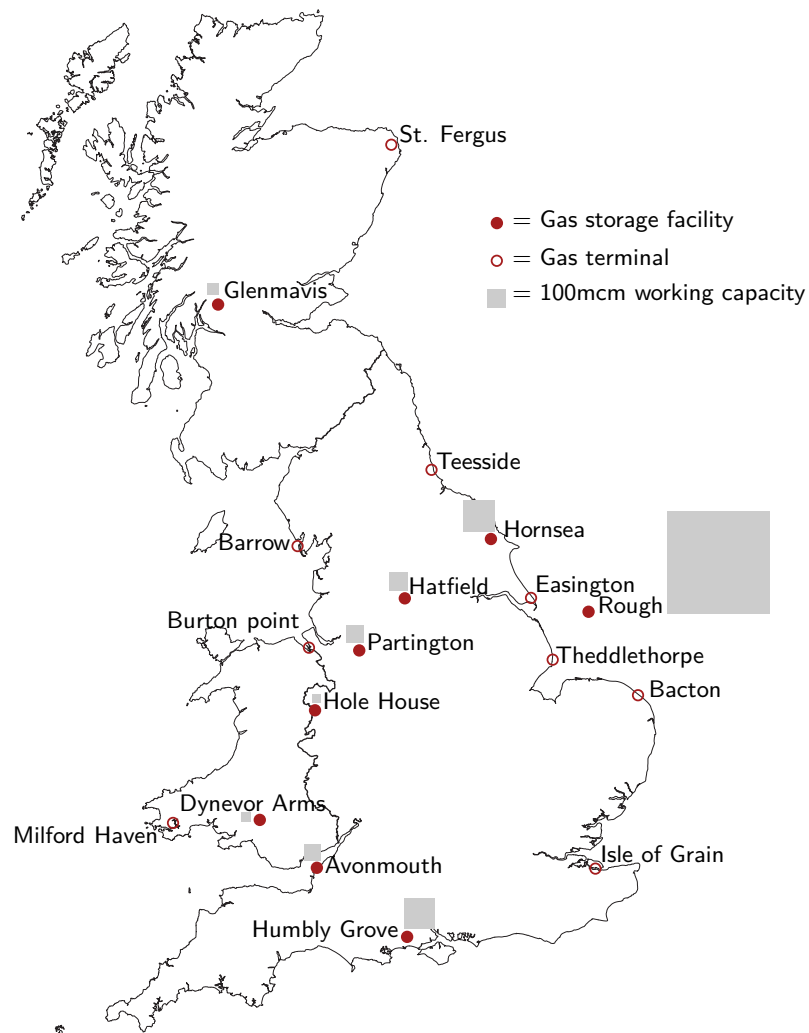


Figure 2.1: Distribution of gas storage facilities and gas terminals. Based on Qadrdan et al. (2010) and National Grid (2008). Map: Ordnance Survey ©Crown copyright 2010

Table 2.1: *Fossil fuel storage on the UK electricity network. Status 2010. Based on Wilson et al. (2010) and National Grid (2011b)*

Type	Capacity [TWh]	Duration [days]	Location
Coal*	43–158	22–82	on site
Gas (long term)	35.5	78	Rough
Gas (medium term)	9.6	20	Incl. Hornsea, Hole House, Hatfield Moor
Gas (short term)	2.3	6	Incl. Glenmavis, Partington and Avonmouth
Total	~90–200		

* based on coal stock estimates

Table 2.2: *Installed pumped storage capacity in the UK. Status Dec 2012. Source: MacLeay et al. (2010); MacKay (2009a)*

Site	Rating [MW]	Capacity [GWh]	Duration [h]	Commissioned	Location
Dinorwig	1728	9.1	5.3	1983	Wales
Cruachan	440	10.1	22.7	1966	Scotland
Ffestiniog	360	1.3	3.6	1961	Wales
Foyers*	216	6.3	29.2	1974	Scotland
Total	2744	26.8			

* 300 GW partially conventional hydro

days for its 28 member states. In both cases countries with domestic oil production, such as the UK, receive relaxed conditions. While many EU and IEA member states publish their strategic reserve level, the exact amount of the UK strategic oil reserve is not known. No equivalent legislation exists to ensure strategic reserves for other fuels, such as coal, gas or electricity stores. The UK has been reluctant to sanction national storage in the past for fear of discouraging commercial investment. Energy companies owning gas storage plants insist that the market can provide all the necessary facilities. However, they ask for tax incentives and lower land rental fees to be provided by the government. (Mason and Ruddick, 30th March 2010)

Mandated storage capacities, calls for support from market participants and concerns over adequacy and security of supply suggest that present market arrangements may not be adequate to bring forward energy storage in the best common interest. This thesis

will return to this question as part of a discussion of the wider benefits of electricity storage in Chapter 6.

2.1.2 Storage technologies

Despite the above-mentioned recent lack of commercial deployment of storage, the literature is rich in storage technology reviews and the approach and conclusions are broadly consistent between them.¹ These typically compare technologies on scales of power, energy (often expressed as the duration of discharge at rated power), efficiency, cost and type of application.

The main technologies included in these studies are listed in Table 2.3 alongside some of the most common categories used to characterise them.

The technology readiness levels (TRL) referred to in Table 2.3 are estimates based on interpretation of the cited literature.²

Aside from the technologies listed in Table 2.3, an increasing number of new technologies is being developed with TRLs presently below 5. These include advanced thermal storage concepts and other novel approaches, which are not covered here in more detail.³

Other concepts include remote storage. In a press release the Department of Energy and Climate Change (DECC) promote an EU super grid, stating that ‘surplus wind energy produced off Britain’s coast [...] could be exported to Norway and used to pump water in its hydro-electric power stations. Electricity produced by hydropower could then be sent to Britain at times of high demand when the wind is not blowing.’ (DECC, 2011b)

‘Second life batteries’ from an emerging electrified transport sector could also influence the grid storage sector. Once the battery performance drops below certain levels it could be replaced in the vehicle. The reduced performance may still be acceptable for grid applications, where batteries are either deployed as a highly distributed resource, or in ‘storage warehouses’, for instance at rapid recharging points for vehicles. (ERP, 2011)

The breadth of possible future options stemming from storage technologies and concepts suggests that a technology specific exploratory study is unlikely to yield valuable insights for the future roles for storage. Too many competing solutions may enter the market and shape future developments. A more generic approach therefore appears more promising.

¹See for instance ARUP (2012); Barton and Infield (2004); Barnes and Levine (2011); Blarke and Lund (2008); Cavallo (2001); Corey et al. (2002); Deane et al. (2010); Denholm et al. (2010); Hunt et al. (2010b,a); U.S. DOE (2011); Swanbarton Limited (2004); Electricity Storage Association (ESA) (2010); EAC (2008); ERP (2011, 2012); Eckroad (2002); EPRI (2003, 2010); Electricity Storage Association (ESA) (2010); van der Linden (2006); Price (2011c); Schaber et al. (2004); Strbac et al. (2012); Taylor et al. (2012); Townsend (2009) or Wilson et al. (2010)

²A TRL of 1 represents technologies undergoing basic research. Technologies in the demonstration phase are ranked 5–6. A TRL of 9 implies technical maturity and that the technology ‘has been thoroughly demonstrated and tested in its operational environment’ (NASA, 2012).

³For examples of novel storage solutions see for instance Isentropic (2010); Garvey (2012, 2010) or Chen et al. (2007)

Table 2.3: Storage technology overview for grid applications. Values represent typically cited ranges and excludes outliers. Based on ARUP (2012), Electricity Storage Association (ESA) (2010), EPRI (2003) Strbac et al. (2012), Taylor et al. (2012), ERP (2011), ERP (2012), Corey et al. (2002), Deane et al. (2010), U.S. DOE (2011) and EPRI (2010). ^a Compressed Air Energy Storage, ^b Uninterruptible power supply

Technology	Scale [MW]	Duration [h]	Efficiency [%]	TRL [1-9]	Deployed [#]	Cost [£/kWh]	Comment
Pumped hydro	200–2000	1–30	75–80	9	>100	150–270	Limited by geology
CAES ^a	5–1000	2–20	55–59	8	<10	80–250	Deployed since 1973, adiabatic technology under development, relies on suitable geology
Sodium Sulphur (NaS) Batteries	1–50	5–10	75	7	300	280–400	Safety concerns after fire issue in Japan in 2011
Lithium-Ion (Li-Ion)	0.01–1	0.1–10	85	9	‘few’	550–2000	High efficiency and energy density at high cost.
Lead Acid Battery	1–10	0.01–10	85–90	9	‘many’	300–750	Widely used as UPS ^b
Flow Batteries	0.2–10	0.5–10	65–75	6	<10	400–550	Capacity scalable via electrolyte tank size.
Liquid air energy storage	>10	>10	55–75	5		166–340	Demonstration plant in operation.
Flywheels	0.1–10	0.01–0.1	85–87	9	‘few’	4800–5500	High cost solution for power quality and frequency regulation services.
Superconducting Magnet Energy Storage (SMES)	1–2	0.01–0.1	90	9	>30	28,000	Used for power quality and frequency regulation services. Potential for cost reduction.
Super Capacitors	0.5–1	0.001–0.01	75–95	8	‘few’	12,000	Self discharge limits efficiency.

Table 2.3 suggests that neither the TRL nor the cost alone give a reliable indicator for commercial uptake. Different technologies appear to have to meet different targets for their specific applications. For example, Superconducting Magnet Energy Storage (SMES) is deployed more widely than flywheels, despite significantly higher costs, potentially in part due to its higher efficiency. The somewhat lower efficiency of pumped hydro or CAES on the other hand, does not seem to put them at a disadvantage over Lithium-Ion batteries, which are not commonly deployed for grid applications. Here the cost appears to dominate.

A technology focus, without consideration of the application's system context, its underlying costs and value structures, therefore provides an incomplete picture in assessing the merit of storage configurations.

2.2 System perspective of storage

Future system contexts may differ radically from today's system. This section reviews the literature on possible changes to the energy system relevant to storage. First, selected UK system studies, which develop scenarios leading out to 2050 are compared. These studies provide a narrative for possible changes. The underlying method and rationale for representing storage, and the divergent conclusions resulting from these approaches are discussed in Section 2.2.1.

Intermittency emerges from these literatures as a potentially significant future driver for storage. Section 2.2.2 is therefore dedicated to literatures related to intermittency in UK future systems. The impact of intermittency on electricity prices as a potential economic stimulant for storage is explored and discussed for its applicability to this study.

2.2.1 Future energy scenarios and transition studies

The complexity of energy systems and the uncertainty over future developments has motivated a range of scenario studies, which aim, not to predict the future, but to create a context in which possible futures can be visualised, compared and discussed.

The use of scenarios dates back to the 1940s, when they were used by RAND Corporation to inform cold war strategy. In the energy context they gained importance as a tool used by Pierre Wack at Shell during the oil crisis in the 1970s to evaluate the company's response options (Hughes and Strachan, 2010a). More recently, scenarios have been developed with the aim of informing policy makers about the options and trade-offs in transitions towards low carbon energy futures.

In the following selected recent energy scenario studies will be compared. The selection is limited to studies with UK relevance and explicit consideration of storage as a technology option. Particular focus is placed on how storage has been represented and simulated, and what their findings suggest for possible future roles for storage.

Table 2.4 lists selected studies with scenarios or projections for entire energy systems. These studies are all set in the context of aiming to reduce overall GHG emission by

80-90% with respect to 1990 levels (often translated as 80-90% CO₂ reductions in the energy sector). The typical target date is 2050, with some studies considering shorter time frames.

Table 2.4: *Selected literature on electricity system scenarios*

Title and reference	Timeframe	Scope	Method
A Roadmap for moving to a competitive low carbon economy in 2050 (European Commission, 2011)	2050	EU	Roadmap with milestones for meeting emission reduction targets ‘based on comprehensive global and EU modelling and scenario analysis’
Projecting Energy Market Trends until 2030 (Fahl et al., 2010)	2030	Germany	Supply and demand projections based on integrated, model-based approach of 4 scenarios
2050 Pathway Analysis (DECC, 2010a)	2050	UK	“Effort” based CO ₂ emission accounting framework
The UK Low Carbon Transition Plan (DECC, 2009)	2020	UK	Consultation based targets and projections
Ofgem: LENS Project (Ault et al., 2008)	2050	GB	Review of other studies, stakeholder workshops, MARKAL model
Ofgem: Project Discovery - Energy Market Scenarios (Marlee and Berge, 2009)	2025	UK	security focused stress test of el.+gas network based on 2×2 scenarios
UKERC2050: Making the transition to a secure and low-carbon energy system (Ekins et al., 2009)	2050	UK	Comprehensive system study, exploring a range of scenarios under emission and resilience constraints, based on UK-MARKAL model

The GHG emission reductions for the power sector are tighter than the overall targets in all of these studies, to make up for sectors that are harder to decarbonise (Ekins et al., 2009; European Commission, 2011). The EU proposes 54–68% CO₂ emission reduction in the power sector by 2030 and 93–99% for 2050. Less ambitious pathway are said to lock in carbon intensive investment. To avoid such a lock-in, R&D and demonstration on the order of €50 billion over the next 10 years, is said to be indispensable. (European Commission, 2011)

The studies in Table 2.4 differ in their approach. The German and EU reports, and to some extent DECC (2009), are targets or roadmaps based on projections, aimed at defining a common approach. The other studies are less prescriptive and explore a range of options with no judgement on their relative merit or probability. The scenarios are typically built around a 2×2 matrix, where one corner of the matrix provides a reference case, which is exposed to two dimensions of change. In the UKERC example these dimensions are ‘system resilience’ and ‘carbon reduction’. All studies make at least a passing reference to storage in the system, with Ault et al. being the most explicit about

its possible role.

UK Energy Research Centre energy 2050 scenarios

The UK Energy Research Centre (UKERC) energy 2050 project has developed scenarios by soft-linking different models including the Wien Automatic System Planning model (WASP), and UK-MARKAL, a market allocation model, which seeks to find the least cost investment option from a wide range of technologies to meet demand under constraints, such as CO₂ emissions. (Skea et al., 2011)

UK-MARKAL operates with six time zones (day and night for summer, winter and intermediate, respectively). Despite this low temporal resolution, the model recognises the need for system balancing and complements large amounts of renewables with reserve capacity. The technology of choice for this service are combined cycle gas turbines (CCGT). The authors of the synthesis report recognise that this is not necessarily the only option.

Storage sounds to be an attractive solution [...] we have to question the capability of the model adequately to capture the opportunities of supporting intermittent power sources.

(Ekins et al., 2009, p.97)

Especially scenarios with very high penetration of renewables are expected to pose a substantial challenge to society and would necessitate advances in storage technology and smart grids.

There is a policy choice to be made about investment in ‘strategic’ storage or other facilities which could probably only be justified if developers could earn a risk-free regulated rate of return on the assets.

(Ekins et al., 2009, p.141)

The emphasis on the strategic nature of the investment hints at concerns about the planning horizon employed in the private sector to deliver solutions in the long term interest of the system as a whole. Secondly the concept of a ‘risk-free regulated return’ removes storage from the market place altogether and it becomes effectively a privately managed state financed asset. This poses the question, if storage and the market are inherently incompatible, or if partial state support may be sufficient to encourage successful uptake. In either case the value of storage to ‘society’ needs to be well understood to justify the exposure of the state to an investment which is perceived as ‘risky’.

Ofgem’s LENS Electricity Network Scenarios

The Ofgem Long-term Electricity Network Scenarios (LENS) project developed four scenarios, also based on MARKAL simulations. Of these, the ‘multi-purpose networks’ scenario has the highest level of storage. This is explained with the high share of non-flexible plant.

Storage is used to allow continued operation of non-flexible plant during the night, with the stored electricity released to contribute to day time demands.

Ault et al. (2008)

The development of storage technologies over time is shown in Figure 2.2. The vast majority of this storage (>85%) is provided by plug in hybrid vehicles. Storage heaters decline to less than 8 TWh, compared to ~11 TWh today. Pumped hydro is phased out in this scenario by 2035 and hydrogen—although considered by the model—does not feature at any stage as a storage vector.

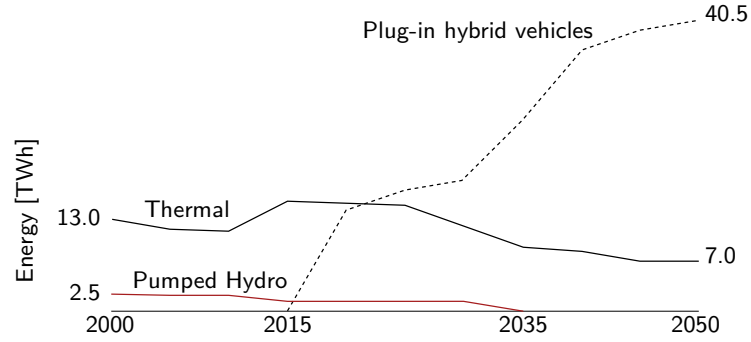


Figure 2.2: *Rise and fall of storage technologies in the ‘Multi-purpose networks’ scenario. Pumped hydro gets phased out as a result of plug-in hybrid electric vehicles. Based on Ault et al. (2008).*

Once built, pumped hydro is relatively cheap to operate and delivers a valuable range of system services (Boon, 2010). The closure of existing pumped-hydro shows the extremes to which scenarios with least cost allocation and assumptions over the availability of electric vehicles for grid balancing can affect the role of storage. Other studies caution the extent to which electric vehicles can deliver cost effective grid balancing. (Slater et al., 2009)

The decline in storage heater capacity, which is seen by some as a promising low cost future storage option (ECCC, 2010), also results from the abundant storage capacity assumed in the transport sector.

Table 2.5: *Levels of storage deployment in 2050 for different levels of effort based on DECC 2050 scenarios. DECC (2010a).*

Level of effort		Storage [GW]	I/C ^a [GW]	Demand shifting
1	little or no effort	3.5	4	
2	ambitious but reasonable	4	10	
3	very ambitious effort, technological breakthroughs	7	15	‘some’
4	limit of what is physically or technically deemed plausible	20	30	‘significant’

^aInterconnects

DECC 2050 pathway analysis

The DECC 2050 scenarios are expanded in detail in DECC (2010a) and further background of the underlying motivation can be found in the Government’s Carbon Plan (HM Government, 2011). The accounting framework provides four levels of storage, ranked by ‘effort’. The levels of effort and their corresponding deployment of storage are given in Table 2.5. With little or no effort, storage is expected to remain at current levels of pumped hydro storage and some interconnects to mainland Europe. If a higher level of effort is assumed, more storage, interconnects and demand shifting take place. The technologies mentioned in the documentation are pumped hydro and, in the most ambitious case for storage, tidal lagoons. The rationale for the choice of storage technology is not given.

Storage is intended to address a ‘five-day anticyclone blocking event’. The numerical logic is set out in MacKay (2009b). In a scenario with 33 GW wind, the average output from wind is assumed to be 10 GW. Should this source not be available for approximately 100 hours, then storage on the scale of $10 \text{ GW} \times 100 \text{ hours} = 1 \text{ TWh}^4$ is said to be required. This ‘ball park’ figure forms the basis for the search for a storage solution and therefore, by definition, favours large scale solutions.

The DECC calculator is not an economic model. It therefore does not evaluate the cost of meeting wind lulls from storage against alternative solutions, such as for instance reserve fossil fuel plants (with or without CO₂ abatement). Neither is the storage capacity considered for any use other than a prolonged wind lull, nor could it be if one assumes that the capacity at the start of the lull period must be full. This could leave the storage asset with an energy turnover of possibly less than once per year, making commercial operation extremely challenging.

Further, the presence of storage has no impact on CO₂ emissions in this model. When questioned about the representation of storage in the model, the Chief Scientific

⁴Note that this is the storage capacity and not the energy turned over as in Figure 2.2

Advisor to DECC, David MacKay, conceded that storage would need to be worked on further in this model, but that CO₂ emission reductions are not the prime motivation for storage. (MacKay, 2011, 2012)

The role of storage is therefore not seriously considered in the framework, which has CO₂ emission reductions as its prime objective and does not consider integration or cost implications in any detail.

Comparison of scenarios

Table 2.6 gives an overview of diverging views on storage as well as the different methods adopted in these studies. The diverging roles and rationales for storage suggest that neither a consensus over the role of storage currently exists, nor a common and robust method for its evaluation is being applied.

Table 2.6: *Differing system balancing solutions in 2050 scenarios with highest levels of renewables.*

Study	Dominant technology	Rationale
Ofgem	BEV (40 TWh)	Storage is present as a by-product of BEV take up
DECC	Tidal lagoons (20 GW)	Uses storage to cover 5-day lull in wind
UKERC	CCGT (20 GW)	Model selects CCGT reserve based on ‘market allocation’ optimisation

One reason for the lack of detail on storage representation in many of these studies stems from the computational complexity of the models involved. The technology choices during a system transition take place on a timescale of decades, while system balancing is a matter of minutes or even seconds—a difference of 5 orders of magnitude.

Averages for supply and demand allow these models to greatly reduce the computational complexity. By doing so, they implicitly assume a certain level of storage in the system, which takes care of any deviations of actual values from the average in a given period (and further assumes that generation occurs prior to demand). For scenarios with high penetration of wind, this may lead to an underestimate of the role for storage applications.

Representing storage within these models is computationally expensive and can make—what is already a complex set of equations—prohibitively difficult to solve.

Attempts have been made to improve the temporal resolution of the MARKAL model by adding time zones, but these are not deemed sufficient for an intermittency analysis. (Kannan, 2008)

Some studies do not disclose their method for representing storage. It is therefore not always possible to judge to what extent the need for storage has been considered. Ekins et al. (2009) and DECC (2010a) state that their models may not fully capture the need or the opportunities for storage.

The difficulty of representing storage in scenario models may thus have led to an underestimate of its role in policy discussions.⁵ Temporal resolution of the modelling framework is critical if the role of storage in balancing supply and demand is to be adequately represented. Such balancing challenges are expected to increase within low carbon energy systems with large shares of intermittent generation. The following section therefore focusses specifically on studies that concern themselves with the integration of intermittent sources into future systems. These allow this thesis indirectly to infer from emerging tensions within such systems, whether an increasing role for storage may emerge.

2.2.2 Intermittency in future systems

The impact of intermittent generation on the energy system was debated as early as 1980 by Farmer et al. and again by Grubb in 1988. Gross et al. (2006) reviewed 150 studies relating to wind and its impacts on intermittency. The assumed penetration of wind in these early studies is low and consequently no major challenges of system integration are identified. More recent work on penetration levels up to 20% still concludes that existing infrastructures are widely adequate to cope with the intermittency on the system (Gross et al., 2006). An overview of the key studies reviewed here is given alongside a brief summary in Table 2.7.

From their review of the literature Gross et al. conclude that the reliability of the system need not be affected by penetrations of up to 20%, but that costs may increase. They estimate the balancing cost at £2–3 per MWh and the additional system margin at around £3–5/MWh (Gross et al., 2006).

Studies on the cost of intermittency have been criticised for not attempting to determine the overall optimal system (including the amount of storage) that provides the lowest cost of energy (Denholm et al., 2010). This shortcoming has been addressed in studies considering higher levels of renewables. In extreme cases, such as those explored by Sorensen or Anderson and Leach, energy is delivered entirely renewably. Here, the use of bulk storage is said to be unavoidable (Gammon, 2010). What is noteworthy, however, is that energy cost in such futures is not necessarily expected to be higher than in fossil fuel based system. (Anderson and Leach, 2004; Sorensen, 2008)

Both Qadrdan et al. and Morris et al. focus on the impact of intermittency on the gas network, which is the part of the energy system currently delivering much of the ‘system storage’. Gas plants are expected to provide balancing services and reserve for intermittent sources, and the gas networks need to cope with increasing swings in demand. Morris et al. and Qadrdan et al. both conclude that gas markets may need to move to intra-day balancing arrangements, but Morris et al. argues that such a change will only become necessary once the penetration of intermittent sources has increased significantly.

⁵Since commencing this study the interest of policy makers has increased considerably with more explicit mentioning in the recent Electricity Market Reform (EMR) consultation and funding opportunities for storage development DECC (2010c, 2012b).

National Grid is simulating the impact of intermittency on their role as system operator. As a result of the increased sensitivity to forecasting error of wind sources, a larger reserve requirement is anticipated (National Grid, 2011b). By 2020 National Grid expect a total reserve need of approximately 8.2 GW. This figure has led IMechE (2012) to conclude that in the 2020s this amount of storage may be required by referring to the National Grid study. However, as Figure 2.3 illustrates, only a small proportion of reserve requirements is presently met through storage, and one can expect that some of the competing options will retain a share of the market well into the future.

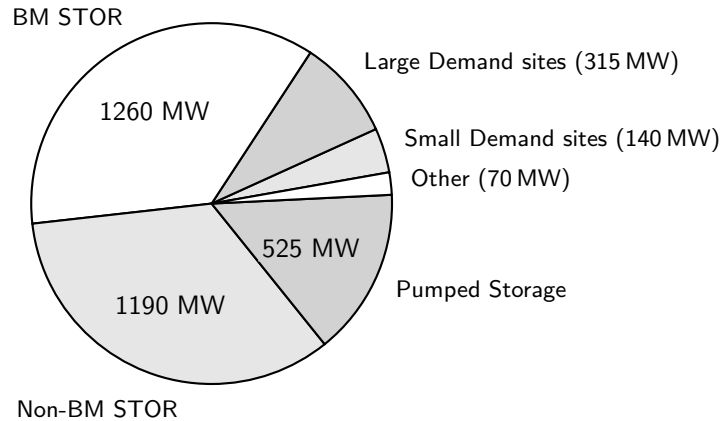


Figure 2.3: *Typical composition of the present 3.5 GW reserve requirement. By 2020 National Grid anticipate a total requirement of 8.2 GW. Based on Welch (2010)*

Intermittency impact on wholesale price volatility

Cox (2009) conducted a comprehensive study of the impact of intermittency on the UK and Ireland, and its wholesale electricity prices. They predict sharp price spikes, driven by CCGT plant operating on low load factors, as well as price drops to, or below, zero, at times of low demand and high wind.

Wholesale prices have also been analysed by Green and Vasilakos (2007, 2010b) and Holmberg and Newbery (2009). The earlier work by Green and Vasilakos implied that, although price volatility increases, the year on year variation was less dependant on wind, than it was on changes in fuel prices. Their model clearly shows significantly smaller variation at the ‘price spike’ end of the cost duration curve than found by Cox, as shown by the comparison between Figures 2.4a and 2.4b. The studies differ in their use of historical data (Green and Vasilakos) and a Monte Carlo simulation (Cox). Cox includes a greater degree of detail in network limitations and the technology characteristics, which may lead to greater sensitivity towards price spikes. In a later paper Green and Vasilakos conclude that ‘electricity wholesale spot prices in Great Britain would be significantly

affected by the amount of wind generation in each hour', but that the effect of volatility would ultimately 'cancel itself out'. This may be the case for consumers, who are charged an 'average' price. However, market participants who are exposed to the spikes are not necessarily the same as those experiencing the drops in prices. The former could benefit CCGT plants, whereas the latter leads to reduced revenue for wind energy producers.

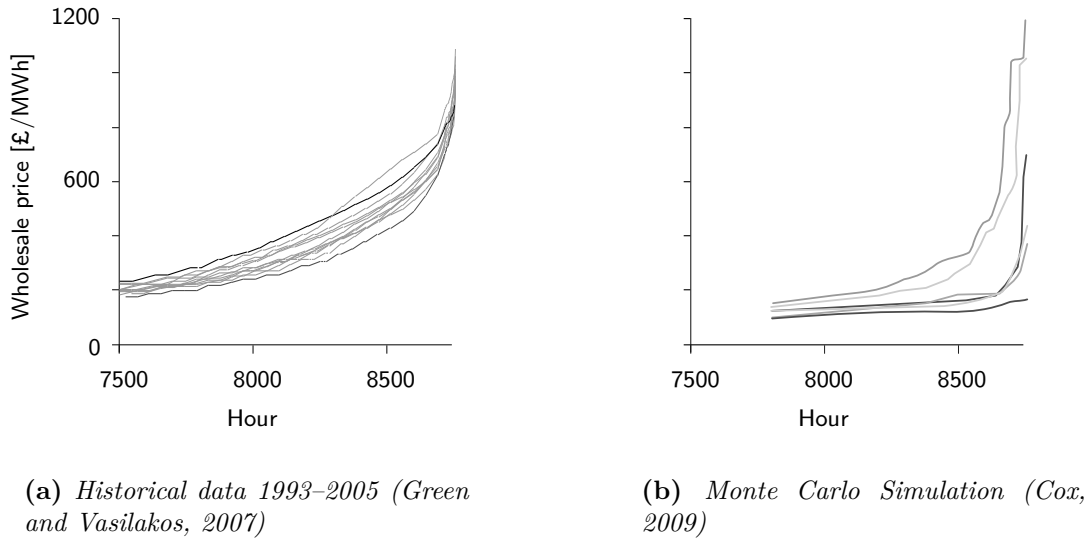


Figure 2.4: Differing long term GB price duration curve projections

The price spikes (and troughs) observed by Cox are modelled on the assumption that significant amounts of wind are added to the GB energy system, with no changes to the regulatory framework. In practice one would expect the market and the policy landscape to adapt in order to mitigate such volatility. Thus, the price volatility approach provides a valuable starting point for a discussion of mitigation options, with the provision of storage being one of these options.

The system perspective reviewed in the previous sections provides an overview of possible changes to future energy systems and challenges resulting from these changes. Fossil fuel based thermal plant, which presently deliver both storage capacity and flexibility to the supply side of the electricity system, reduce in their relative share in many future scenarios. Furthermore, intermittent sources of energy, once they reach high levels of

penetration, could drive up the cost of peaking energy, while depressing wholesale prices during periods of low net-demand. Although some of the system models do not feature significant storage deployment, the high level perspective suggests a potentially fertile environment for future uptake.

2.3 Engineering perspective of storage

This section changes the perspective from the electricity system as a whole, towards storage technologies and their operation at an engineering level. This includes a review of literature on the operation of storage in Section 2.3.1 and its role in future systems in Section 2.3.2.

2.3.1 Reviews of storage operation

A number of studies and demonstration projects have investigated the operation of storage directly associated with individual intermittent sources.^{6,7} Such studies can provide specific results and offer optimised configurations (Bathurst and Strbac for instance proposes to use 6 MW with 6 hours of storage for a 10 MW wind farm).

A detailed model has also been developed as part of the Value Chain Optimisation Tool (PLATOS) presented by KEMA (KEMA, 2010a). The approach aims to identify the optimal technology choice, from a wide range of options, which is ‘best for the system’. Model output includes:

- Optimal locations of storage systems
- Optimal number and type of storage systems
- Required specifications for storage system
- Optimal set points for storage systems
- Performance indicators for each storage management algorithm

The model is highly specific to system mix, network configuration and load profiles, and recognises the need for detailed and time resolved simulation.

Black and Strbac (2007) simulate a short period with high temporal resolution, based on wind forecast errors and estimate the resulting value of storage. The scope of storage technology is limited to short duration (energy:power ratio is set to 6 minutes). This is arguably the commercially most attractive type of storage. Longer duration, especially beyond 1 day, is said to be unlikely to become commercially viable (Bathurst and Strbac, 2003; Barton and Gammon, 2010). Black and Strbac (2007) conclude that ‘much of storage’s value comes from handling the high frequency of smaller imbalances’. This, however, is also the most competitive part of the market and other technologies and solutions may displace storage at lower costs. These could for instance include smart appliances.

⁶For PV examples see Richards and Conibeer (2007); Maclay et al. (2007) and Solomon et al. (2010)

⁷For wind examples see Aguado et al. (2009) and Bathurst and Strbac (2003)

Alternatives, such as diversification of wind through networks as a first order response to intermittency, are not always considered. Thus, the call for more holistic studies is growing (see Gammon (2010) and Korpas and Gjengedal (2006)).

Blarke and Lund develop a more generic framework for assessing the value of storage. They define a ‘storage and relocation coefficient R_c ’, as the statistical correlation between net electricity exchange between relocation technology and system, and the electricity demand minus intermittent renewable energy production (Blarke and Lund, 2008). This concept allows them to compare the value of different means of matching intermittent generation and demand, including storage.

In their review of the economic viability of storage technologies Schaber et al. place particular emphasis on the importance of the round-trip efficiency of storage technologies. They argue that, ‘all else being equal’, efficiency is of ‘paramount importance’. This is a view that is commonly held, especially in response to low round trip efficiency of a hydrogen cycle (Schaber et al. cite 47%). In 1998 Scherer and Newson conclude that the technology cost is less important than efficiency. In a later study Black and Strbac (2006) come to the opposite conclusion that storage efficiency has a rather minor impact on performance. Underlying these divergent views are fundamentally different assumptions about the market in which storage operates. If storage trades in markets with consistently high electricity prices and small trading margins, storage does indeed require high efficiency. On the other hand, within systems comprising high levels of intermittent generation, electricity prices have been shown to become volatile downwards as well as upwards (see Section 2.2.2). In such cases efficiency requirements may become less stringent. The commercial importance of storage efficiency will be directly addressed as part of the techno-economic analysis in Section 5.3.4.

2.3.2 Future roles for storage

Table 2.8 gives a summary of literature on the role of storage in future energy systems. A number of these studies has been published in the recent past, indicating a rising interest in the subject. The range of methods is considerable, including qualitative considerations with stakeholder workshops, technology reviews, scenario models and experimental studies in niche markets.

Table 2.7: *Studies of the intermittency impacts on the energy system*

Title	Wind penetration	Summary
UKERC: The Costs and Impacts of Intermittency (Gross et al., 2006)	20% of Energy in 2030	Review of intermittency studies. Concludes price rises, but no fundamental system changes
Market behaviour with large amounts of intermittent generation (Green and Vasilakos, 2010b)	20 GW in 2020	Wholesale prices will be significantly affected, but volatility cancels out over time.
Poyry: Impact Of Intermittency: How Wind Variability Could Change The Shape Of The British And Irish Electricity Markets (Cox, 2009)	33 GW in 2020, 43 GW in 2030	Increased electricity price volatility upward and downwards, from $\gg$ £1000/MWh, to below zero.
Poyry: How Wind Generation Could Transform Gas Markets In Great Britain And Ireland (Morris et al., 2010)	33 GW in 2020, 43 GW in 2030	Wind will impact gas price volatility as well as electricity
Impact of a large penetration of wind generation on the GB gas network (Qadrdan et al., 2010)	25 GW in 2020	Predicts line-pack depletion in gas networks on low wind days
Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand (Sinden, 2007)	25 GW	Identifies a trend of high wind energy production during high demand periods

Table 2.8: *Selected studies exploring the possible roles for storage in future electricity systems*

Title and reference	Method	Key points
The Role of Energy Storage with Renewable Electricity Generation (Denholm et al., 2010)	Treats storage as an economic question. Compares cost/benefit to other available options.	Studies on the cost of intermittency generally do not attempt to determine the optimal system and thus do not include storage.
Electric Power Industry Needs for Grid-Scale Storage Applications (Hunt et al., 2010b)	Qualitative and stakeholder workshop based review of storage technology and needs	Current market structure does not recognise the benefits of energy storage. Weak stakeholder understanding. Sets out technology targets for different types of storage.
Utility-Scale Storage of Renewable Energy (Schaber et al., 2004)	Review of technologies based on efficiency.	Points out the difference in efficiency between storage technologies, ranging from <50% for hydrogen to over 80% for batteries.
Energy storage in the UK electrical network [...] (Wilson et al., 2010)	Contrasts conventional fossil fuel storage with rechargable forms of storage.	Storage will be a key enabling technology, increasing the impact of demand side management (DSM) and improving resilience throughout the network. Key questions concern the scale and location and how a market can be created.
The production of hydrogen fuel from renewable sources and its role in grid operations (Barton and Gammon, 2010)	Three UK pathways modelled as scenarios with dynamic supply demand balancing.	Expect 28 GW of virtual storage in 2050. Surplus hydrogen available not before 2030.
Hydrogen in the Future Energy Generation Portfolio (Gammon, 2010)	same as Barton and Gammon (2010)	Understanding hydrogen's role requires a holistic view of the total energy system. Significant hydrogen markets are an inevitability in a low carbon energy system.
The use of Energy Storage on the Modern Power Network (Reid, 2011)	Practical application in Shetland, Northern Isles New Energy Solutions (NINES). Six comprehensive system models.	'Stubborn demand' limits scope of DSM. Comprehensive portfolio of storage technologies is needed.

While a large body of literature covers the technology and characteristics of storage, Denholm et al. argue that the role of storage in the energy system is ultimately an economic question (Denholm et al., 2010). They set out the drivers for storage as:

- advances in storage technologies;
- an increase in fossil fuel prices;
- the development of deregulated energy markets, including markets for high value ancillary services;
- challenges to siting new transmission and distribution facilities; and
- the perceived need and opportunities for storage with variable renewable generators.

The complexity and uncertainties of the economics of storage, explored in Section 2.2.2, led Denholm et al. to conclude that these may pose a barrier to deployment:

Because the economic analysis is difficult, and benefits of storage are often uncertain, utilities tend to rely on more traditional generation assets, especially in regulated utilities where risk is minimized and new technologies are adopted relatively slowly.

Denholm et al. (2010)

The concern about market structures also features in a U.S. Department of Energy (DOE) study by Hunt et al.. Their review builds on a stakeholder workshop (although the authors comment that the stakeholder understanding is ‘weak’). No less than 17 grid storage applications are identified by Hunt et al.. They recognise the importance of technology development and give some very specific technology targets for different types of application. The main conclusions state that current market structures in the U.S. do not recognise the benefits of energy storage. (Hunt et al., 2010b)

In a separate study for the DOE the Electricity Power Research Institute (EPRI) attempts to estimate both the market size and the expected value of energy for the different services based on a bottom up assessment. The resulting graph for the U.S. is shown in Figure 2.5. The aggregation of these independently derived values is problematic. Some combinations may be synergistic and aggregate well, while others rely on contradictory operating patterns and are mutually exclusive, or accrue in different locations on the network.

Although the graph implies some degree of certainty about the scope and value of storage services, it is important to note that these estimates are sensitive to a number of assumptions, such as time horizon, and market frameworks.

The UK literature also refers to concern over unsuitable market structures. Wilson et al. states that the question of how to create a market for storage is still unanswered and argues that common good characteristics of storage and wider benefits are presently not included in engineering models (Wilson et al., 2010; Hall, 2011).

No data equivalent to the EPRI study are available for the UK or Europe. The importance of carrying out studies that are specific to the UK is illustrated by differences between U.S. and UK perceptions of value. Reid (2010) rates the relative importance of

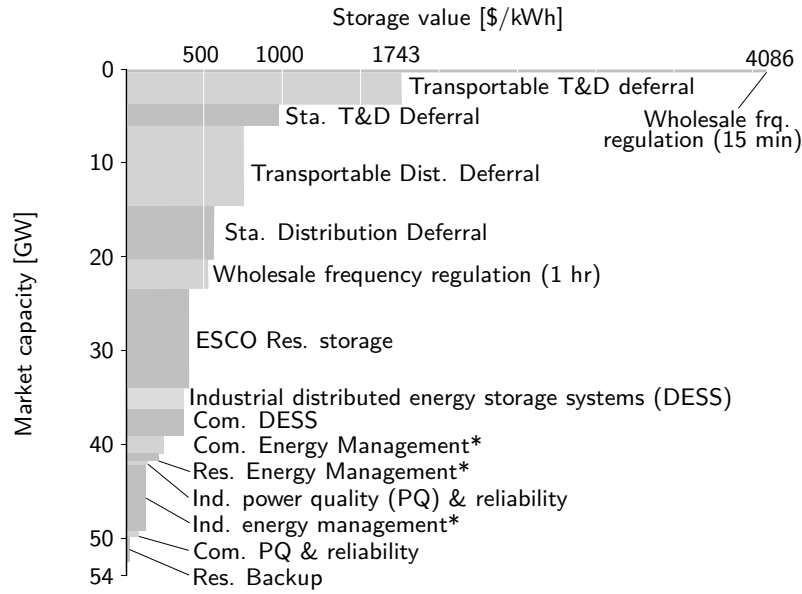


Figure 2.5: Value and scope for a range of energy storage services. (*sta.*=stationary, *com.*=commercial, *res.*=residential, *ind.*=industrial)
Source: EPRI (2010)

storage value as shown in Figure 2.6. Unlike EPRI, he estimates the case for distributed storage, where arbitrage is expected to provide greater value than capital savings (Reid, 2010). This could reflect fundamentally different network structures, with longer distances between generators and load centres in the U.S. compared to the UK. Although some aspects of this thesis may be applicable more generally, some of the energy system specific features suggest that the role of storage may differ between the US, the UK, Europe and other system contexts.

As indicated in Section 1.1, the UK is unlike other energy systems in that it is islanded, densely populated and has one of the largest wind resources in the world. Nonetheless, this thesis aims to frame the system context such that lessons for other regions may be extracted.

Richard Smith from National Grid states that the potential of storage is not yet known. He explains the lack of studies in this area by the fact that many of the issues are not expected to arise for another decade. (ENDS, 2011)

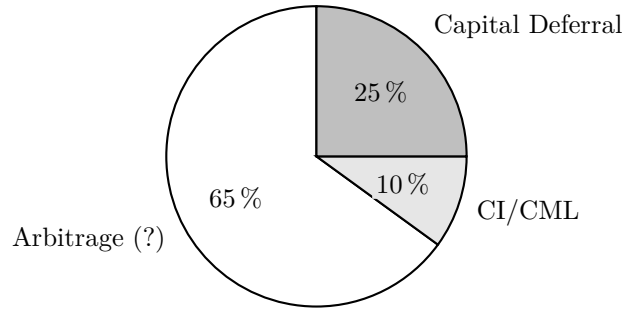


Figure 2.6: *Benefits case for network embedded storage. (CI=Customer interruptions, CML=Customer minutes lost). Based on Reid (2010). The question mark suggests that the benefit from arbitrage is uncertain.*

2.4 Discussion and gaps in the literature

2.4.1 Storage in the literature

The prospect of energy systems with high shares of renewables or other forms of low carbon generation has led to a renewed interest in the subject of electricity storage with a growing number of publications over recent years. Intermittent generation is commonly cited as the key change that drives the ‘need for’ and the ‘value of’ storage.

Two broad classes of models to simulate storage within electricity systems can be distinguished: *engineering* models and *system* models. The former class focusses on specific technologies and assesses their techno-economic performance in a given system context. The latter class is concerned with the composition of the system at a national level and seeks feasible or least cost solutions under constraints, such as carbon emission targets.

Several engineering model based studies have been undertaken, focussing on available technologies and existing markets. These studies tend to identify commercial opportunities (or their absence), and point towards considerable uncertainty and policy dependency for storage applications. Some of these studies further refer to ‘wider system benefits’, which should be considered in the assessment of storage. It is however not possible, based on this class of model, to quantify the scale of such ‘wider benefits’, unless their scope is expanded significantly.

In theory, system models should be able to inform our understanding of the value of such wider benefits, by including trade-offs between storage and alternative solutions. System models, such as MARKAL, Energy Technologies Institute (ETI) ESME model or the DECC2050 accounting framework, do attempt to include storage. They fail, however, to represent storage adequately due to their lack of temporal resolution or limited ability to capture balancing requirements with respect to alternative balancing options, as discussed in Section 2.2.1. Furthermore, system studies come to widely

differing conclusions on the type and role of storage, in part due to explicit and diverging assumptions about the best use of storage (tidal lagoons for wind lulls or BEVs for balancing).

2.4.2 Gaps in the literature

This chapter has shown that current studies into the future UK energy system either lack a dedicated representation of storage, or that the assumptions around its uptake are simplified to a point that their conclusions may substantially over- or underestimate the role for storage in future scenarios.

The complexity of the subject is one of the reasons many models do not adequately represent storage. A vast spectrum of temporal resolution and sensitivities to boundary conditions and assumptions make it a challenging subject for models that were not developed with storage in mind. System models tend to sacrifice temporal resolution, while engineering models fail to represent wider system developments.

Time averaged load profiles implicitly assume that energy can be shifted in time. This failure to overtly acknowledge storage requirements can lead to an underestimation of the storage capacity needs in future systems.

Similarly, simplified assumptions can lead to very high estimates of the need for storage, as shown in the example where a prolonged wind lull is to be met entirely from storage.

Approaches dealing with storage more directly, sacrifice (by the same constraint of computational complexity) insight into the broader role for storage. A common approach in such engineering studies is to assess the commercial (rather than the system) value of storage for a given situation. They therefore become case specific, often with reference to one particular type of storage technology, and limited potential to extrapolate conclusions for the wider systems and their longer term transitions.

System models and storage specific engineering models thus presently exist alongside each other with limited ability to be integrated or soft-linked.

Neither the literature on storage, nor transition studies reviewed in Section 2.2.1, address the role of stakeholders in the deployment of storage into future systems. Models such as MARKAL, assume an almost automatic process of investment in least cost solutions. This has led to the critique by Hughes and Strachan (2010b), which points to a lack of agency attributed to key actors during future transitions in scenario studies more generally. For storage specifically, the absence of agency constitutes a potentially important omission. Neither the role of incumbents to drive or inhibit storage deployment, nor the mechanism by which beneficiaries reward storage are well understood or discussed in this body of literature.

The review of literatures on system modelling, storage modelling and transition of new technologies identified a gap in the literature relating to the future role of storage in three areas:

1. lack of a dedicated approach to represent storage operation dynamically within system studies;

2. limited understanding of changing drivers for storage over time; and
3. insufficient consideration of key actors in adopting storage solutions.

The objectives 2–4 of this thesis, set out in Section 1.3, seek to address these gaps, by developing a method to represent storage in generic techno-economic terms, by exploring the commercial proposition and key drivers for storage, and by giving weight to key actors through a socio-technical perspective. The fifth objective relates to the integration of these themes to address the overall research question, first formulated in Section 1.2:

What influences the role of electricity storage in future low carbon energy systems?

The three sub-questions relate to the above themes and can be further refined based on the findings of this literature review as follows:

1. What are the techno-economic conditions for commercial viability of electricity storage on the GB network?
 - Under which conditions does storage become commercially viable?
 - How does increased intermittency affect the commercial value?
 - How does storage compare with alternative solutions?
2. How do the wider benefits affect the case for electricity storage?
 - What are the external benefits for different types of storage?
 - How are these benefits perceived among different stakeholders?
 - What tensions exist between stakeholders in relation to storage?
3. Which factors shape the uptake, configuration and operation of storage?
 - What barriers could inhibit the uptake of storage?
 - What is the role of stakeholders and institutions in bringing storage to market?
 - How do different support mechanisms affect the role of storage?

The following chapter proposes an analytical framework, which seeks to address these questions by drawing on a selection of methods from different disciplines. These methods are intended to address the sub-questions and also inform each other for a better understanding of the factors influencing the future role of storage, thereby addressing the overall research question.

Methods to assess the future role of storage

INTERACTIONS OF STORAGE with the wider energy system are complex. The previous chapter identified a gap in the literature relating to dedicated consideration of storage in system models and pointed out shortcomings in the methods employed in the literature on the future role of storage. In this chapter an analytical framework is proposed that addresses this gap and takes account of storage specific techno-economics, while also considering wider system interactions. The ‘whole system perspective’ is intended to remain manageable in scope by combining three approaches:

1. Techno-economic analysis
2. Stakeholder engagement, and
3. Transition theory.

This chapter begins with a discussion of the underlying research philosophy, which guides the choice of methods and the scope of their implementation. Each of the above approaches will then be introduced and critically reviewed in turn in Sections 3.2, 3.3 and 3.4, before the integration into an analytical framework to be used as part of this thesis is explained in Section 3.5.

3.1 Research philosophy

This section introduces four underlying approaches guiding this study: a long term perspective; a technology agnostic approach; exploratory, rather than predictive, analysis; and inter-disciplinarity in the choice of methods. Each of these principles and the rationale for its adoption is briefly explained here.

3.1.1 Long-term perspective

UK policy is often said to suffer from short term thinking, guided by immediate pressures and influenced by commercial and financial sectors with a preference for projects with short pay-back periods. (Kay, 2012; Mayer, 19th July 2012)

Transitions of large technical systems take time and the UK targets for GHG emission reductions going out to 2050 do reflect this. The role for electricity storage may be affected by gradual changes over time during this transition. A long term perspective allows this thesis to capture these changes and to examine the contribution storage could make towards realising societal goals underpinning the desire for sustainable energy systems.

Investment decisions on storage tend to be taken on short to medium term time scales¹ and this study seeks to contrast this perspective with the impact storage could have when considered over longer periods.

The long term perspective allows this thesis to explore not just the commercial factors affecting storage, but further provides some insight into any potential strategic considerations as part of a low carbon transition and in achieving wider societal objectives of a secure, affordable and sustainable energy system as set out in the UK Governments Carbon Plan (HM Government, 2011). Storage relates to all three of these objectives. It can integrate variable sources and thereby increase the share of low carbon energy in the supply mix, while maintaining security of supply. And if deployed at the appropriate level, for given costs, overall system costs should be reduced as a result.

Furthermore, as the system context changes, so do the technical and cost requirements for storage. A long term perspective can inform the trends in technology development that would become most valuable as the system decarbonisation progresses.

At the same time, long term explorations are faced with high degrees of uncertainty. The following approaches seek both to acknowledge and to redress the inherent uncertainty around future developments to some extent.

3.1.2 Technology agnostic

A technology agnostic approach is adopted for several reasons. Firstly, the long term perspective makes predictions around technology development and innovation inherently difficult. Numerous radically different technologies are presently under development (spanning from cryogenics to air bags beneath the sea). It is not within the scope of this study to predict which of these is likely to reach certain cost / performance targets.

Furthermore, a technology based approach is in danger of bias towards existing technologies by focusing on their properties at the expense of alternative configurations that have not yet developed, potentially as a result of difference between past and future drivers for storage.

Lastly, this representation of storage is expected to allow for some of the results to be interpreted in more general terms. The generic definition of electricity storage could

¹See for instance McCrone (2011) for a short term perspective on the value of storage.

potentially be further expanded to include thermal storage or even demand side response (see Grünewald and Torriti (2012)).

3.1.3 Exploratory

The long term perspective discussed above also has implications for the nature of data collection and analysis (see Saunders et al. (2009, Ch. 4)). The regulatory environment, the type and role of institutions and the future system composition are all uncertain. It is not the intention of this study to attempt any predictions around more or less likely developments, but rather to illuminate the discussion by exploring different configurations and identify trends, commonalities and sensitivities.

The regulatory environment and its influence on storage uptake forms part of the focus of this study. It is therefore not assumed to be known *a priori*. Instead, the analysis begins from a standpoint of ‘perfect market’ conditions. The impact of different types of regulation is then reviewed *post hoc*.

Similarly, it is not possible to reliably predict the changing role of institutions in influencing the uptake of storage. The analysis, again, begins by excluding their role and then goes on to review how developments might be affected by different institutional arrangements.

The long term development of future system compositions has been the subject of detailed studies developing future scenarios, which—even if no more or less probable than each other—provide an attempt at an internally consistent narrative for future pathways. This study builds upon selected scenarios and explores the role of storage within them.

3.1.4 Interdisciplinary

The literature review in Chapter 2 identified different disciplines, which are presently applied in forward looking studies. These include numerical modelling studies, rooted in economic and engineering principles, as well as attempts to conceptualise the dynamics taking place during the transition of large technical systems and the processes involved in the adoption of new technologies.

It is postulated here that both of these approaches are relevant to inform the future role of storage and, moreover, by combining insights from each, a fuller picture of opportunities and challenges can emerge.

As stated in Section 2.3.2, Denholm et al. (2010) view the ‘need’ for storage ultimately as an economic question. The literature review established a lack of dedicated dynamic modelling to inform the economic viability of storage in a whole system context. A time

resolved techno-economic model will therefore be developed and used to address this gap. This model is explained in Section 3.2.

Identifying economically viable conditions is, however, not sufficient to address the research questions of this thesis. To understand possible future roles of storage, the agency of actors responding to such economic signals should also be considered, as concluded in Section 2.4. These actors, their preferences and practices, shape the selection of technologies and investments and influence developments during future transitions.

This thesis therefore seeks to engage with these stakeholders. They can provide expert insights, which guide the analytical work, and further reveal preferences and respond to the results of the techno-economic analysis. The methods by which stakeholders are engaged is explained in Section 3.4.

To combine the techno-economic method and stakeholder engagement into an analytical framework, this thesis draws on aspects of transition theory. Economic drivers can thus be discussed alongside system dynamics in a heuristic framework, which integrates the interdisciplinary work streams. Relevant aspects of transition theory will be introduced in Section 3.3.

3.2 Techno-economic analysis

Techno-economic analysis, also referred to as engineering-economics, is widely applied in literature. This section begins with a definition of techno-economics and its purpose in relation to this study, before focussing on some of the specific analytical tools employed here.

Techno-economics can be described as the

application of economic techniques to the evaluation of design and engineering alternatives. The role of engineering economics is to assess the appropriateness of a given project, estimate its value, and justify it from an engineering standpoint.

NIST (2008)

While NIST (2008) refers to ‘given projects’ the abstract nature of the method make it equally applicable to hypothetical cases and future scenarios. The underlying principles are therefore explored here.

Panneerselvam (2006) describes the flow within an economy as the exchange of goods, services, resources and money. Technical systems represent a constituent part of such an economy. Each technical system consists itself of one or more artefacts including technologies that can be represented as units with clearly defined input and output flows as shown in Figure 3.1. Relationships between these can be expressed as functions. The properties of the technical system are given as parameters, while their configuration (i.e. the extent to which each of them applies) can be variable. This allows this thesis to examine optimal solutions and sensitivities to different configurations.

The properties of the technical system can either be based on observed values from existing systems, or expected future values in the case of exploratory studies. The set of

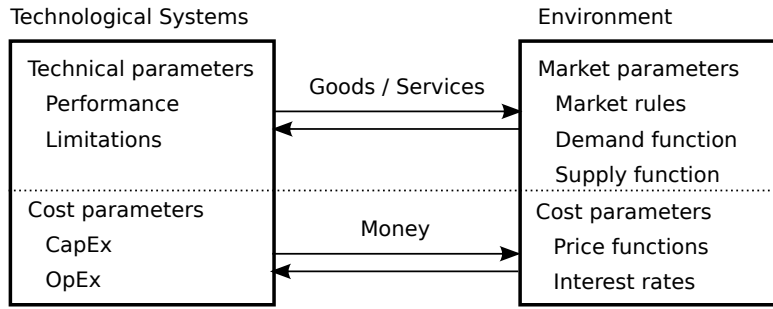


Figure 3.1: Schematic representation of a techno-economic model showing the exchange of goods, services and money between a technical system and its environment.

properties Φ_i of the system and their configuration variable x_i describe the relationship between inputs and outputs in their generic form as

$$\chi_j^{out} = f(\chi_j^{in}, \Phi_i x_i) \quad (3.1)$$

where χ are input and output flows.

Linked to the technical configuration are capital costs for the technology itself (also referred to as capital expenditure or CapEx). For complex systems, several properties of the system can be linked to their own capital cost. This distinction allows a solver to seek cost optimal configurations. The capital cost can thus be written as

$$CapEx = C + \sum_i \Pi_i x_i \quad (3.2)$$

where C are configuration independent system costs and Π_i is the nominal cost of property Φ_i .

During the lifetime of the system operation and maintenance costs apply which are expressed as a function of the technical configuration and its exchange of goods and services with the environment. Typically (but not necessarily) systems incur costs for inputs and receive revenue for their outputs. Both of these flows have to be discounted to account for their time value. Payments which occur in the future have a future value FV and an equivalent present value PV . This present value is lower to account for the opportunity cost as represented by an annual interest rate, discounting the future value as per

$$PV = \frac{FV}{(1 + r)^n} \quad (3.3)$$

with r as the interest rate per year, and n the number of years between payment and the present.

The operating costs accrue for goods and services received at price $\pi_j(t)$ and are discounted per (3.3) to

$$OpEx = \sum_t \sum_j \frac{\chi_j^{in}(t) \pi_j(t)}{(1+r)^t} \quad (3.4)$$

In a similar way the gross value is calculated from the system outputs (χ_j^{out}) and the market price of each output at the time.

$$Gross\ value = \sum_t \sum_j \frac{\chi_j^{out}(t) \pi_j(t)}{(1+r)^t} \quad (3.5)$$

Changes to gross value resulting from changes to the configuration parameters χ_j can be observed. Parts of this study will only consider the gross value of storage, and leave out the deduction of technology specific costs. However, in some cases technology options can be better contrasted when comparing their net present value (NPV), which can be derived from 3.2, 3.2 and 3.5 as

$$NPV = Gross\ value - OpEx - CapEx \quad (3.6)$$

A solver can seek to optimise the NPV by trading revenue against cost considerations through alteration of one or more control variables (x_i), such as scale of installation or technical performance.

3.2.1 Generic representation of storage technologies

The physical principles employed in present storage technologies span from simple mechanical systems, developed in the early 19th century, to advanced electro-chemical solutions currently undergoing research in laboratories around the world. Some are designed to reduce cost through economies of scale, while others aim for higher performance. The literature on storage technologies is comprehensive, as mentioned in Section 2.1.2.

This thesis neither attempts to predict future developments in the storage technology sector, nor does it estimate their cost developments. Instead the ‘technology agnostic’ approach focusses on the main characteristics of storage. From this perspective it does not matter if electricity is stored using batteries, compressed air or heat, so long as observable properties can be compared.

Taking a ‘black box’ approach to storage reduces the technology to the level of a tool. Rip and Kemp (1998) do caution that this approach can disguise some of the complexity of technical configurations. While some of the more ‘technical’ characteristics can be captured this way, other features may be lost. Their significance will be discussed as part of the limitations of this approach in Section 3.2.4.

For the exploratory purposes of this study the generic representation allows this thesis to explore fundamental trends in the development of the value of characteristics of storage and broader applicability, as set out in Section 3.1.2. It further avoids bias towards existing technical solutions and instead focusses the analysis on fundamental

properties and their value to any future system. Subsequently one may wish to contrast these findings with actual technologies. In this study such application is limited to selected cases.

3.2.2 Storage properties

Scale and location

Future networks are expected by some to become more distributed. They could comprise a greater participation from the demand side as well as distributed generation.

Storage is faced with similar choices: current pumped hydro storage systems are remote from demand centres and feed into the transmission system. Large scale systems benefit from economies of scale, and extreme solutions have been suggested, such as tidal lagoons. (DECC, 2010a)

At the other extreme, distributed storage may support smarter distribution networks. The most common example is residential thermal storage. In electrified heating systems it provides a dispatchable load, and thus, a form of distributed electricity storage. Other concepts consider micro-storage at the residential level using second life car batteries. Figure 3.2 gives a conceptual overview of scales for storage.

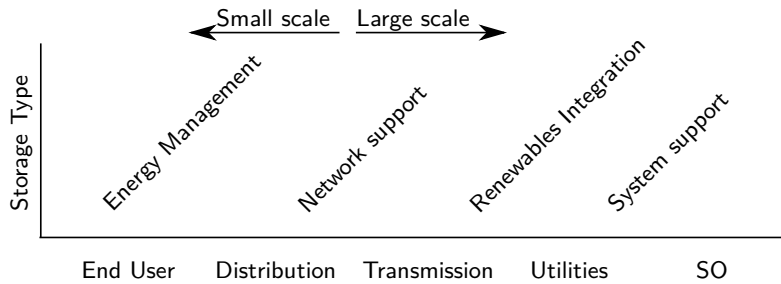


Figure 3.2: Possible locations for different types of storage on the energy system. Large scale solutions suit the high voltage end of the energy system, whereas smaller systems can be located closer to demand. Each location brings about a different set of benefits. (SO = System Operator)

In a techno-economic model ‘scale’ can be represented in different ways. Three units of measurement can be considered:

Power (kW) The maximum power produced during discharging, or maximum load while charging. [kW]

Energy (kWh) Also referred to as energy capacity or reservoir size. The maximum storage content limiting energy uptake. Depending on technology storage energy capacity scales with power or can be configured independently.

Voltage (kV) Defines which part of the network storage can be connected to. This is not necessarily the voltage internal to the storage technology, but the voltage at the interface. 230V–33kV is classified as low voltage and can be put to use in distribution networks. Higher voltage systems are treated as transmission network service providers.

Aside from electrical location on the network, geographical location matters to the interaction of a storage system with its environment. For instance, the north of the UK, with an abundant wind resource will lead to different use profiles than a load constrained distribution network in the south of England. This distinction can only be modelled with representation of the network infrastructure. Modelling of network flows is, however, beyond the scope of this study and instead distinctions in geographical location will be dealt with qualitatively, based on other models with better network representation.

Storage duration

Storage can operate on short time scales to deal with real time imbalances on the system or hold reserves for long periods of time as an insurance for rare events threatening supply security, as illustrated in Figure 3.3.

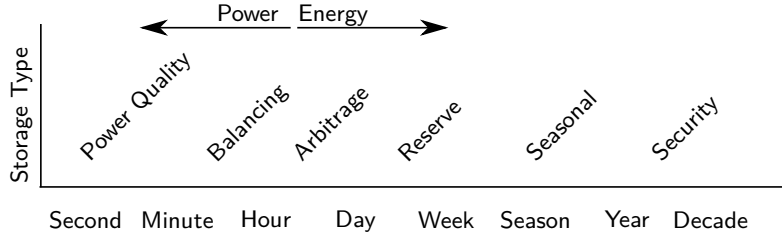


Figure 3.3: Types of storage applications and timescales over which energy is stored for. For short duration storage power is the overriding cost factor, whereas longer storage periods call for solutions with low energy related cost.

In practice storage operates on a range of timescales,² and characterising storage by ‘timescale’ is therefore not meaningful. Instead ‘storage duration’ is used as parameter. Storage duration (τ) describes the ratio between the amount of energy a system can store and the power at which the energy can be delivered and can be measured in hours. It could be seen as the time it would take to fully discharge a full storage reservoir at the rated power. In practice this is not necessarily how storage is operated. Although the storage duration is not directly related to the duration for which energy remains stored, it is used in this study as a proxy. Short storage durations tend to deliver fast response services, whereas long duration storage has the ability to shift energy over longer periods of time.

²Dinorwig pumped hydro, for instance, operates fast response as well as in arbitrage market.

Efficiency

The round-trip efficiency of a storage system (η_{sys}) is the ratio of energy returned from a storage device (E_{out}) to the energy that was originally used to charge it (E_{in}).

$$\eta_{sys} = \frac{E_{out}}{E_{in}} \quad (3.7)$$

Two refinements to the generic definition of efficiency are necessary in the context of electricity storage. Firstly, efficiency can be a function of time. Batteries exhibit self discharge, hydro reservoirs can leak or evaporate and most other systems will suffer some form of loss over time. For the operation of storage a high time related loss will favour faster charge/discharge cycles.

The energy remaining after self discharge period (t_1) can be derived from the self discharge rate η_{self} as

$$E_{t_1} = E_{t_0} \times \eta_{self}^{(t_1-t_0)}. \quad (3.8)$$

The resulting ‘decay’ of energy available from a storage system is shown for the example of systems with 10%, 50% and 90% monthly self-discharge in Figure 3.4.

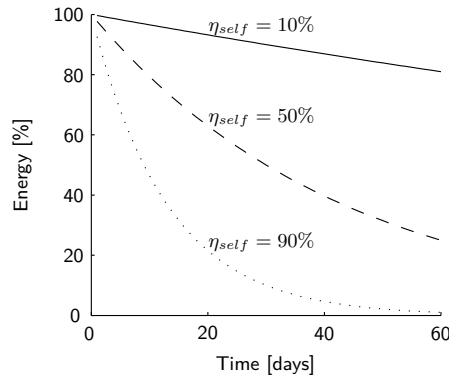


Figure 3.4: Energy remaining as a result of self discharge. Examples for self discharge specified as 10%, 50% and 90% loss per month respectively.

A further refinement to 3.7 is the distinction between charge and discharge efficiency. The context for the two operations could be very different in future systems. Charging would happen during periods of high wind and low electricity prices. A lower charge efficiency means that more energy is required to fill the capacity, but the price penalty is lower, compared to the time of discharge. Here, when prices are higher, every kWh held in storage that can not be converted back is a more costly loss. If energy capacity is cheap, it may therefore be preferable to increase capacity and operate lower (thus cheaper) input efficiency. The model distinguishes between input and output efficiency.

The product of charge efficiency (η_{in}), discharge efficiency (η_{out}) and self discharge losses with storage duration from $\eta_{self}^{\Delta t}$ make up the total round trip efficiency of the

system

$$\eta_{sys} = \eta_{in} \times \eta_{out} \times \eta_{self}^{\Delta t} = \frac{E_{out}}{E_{in}} \quad (3.9)$$

Ramp rate

The ability of storage to capture some of the most valuable markets depends on the ability of storage to follow demand profiles and respond to requests quickly and reliably. Aside from energy availability, the speed of response is therefore important. The market with some of the highest electricity prices is the ancillary market. Mechanisms, such as the ‘Frequency Control by Demand Management’ (FCDM), for instance, require a 2 seconds response (National Grid, 2011a). While very attractive as an additional source of revenue, the scale of such markets is capped. Currently they are estimated to amount to around £80m per year (National Grid, 2011b, p. 74). Even if—as some experts expect—this market doubles or triples over the coming decades, it still constitutes only about a tenth of the balancing market in size and is therefore only a small share of the overall market for storage (Dale, 2011). Furthermore, accurate representation of these trades on a second-by second time scale within a time resolved model is data intensive and computationally expensive. Such markets, and the scope for storage to participate in them will therefore be discussed outside the techno-economic model.

The demand following constraint in the model is expressed through the maximum rate of change ($\dot{P}_{max}$) and the difference between the power (P) in the previous period and the demand for storage (D) in the present period.

$$P(t) = P(t-1) + \min(D(t) - P(t-1), \dot{P}_{max}) \quad (3.10)$$

This constraint applies for ramping up as well as down during charge and discharge cycle. The resolution of $\dot{P}_{max}$ is limited by the resolution of the time series of demand.

3.2.3 System context

Storage is deeply embedded into the energy system in many ways. Its role and operation therefore depends strongly on the system context. For large technical systems, with the complexity of the electricity system, some steps have to be taken to reduce the level of this complexity. The reduction process has to balance computational constraints with appropriate detail on aspects relevant to the research question.

Barton and Infield argue that it is possible for key aspects to be represented with a simplified probabilistic approach (Barton and Infield, 2004). However, their work does avoid specifying the energy capacity of storage, which significantly relaxes the need for sequential data. Black and Strbac take a similar approach of not specifying the storage energy capacity, but in later studies refine their model to take account of capacity constraints (Black and Strbac, 2006, 2007). Only with a detailed time series can instances be established when storage is depleted and when it reaches capacity. And this requires high temporal resolution and sequential data.

In the spirit of the long term exploratory nature of this study, no assumptions around the market and regulatory framework of future systems are made. Instead an idealised electricity wholesale market is assumed, in which price volatility is allowed to respond freely to changes in the plant mix. This approach, explained in more detail in Section 5.1.2, allows a simplified representation of the economic environment for storage with high temporal resolution.

While the short term temporal resolution cannot be relaxed, some simplifications in long term developments are made. The generation mix is informed by scenario studies and is not modified except for some peaking plant that may be retired in the presence of storage. The core scenario under investigation is the DECC 2050 Grassroots scenario, which is made up of a large share of wind energy. This pathway is complemented by a predominantly carbon capture and storage (CCS) and a nuclear based scenario.

Operating strategy and foresight

The extent to which foresight is available to the simulated storage operator is a non-trivial problem. For a computer algorithm it is possible to optimise the return under consideration of all possible combinations of charging and discharging. In practice a considered judgement has to be taken about the future price development. This could be based on experience (predicting demand profiles based on historical data) or simulation (wind forecasting over the next four hours). Figure 3.5 illustrates the difference between trading positions with different levels of foresight.

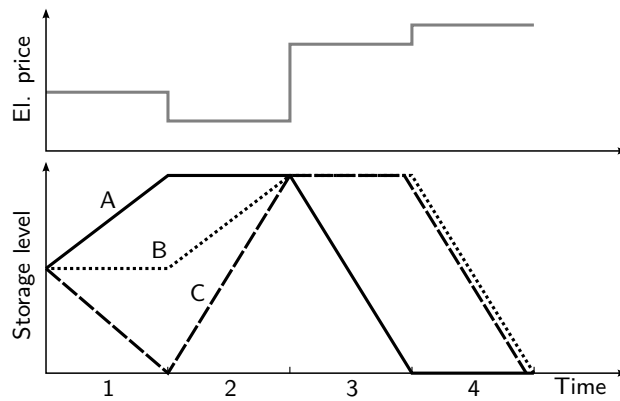


Figure 3.5: *Illustrative example of operating strategies. Differences in response to electricity price, depend on the level of foresight. Trader A reacts to price levels statically, whereas B realises higher margins as a result of foresight and delayed action. Trader C further increases the value by ‘dumping’ capacity in period one.*

Trader A operates a simple strategy. Below a given minimum price he charges, and above a certain price he discharges. Trader B, on the other hand, using a degree of

foresight. In period 1 he expects the price to drop further and waits until the second period before charging. The same foresight also makes this operator hold the energy, unlike Trader A, during period three to realise a higher sales price in period 4. A yet more strategic Trader C might even discharge (dump) capacity in period one, to maximise revenue from the margin between periods two and four.

As this simple example illustrates, the degree of foresight and the confidence in this foresight can substantially improve the trading position and lead to three different operating profiles.

Sturt (2009) developed stochastic methods to emulate the decision making process as a rolling decision tree. Here, the actor has a set of choices in each time period and selects one based on a probability distribution of future expectations. This choice leads to a new set of choices in the next period and the procedure repeats itself.

This study will start from the cautious assumption that storage operators do not have foresight and explores the effect of foresight in different circumstances separately.

3.2.4 Limitations of the techno-economic approach

Techno-economics offer a tool to explore possible future values for storage in wholesale electricity markets. However, several simplifications have to be made to represent storage and its system context.

High temporal resolution is important and this study draws on data with one hour resolution or better. Higher resolution data are not available and would lead to increased computational complexity. This leaves sub-hour transactions, such as provision of ancillary services, outside the scope of enquiry.

The omission of a network model, which also greatly simplifies the model complexity, could disguise opportunities for storage in constrained regions. To better include these, temporally and spatially resolved demand data would be needed, which presently is not publicly accessible.

Wholesale electricity markets provide a simplified version of often complex and regulated market interactions, which are more challenging to simulate. However, when interpreting the model results one needs to be mindful of this simplification.

The techno-economic approach lends itself to a numerical representation of storage and its system context. The transition of new technologies into established systems does, however, involve considerable interaction with actors, stakeholders and institutions, which are not readily included in techno-economic models.

Techno-economic models can inform a first order condition of commercial viability. To answer the research question from Section 1.2 it is necessary to widen the unit of enquiry. ‘Successful uptake’ of a new technology requires more than merely the proposition of a positive NPV. Section 3.4 explains the role of stakeholders and how their engagement can inform the process of technology diffusion, and how this insight can be applied within an analytical framework.

3.3 Socio-technical transition theory and the MLP

This section seeks to develop a heuristic approach to build upon the insights from the techno-economic model and integrate them into an analytical framework, which can inform the discussion on uptake and future roles for storage.

Literatures on the relationship between technological and social systems have developed the concept of ‘co-evolution’, which suggests that social systems are changed by technology, but importantly that technology itself is shaped by society (Hughes, 1986). Evolutionary economics attempts to expand upon neo-classical economics, which is based largely on static equilibria (Nelson and Winter, 2002). From this field emerged the innovation literature and the discipline of socio-technical transitions, which extends beyond the view embedded in many equilibrium models of efficient market allocation through least cost optimisation.

Transition theory advocates a change in perspective from artefacts and black boxing towards an understanding of technological change as a process involving a broader set of actors (Kemp, 1994; Rip and Kemp, 1998; Geels, 2002). This perspective challenges the concept that technologies act as an external force that change society around them. In this perspective, also referred to as *cannonballing*, an inert artefact impacts and thereby dents or ruptures the socio-technical regime. As proponents of transition theory argue, this perspective misses the importance of the surroundings (the socio-technical regime) as a crucial condition for the successful uptake.

Technological transition (TT) theory suggests that transitions ‘not only involve changes in technology, but also changes in user practices, regulation, industrial networks, infrastructure, and symbolic meaning or culture’ (Geels, 2002). The TT perspective does not see technology itself as the external driver behind transitions (the so-called ‘technology push’). It further rejects the notion of adoption of technology as a linear process (‘demand pull’). Technology is seen instead as ‘powerless’ and it is its environment that under certain conditions allows this technology to ‘make a difference’. It is thus itself a part of a societal transformation. (Kemp, 1994)

Rip and Kemp (1998) coin the concept of *configurations that work* to broaden the perspective beyond the mere physical artefact of a technology. *Configurations that work* explicitly include the linkages that make up working systems. This notion of interconnectedness is even more extensively expressed by Hughes (1986), who speaks of a *seamless web* comprising artefacts, entrepreneurs, networks, regulators and others that make up large technical systems.

While the notion of a *seamless web* provides a useful theoretical concept, it is by its very nature unwieldy as a framework for analysis. A more applicable perspective has been developed by Geels (2002), who developed an approach which views the system as three distinct hierarchical levels, termed the multi-level perspective (MLP). It comprises a niches level, a the socio-technical (ST) regime level, and a ST landscape level (Geels, 2002). Radical innovation is said to take place in niches (Schot, 1998). The uptake of innovations, however, depends on the ST-regime, which is the ‘rule-set [...] embedded in institutions and infrastructures’ (Rip and Kemp, 1998). Changes in the slow moving

ST-landscape can bring about tensions within regimes or between regimes, which lead to re-configurations during which new technologies and practices can diffuse into the existing regime, and in turn reshape it.

A graphical representation of the three levels and some of the dynamics between them is illustrated in Figure 3.6. The primary rationale behind the discrimination between the levels is the ‘structuration of activities in local practices’ (Geels, 2011) resulting in radical change taking place predominantly in niches, whereas landscapes are slower to change. The three levels will now briefly be introduced in turn.

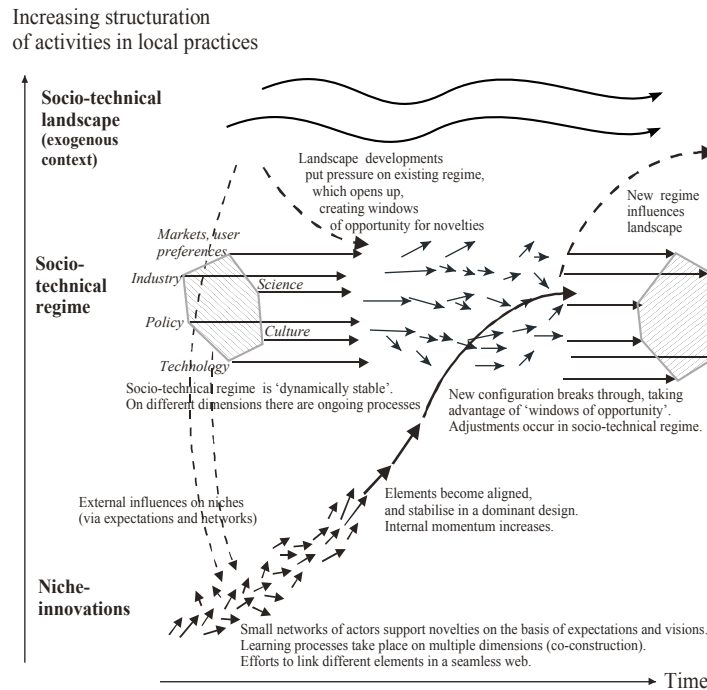


Figure 3.6: Illustrative representation of the Multi-Level Perspective. Based on Geels (2011).

3.3.1 The socio-technical landscape level

The sociotechnical landscape is a landscape in the literal sense, something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us.

Rip and Kemp (1998)

The energy landscape metaphor is used deliberately by Geels to refer to its ‘hardness’. Timescales over which change takes place are long and the changes tend to be gradual in nature. Staying within the metaphor, changes within the energy landscape are predominantly the result of steady erosion processes rather than sudden seismic shifts. This is

because the energy landscape is defined as a set of dominant assumptions, values and a deeply rooted socio-economic status, which encapsulate the ‘key philosophy behind policy making trends’. (Shackley and Green, 2007)

In practice, however, major geo-political events can have a more immediate impact on the socio-technical landscape. Examples of sudden changes in the energy landscape include the oil-shock in the 1970s or the Fukushima Daiichi nuclear disaster in 2011, which had immediate effects on policy for instance in Germany. The landscape level has therefore been refined beyond the earlier concept of ‘hard and stable’ landscapes that change slowly or not at all. Van Driel and Schot (2005) broke the landscape level down into 3 types of change dynamics, as:

1. factors that do not change (or that change very slowly), such as physical climate;
2. rapid external shocks, such as wars or oil price fluctuations; and
3. long-term changes in a certain direction (trend-like patterns), such as demographic changes.

The current landscape pressures relevant to the UK energy system have been listed by Foxon et al. (2010) and are categorised in Table 3.1 on page 72 alongside their relevance to electricity storage.

Table 3.1: *Types of landscape pressures and their relevance to the role of storage. Based on Foxon et al. (2010).*

Category	Origin of pressure	Relevance to EES
Public perception	Public awareness of climate change and willingness to accept and undertake changes in response. Brown-outs and black-outs as a result of increased network demands shift willingness to accept additional measures	Selection of storage technologies that directly interfere with the public, especially relating to visual impact, perceived health and safety concerns and spatial impact; potential to mitigate impact on the public as a result of deep de-carbonisation (such as additional transmission lines or plant capacity).
Political will	Government commitments to meet national and international targets for emissions reductions and promotion of low carbon energy sources	Strong impact on the key rationale for the need for storage.
Market structure	Ideological commitments to liberalized energy markets	Challenge of valuing common good characteristics of storage
Energy security	Concerns over security of primary energy supplies, external factors leading to high oil and gas prices	Greater storage capacities with long time constants to provide reserve
Affordability	Concerns about energy affordability and fuel poverty	Requires strategic investment and operating strategy to reduce system costs with a mechanism to pass on savings to consumers.
Supply security	Factors which threaten physical disruption of external supplies (war, terrorism, foreign governments limiting supply, etc.)	Requires large storage capacity and capacity held in reserve
Financial	Changes in the international economic and financial situation.	Capital intensive long term investments critically depend on affordable finance

3.3.2 The socio-technical regime level

Rip and Kemp define a technological regime as follows:

A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems—all of them embedded in institutions and infrastructures.

Rip and Kemp (1998)

This definition has been further developed by Geels (2002) and he refers to socio-technical regimes as ‘semi-coherent set of rules carried by different social groups’. Geels (2004) defines the ST-regime to explicitly include the ‘users’ of technology, which had hitherto often been ‘simply assumed to be ‘out there’’. Seven dimensions have been suggested for consideration: technology; user practices and application domains; symbolic meanings of technology; infrastructures; industry structure; policy; and knowledge (Berkhout et al., 2003; Schot, 1998). Geels himself calls this definition ‘somewhat abstract’. Drawing the boundaries of such a ‘semi-coherent’ set of rules is not an exact science and requires careful consideration for the particular subject under consideration (see also critique in Section 3.3.4). An example for systems of electricity provision and use considers eight dimensions and has been presented by Geels (2010) as shown in Figure 3.7.

Unruh (2000) identifies mechanisms by which the regimes can develop into ‘self-referential systems’. These include the development of core competencies, leading to continued re-investment in dominant designs, path-dependency and technology lock-in. Dominant designs are said to gradually emerge as a result of accumulated efforts, which over time establish one pathway (or set of pathways) as effective. These can attract a significant market. Product revenues lead to innovation and skill development, which puts potential entrants increasingly at a disadvantage (Nelson and Winter, 1982, 2002). Arthur (1989) argues that this feedback mechanism can lead to lock-in of established technologies, preventing newcomers from entering the market, even if these were potentially superior. Which set of technologies emerges as successful is therefore not merely a matter of their individual performance, but depends on historic developments. This notion challenges the concept of efficient markets, since chance events could lead to ‘inferior’ technologies establishing themselves as dominant designs. A commonly cited example of such path dependant developments is the ‘historical accident’ of the QWERTY keyboard. David (1985) suggests that the absence of perfect future markets can lead to premature standardisation, which can subsequently be upheld by decentralised decision making. This path dependency in the uptake of technologies is not necessarily captured in least cost allocation approaches, such as the techno-economic models discussed in Section 2.2. A detailed understanding of the existing regime, its practices and the landscape pressures upon it, is therefore crucial for a discussion of the possible selection and uptake of new technologies (Foxon et al., 2010).

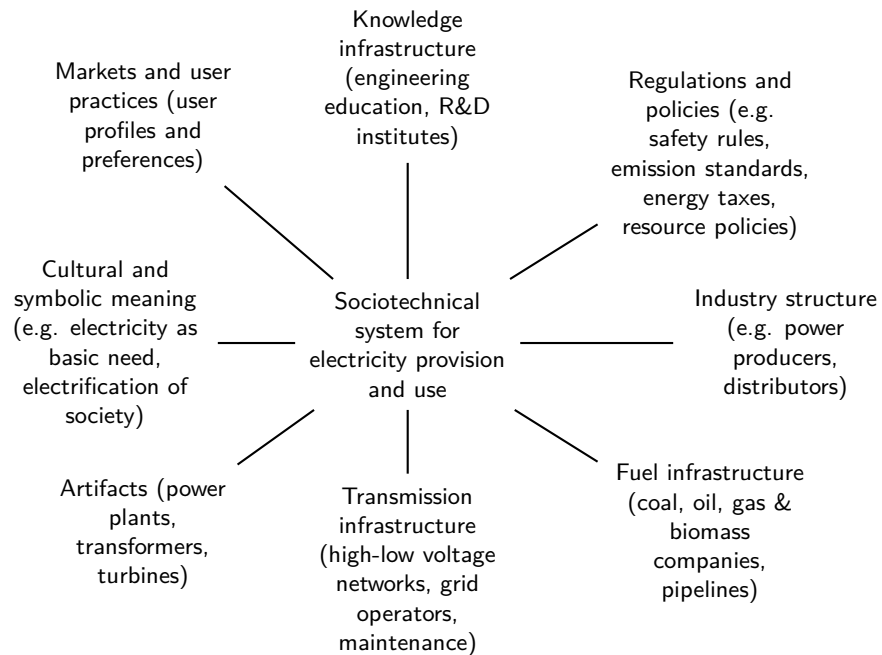


Figure 3.7: *Example of the components of a socio-technical regime for the electricity sector by Geels (2010)*

3.3.3 Niches

Niches [...] are important for the further development of a new technology: demonstrating the viability of the technology makes it possible to attract investment, and gain support from other firms and public policymakers.

Rip and Kemp (1998)

Niches provide spaces within a market environment, which are ‘protected against excessively harsh selection’ (Rip and Kemp, 1998). These can be technology specific, such as a unique performance feature, or be created by particular circumstances that necessitate hitherto unconventional solutions. As such, niches can be naturally occurring, or be the result of deliberate and strategic ‘niche management’.

The protected spaces they create can have multiple aspects that support the integration of a technology beyond their initial niche application. These can include cost reduction and technological improvements. Furthermore niches can foster learning about benefits and disadvantages of technology options and ‘stimulate changes in social organisation’. They further support the development of a constituency, including public

agencies, industrial and commercial actors, whose ‘semi-coordinated actions’ are deemed important in the wider diffusion (Rip and Kemp, 1998).

These factors are of particular importance for highly integrated and interconnected technologies, such as electricity storage. In the transition literature niches are often described as the origin of radical innovation, a notion that will be discussed further in the following section and also forms part of the discussion in Chapter 4 on historic cases of storage uptake.

3.3.4 Critique of socio-technical transition literature

Despite its widespread application in the transitions literature, the MLP is not without its critics. A particular concern of Genus and Coles (2008) in their critique of the MLP is its lack of a systematic method. Case studies are said to be carried out without a common analytical framework and secondary sources are claimed to be ‘uncritically accepted’. Although Geels (2011) rebuts this criticism by stating his case studies were aimed more at ‘illustration and exploration’ and points out that no specific empirical mistakes were cited, the reliance of the MLP on interpreted and secondary data makes it vulnerable to the accusation of lack of rigour or subjectivity.

The specification of what constitutes a ‘regime’ is somewhat vague and open to interpretation (and thus misconceptions). Rip and Kemp’s definition does not give a strong indication of where the boundaries should be drawn. This provides both a strength and a weakness. On the one hand, it allows analysis of a wide range of topics with different scope. However, it also opens up the possibility of poor boundary definition with regime sets that are inconsistent, overlapping, incomplete or self-contained.³ In the absence of a common framework it is up to the analyst to be mindful when defining the relevant socio-technical regimes.

The regime level is challenging also, because a balance has to be struck between inter-regime and intra-regime tensions. It is perfectly feasible (and tempting) to cast the net wide enough such that a single regime gives a somewhat homogeneous representation of the system. More attention to *multi-regime* interaction has been advocated and employed by Geels (2007), Konrad et al. (2008) and Raven (2007).

A further source of ambiguity is the often interchanging terminology of *regime*, *system* and *rules*. Genus and Coles (2008) and Markard and Truffer (2008) call for greater specification and delineation in the terminology. In the strictest sense *systems* will refer to measurable and tangible elements, whereas the term *regime* specifically refers to ‘intangible and underlying deep structures’ (Geels, 2011).

The dominant direction of developments in early MLP literature is ‘bottom-up’, starting in a niche and ‘working its way up’ into the regime level. The application of a multi-level perspective in the Netherlands has led policy makers to emulate conditions observed in successful historical transitions (Kemp and Loorbach, 2006). The focus of their perspective has tended to be on technologies that could be traced back to a ‘niche based conception’. Thus, these MLP informed policies aim to create conditions

³A storage regime inside an electricity supply regime could be such a self contained regime

through *strategic niche management* that constitute niche markets from which new (and sustainable) technologies can diffuse into the socio-technical regime. A body of evidence to support the success of this approach exists in the form of CHP in the Netherlands or PV in Germany (Raven, 2007; Jacobsson and Lauber, 2005).

This ‘bottom up’ direction is also manifest in the graphical representation of the MLP (see Figure 3.6), which suggests an upward movement originating at the niche level. Berkhout et al. (2003) asserts that this constitutes an ‘undue emphasis’ on niche driven processes. Geels (2011) agrees that ‘more explicit attention needs to be paid to ongoing processes at the regime and landscape level’. The MLP has developed in response to this criticism and now considers different transition types, which will be discussed in more detail in Section 4.5.4.

A potential limitation of the MLP is that it is rooted in historical case studies with an *ex-post* analysis of events. To what extent is the past a guide to any future transition? An argument can be made that with careful deconstruction of the dynamics of past transitions valuable insights into possible future transitions can be gained. Such studies are undertaken *inter alia* by the Transition Pathways project (Arapostathis et al., 2013). Their work does however put some caution on the extent to which such studies should be used to make firm statements about the future. (Foxon et al., 2010)

One difference between past transitions and the one facing the UK electricity system in particular, is the role of consumers as agents. Decarbonisation is so far not a consumer driven process, but rather politically led. Smith et al. (2005) therefore calls this a ‘purposive’ as opposed to an ‘emergent’ transition. In fact, the UK policies explicitly aim to interfere with the energy service experience of consumers as little as possible. Geels (2006) attempted to address this shortcoming with a study of a ‘purposive’ regime transformation motivated by the social problem of poor hygiene. This type of transformation can be said to bear a closer relation to the transformation towards a sustainable energy system.

Both Smith et al. (2005) and Genus and Coles (2008) suggest that the MLP should allow for more analysis of agency to reflect powerful agents and other strong political influences. Geels strongly rebuts this criticism by stating that the MLP is ‘shot with agency’ (Geels, 2011). He does concede, however, that the inclusion of insights from auxiliary theories could provide enhancements in this area.

3.3.5 Applicability and limitations of technological transition theory

The concept of the MLP was developed and refined based on a number of historic case studies, including the transition from sailing to steam ships, motor cars, sewage systems (see for instance Berkhout et al. (2003); Geels (2006); Kemp and Loorbach (2006) or Verbong and Geels (2007)). The resulting representation is not intended as an ontological description of reality, but as ‘analytical and heuristic concepts to understand the complex

dynamics of socio-technical change'. Geels (2002)

Frameworks such as the MLP are not 'truth machines' that automatically produce the right answers once the analyst has entered the data. Instead they are 'heuristic devices' that guide the analyst's attention to relevant questions and problems. Their appropriate application requires both substantive knowledge of the empirical domain and theoretical sensitivity (and interpretive creativity) that help the analyst 'see' interesting patterns and mechanisms.

Geels (2011)

Despite this limitation in drawing 'hard conclusions' from an MLP approach, it can provide a useful tool in the analysis of long term and large scale transitions, such as those occurring in the UK electrical energy system. The caution that the conclusions strongly rely on a robust approach in gathering the supporting data and analytical insight is important for the formulation of the methods for the framework of this thesis.

The literature applying the multi-level perspective to grid-connected energy storage is very limited. Herrewijn developed distinct scenarios for storage uptake and discusses the relationships between the three levels in each case, supported by stakeholder interviews. The qualitative nature of the discussion does however limit the strength of conclusions that can be drawn from such analysis. Although actor relationships are referred to, specific tensions between these actors are not further discussed or translated into policy implications. (Herrewijn, 2011)

The application of the MLP in this thesis will be mindful of the criticism discussed in Section 3.3.4. In particular, the suggestion of an undue focus on the role of niches as the source of transition will be dealt with in Section 7.2. The role of possible tensions within the regime level will also deserve some specific attention and will be addressed in Chapter 6.

Despite the broad lens applied by the socio-technical perspective, it does not provide us with greater certainty about future development. On the contrary, the confidence with which neo-classical economics aspires to 'predict', which technology *should* be selected, can not be matched with a ST-perspective. It rather provides a framework that allows for the inclusion of insight into the complexity and interdependency of co-evolving processes and thus guards against undue certainty over future pathway predictions. In this capacity it provides a useful and complementary function to the techno-economic analysis.

Transition theory can provide a framework to explore why radically new technologies, such as electrical energy storage, may find it difficult to establish themselves in existing markets, even if under strictly commercial considerations they would be expected to be 'selected'. Geels argues that this is because 'regulations, infrastructure, user practices, maintenance networks are aligned to the existing technology' (Geels, 2002). Since other disciplines do not assign sufficient weight to these factors, it is deemed important to incorporate this perspective into the analytical framework of this thesis.

Based on the literature on historic cases of technological transitions it is not possible to conclude whether the theory can be applied in its present form to the future uptake

of electricity storage. Especially the notion of ‘dominant designs’ from the innovation literature may not be applicable to storage. Chapter 4 will therefore follow the example of the literature on the MLP and apply a socio-technical transition perspective to historic cases of storage uptake first. This exercise seeks to address two methodological questions: to what extent does electricity storage fit this analytical method, which has been developed around past transitions of distinctly different technologies, and following on from this, how confident can one be when applying insights from past transitions to future uptake of storage.

3.4 Stakeholder engagement

The importance of analytical insight in the application of a socio-technical perspective calls for a detailed understanding of the existing regimes, as stated in the previous section. Hughes and Strachan (2010b) further argue that modelling studies lack agency for their actors to influence pathways and institutional factors are thus not well represented in such models. This is the case for system models, which were the focus of Hughes and Strachan (2010b), but also applies to the techno-economic approach described in the previous section.

This section discusses a set of methodical issues concerning engagement with stakeholders in socio-technical regimes and also describe briefly the process followed in the course of the research for this thesis.

One approach, followed by Strachan (2011), is to quantify behavioural aspects and include them in the model. Barriers to deployment can be expressed in monetary terms and included as hurdle rates; the failure to adopt otherwise commercially viable options can be internalised through a ‘hassle factor’; and sensitivity to upfront costs can also be included in economic terms. Strachan (2011) introduces behavioural factors into energy-economic modelling in the form of ‘intangible costs’. Furthermore, a value representing ‘market heterogeneity’ accounts for different sensitivities to cost differentials required to shift preferences. This method is a powerful extension to existing models. However it relies on value judgements to translate ‘intangible costs’ into numeric parameters. Before such a quantification of behavioural aspects can be attempted, a detailed qualitative approach is needed to understand the underlying causes for ‘intangible costs’ and thereby make them more ‘tangible’.

The literature provides only limited insight into the relationship of stakeholders with storage. Two approaches are therefore taken to enquire the underlying beliefs and attitudes. First, a workshop can provide a platform for engagement on the issues relating to storage. Secondly, semi-structured interviews are a method explored for gaining a more in depth understanding of emerging issues. The following sections explain the rationale and method behind the two approaches.

3.4.1 Stakeholder workshop

Stakeholder workshops are a popular way in which to consult ‘the community’ and engage them in the decision making process. In the UK several public bodies actively encourage workshops through funding and facilitation. Ofgem, DECC and UKERC, among others, routinely run workshops as part of their stakeholder engagement agenda.⁴

Two types of motivation should be distinguished: the workshop organising committee aims to address specific research questions and to gain a better understanding of pertinent issues through engagement with the workshop participants. This can also include the ‘testing’ of a hypothesis or a proposal by collecting reactions from the workshop group.

The interests of participants themselves, on the other hand, could include a desire to ensure that their position and requirements are recognised by the community as well as for them to learn through the engagement with other participants. Thus, both sides stand to contribute to and benefit from the process.

For the convenor the motivation to hold a workshop extends beyond the expediency of dealing with many stakeholders in one go, rather than one-to-one. The dynamics of bringing stakeholders together does itself provide a context in which participants engage constructively with trade offs between the interests of groups. A stakeholder workshop can facilitate the process of identifying the underlying tensions by creating conditions in which the participants ‘cocreatively meet their individual and collective needs’ (Holman and Devane, 2007).

The mutually beneficial intention behind stakeholder workshops leads to a common two part format. Presentations and scene setting material can provide participants with recent research findings or thinking, and opportunities can be created for participants to contribute to this process. Part two can involve the actual ‘work’. Here participants are set ‘research questions’ or ‘themes for consideration’, typically in break-out groups with facilitators, and report their findings back to the wider group for discussion.

The active engagement makes workshops a more involving process than interviews, but they equally bear risks. Quieter participants may find it harder to make their voice heard, or ‘assumed consent’ can override alternative points of view. It is the role of facilitators to guard against these pitfalls and moderate the discussion, such that contributions are actively encouraged.

Engagement strategies can support the process, make the experience more interesting for participants and thereby increase their involvement. Numerous approaches have been considered and applied (see for instance Holman and Devane (2007)). Recent workshops have taken advantage of modern media as alternatives to flip charts and post-it notes⁵ allowing participants to interact in new and stimulating ways.

⁴For examples see Ofgem (2012); UKERC Meeting Place (2012) or DECC (2012c)

⁵Cooper et al. (2012), for instance, allowed participants to vote on business models using their mobile phones

3.4.2 Semi-structured interviews

While workshops can provide an effective method to gather group opinions, it may in some instances be necessary to gain further in-depth insight into stakeholder views, for which interviews are considered here.

Saunders et al. (2009) and Robson (2002) distinguish three types of interviews: structured, semi-structured and unstructured interviews. Structured interviews are suited to descriptive research, whereas unstructured interviews are frequently used for exploratory studies. Semi-structured interviews combine explanatory and exploratory insight. For the purposes of this study, which seeks to compare and contrast stakeholder views based on their present position in the system as well as their beliefs and attitudes towards future developments, semi-structured interviews provide sufficient structure, while enabling a flexible approach. Robson (2002) refers to the ability to modify ones line of enquiry as one of the strengths of this approach in ‘investigating underlying motives’.

The semi-structured approach was therefore employed in its widest sense. An overly formulaic approach did not suit the complexity of the subject matter. Questions were therefore kept open ended and allowed the candidate to express their own perception and draw on their own expertise.

To this end, broad sets of questions were formulated to suit each interviewee and to allow them to contribute their particular view point. The generic themes are shown in Appendix Table B.8.

The selection of interviewees and the conduct of the interviews is explained in detail in Section 6.3.2.

3.4.3 Limitations of stakeholder engagement

The interview process itself is subject to a number of biases, as discussed by Saunders et al. (2009, p. 326). The themes of the interview are pre-defined. Although every effort is made to formulate questions ‘openly’ and to allow the interviewee to freely answer and explore areas perceived as relevant by them, it is not possible to conclude that the extent to which specific subjects are mentioned in the interviews reflects the interviewee’s perceived importance of this subject. Undue quantitative analysis of interview material, such as the number of citations of a particular keyword or subject, will therefore not be attempted.

Semi-structured interviews are time intensive. Contacts need to be established and meetings agreed. Robson (2002) estimates 10 hours of transcription time for every hour of interview time. Analysis of qualitative information also requires significant amounts of time. The number of interviews was therefore limited. It was not the intention of these interviews to provide statistically significant data. Their insight relies rather on the interpretation of in depth conversations. Even if a larger number of interviews might alter some of the results, the basic trends identified from the stakeholders engaged here are expected to remain valid.

A workshop setting can stimulate discussion by bringing together a range of view points. The downside of this process is the possibility to undermine less articulate or

unconventional contributions. A balance between open discussion and more managed engagement is intended to minimise this risk. Round table discussions favour the expression of well formed, established and confident contributions, while smaller group activities, facilitated by participants with a brief to engage the whole group in the task, can tease out more subtle considerations. Both were therefore used.

Audio recordings further allow for contributions that did not shape the ongoing discussion to be picked up and considered in follow up interviews, away from the pressures of group dynamics.

Finally, the stakeholder engagement process itself does not constitute a method of analysis, but rather forms part of the data collection process. To interpret the results, findings are embedded into a wider analytical framework, which will be discussed in the following section.

3.5 The analytical framework

The last three sections introduced techno-economic modelling, transition theory and stakeholder engagement as methods that could individually address aspects of the research questions and briefly outlined their application to the research reported in this thesis.

A conceptual decision flow diagram that combines some of the questions a policy maker may ask of storage is shown in Figure 3.8. The process is iterative, but one could start with the question whether storage adds value to the system as a whole. If this is not the case there is no need to proceed and no role for storage exists. In this thesis the system value is approached qualitatively through the stakeholder engagement.

A positive system value leads on to ask if storage is likely to be commercially viable. Here, this is done through the techno-economic analysis. Should storage turn out not to be viable, support mechanisms can be considered to make the system value accessible. Equally, if the net present value is positive, but uptake is not forthcoming, support should be considered. Dynamics that could inhibit market uptake despite commercial viability will be informed through the socio-technical perspective of the transition process.

Support mechanisms for storage could alter the operational characteristics of storage and for this reason the system value must be reconsidered iteratively for each case.

Figure 3.8 is merely intended to illustrate the logic of different conditions that influence the role for storage. It is not applied in a methodical sense. The process steps followed in this thesis are shown in Figure 3.9, which combines the three approaches as components of the analytical framework.

Each addresses one of the three research questions. The techno-economic model explores the conditions for commercial viability (research question 1), the socio-technical perspective addresses the wider benefits of storage (research question 2), and the combined insight from these two approaches feeds into the transition perspective, which is concerned with the third research question on the uptake conditions for storage.

Combining these approaches into a single framework requires iterative and qualitative interfaces. Iterative, because insight from one approach can inform another and in turn

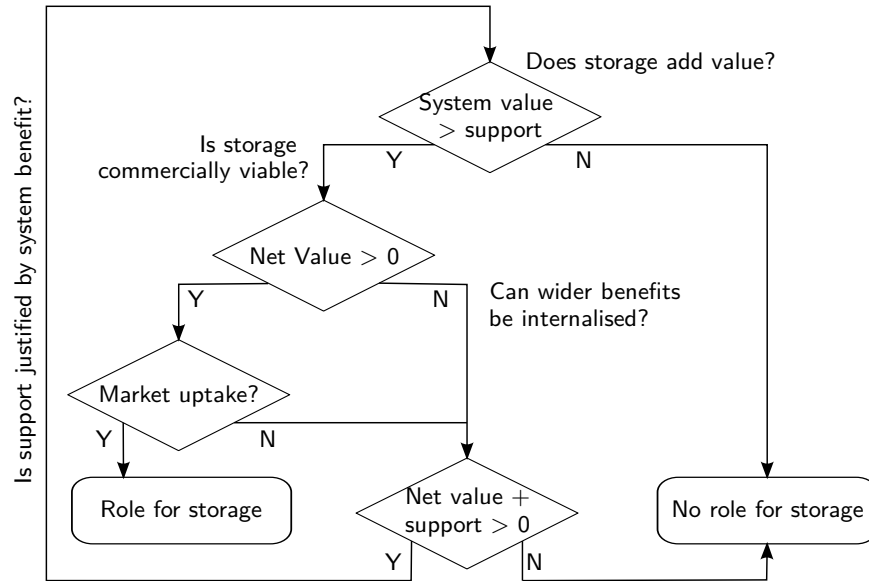


Figure 3.8: *Decision process justifying support for storage. Support should be considered where a positive system value is not met by commercial viability. Feedback of support mechanisms can alter the system value, which leads to an iterative assessment process.*

produce feedback. And qualitative, because the units of enquiry differ. The techno-economic approach is rooted in monetary units and quantitative comparisons, whereas the socio-technical perspective deals with perceptions. The transitions perspective relies on the interpretation of these value judgements.

The connections between these approaches and flows of information are shown in Figure 3.9 as arrows. The underlying process can be explained by a conceptual example. Starting with the techno-economic model, a certain commercial preference for a set of storage characteristics can be established, which informs the socio-technical perspective. During the stakeholder engagement the attractiveness of this configuration is tested against stakeholder preferences. This process may reveal barriers, which can be included in the assumptions and feed back into the techno-economic model to produce a stakeholder adjusted set of results. Both the original and the adjusted set, provide inputs into the transition model. The former with potentially stronger commercial drivers, the latter with better alignment with stakeholder preferences.

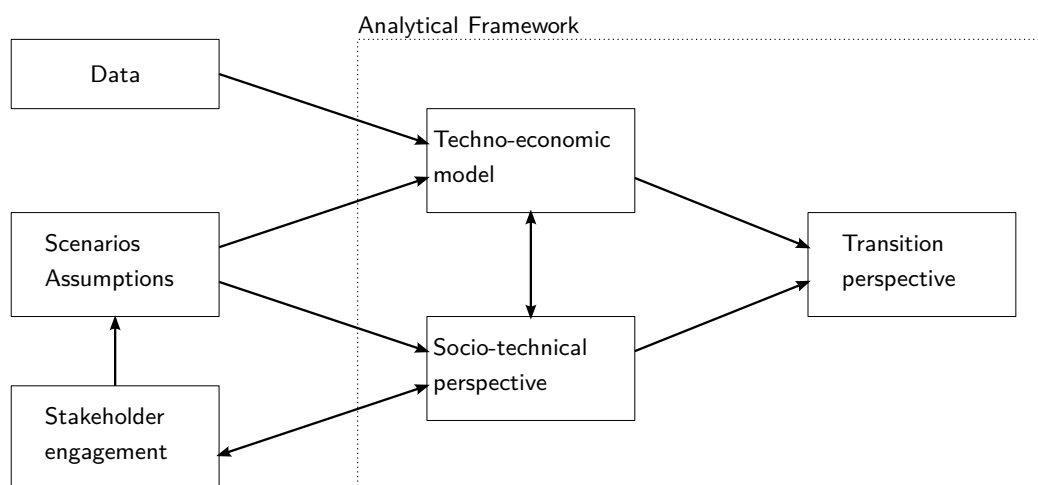


Figure 3.9: *The analytical framework. Arrows indicate flows of information, which in some cases are bi-directional.*

Three approaches to assess the future role of storage have been discussed in this chapter. None of them are deemed sufficiently complete to analyse the the future role of storage on their own. By combining their different insights into a single framework, it is postulated that deeper insight can be gained, not only into the commercial prospects for storage, but also the particular dependencies on landscape changes and developments at the niche level, which will be used to inform policy challenges in this area. In the following chapters, the three approaches are applied in turn, beginning with the application of the socio-technical perspective to the transition of historic cases of storage uptake. Chapters 5 and 6 will populate this framework with techno-economic and socio-technical data and insight. Chapter 7 then applies the framework with the specific aim of exploring uptake dynamics.

Historic cases of storage deployment from a socio-technical perspective

Just as soon as a man gets working on the secondary battery it brings out his latent capacity for lying. [...] Scientifically, storage is all right, but, commercially, as absolute a failure as one can imagine.

Thomas Edison, 2 February 1883

Inside of 15 years the entire vehicle traction in large cities in the United States will be done electrically & I am now manufacturing the battery that will permit this to be brought about commercially.

Thomas Edison, 6 May 1908

TO TEST THE APPLICABILITY and identify limitations of the analytical framework with respect to transitions of electricity storage, this chapter applies the approach introduced in Section 3.3 for socio-technical transitions. Section 4.1 introduces three historic periods of storage deployment (or its failure). Two specific projects are selected for a more detailed case study and assessed from a socio-technical perspective in Sections 4.3 and 4.4. Lessons from this review and specific considerations for storage uptake are discussed in Section 4.6.

4.1 A brief history of storage deployment in the UK

The recent resurgence in interest in energy storage follows a long and volatile history of periods when storage was felt to be either ‘a waste of time’ or a ‘vital component of the future energy system’. Pioneering grid storage projects have been undertaken in the UK during different periods. First, in the early days of electricity networks towards the end of the nineteenth century, again in the early second half of the twentieth century, and for a third time at the beginning of the twenty-first century. These endeavours were followed by periods of little or no interest in further development and deployment. These three periods are described here to provide the context for the specific case studies in Sections 4.3 and 4.4.

4.1.1 Battery storage in early DC networks

The first period of grid storage deployment goes back to the very beginning of electricity networks themselves. During the 1880s, when small generators began to be connected to local loads in the UK (almost exclusively for lighting), load profiles were notoriously ‘peaky’. An illustrative example of such early profiles is given by Schallenberg (1981) and shown in Figure 4.1. To satisfy peak load, during the evening, when lighting was used, generators would have to be sized accordingly. Thus, for most of the day they would remain idle or under-utilised.

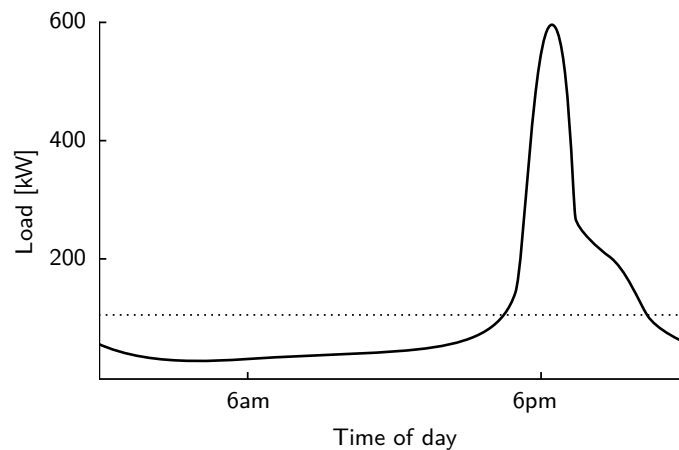


Figure 4.1: Load profile illustrating the high peak to average load ratio experience in early DC networks, primarily used for evening lighting. Source: Schallenberg (1981)

In this context battery storage technologies were highly desirable to perform load levelling. They enabled generator owners to meet higher peak loads and run their generators more efficiently and effectively. DC generators, in particular, took advantage of battery technology. Even some AC generators (then still the minority of generators) went to the expense of fitting rectifiers, such that they could reap the benefits of storage. In 1910 nearly all direct-current and around 20% of alternating-current stations in the UK used batteries. The steady growth in battery deployment between 1891 and 1910 is shown in Figure 4.2. The use of storage batteries for load levelling had become ‘standard practice’. (Schallenberg, 1981)

The successful uptake was not the result of high technical performance. The first commercial cells were notoriously unreliable. Neither had they been developed with grid storage in mind. It was the prospect of the vast market in electrified transport, which attracted developers, such as Thomas Edison in the U.S., to drive research and development activities into new and better batteries. Grid applications and use in streetcars became rather disappointing runner up prizes, once the internal combustion engine had established itself in passenger transport. (Carlson, 1988)

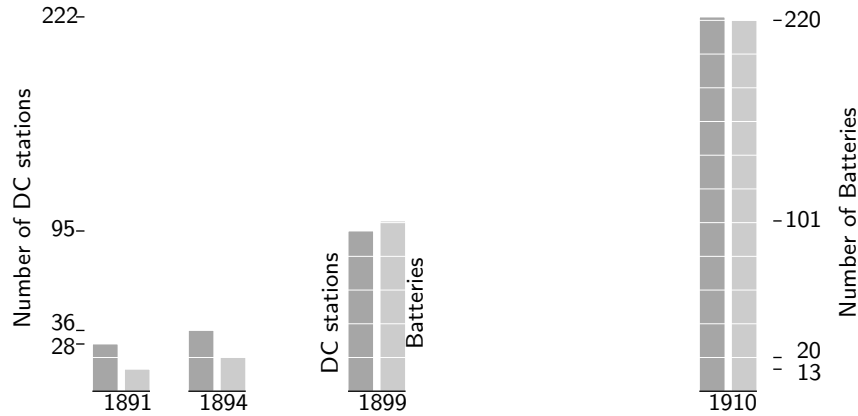


Figure 4.2: *Number of DC power stations and deployed storage batteries in the UK. In 1899 the number of batteries exceeds the number of DC stations, because some AC stations even consider storage valuable enough to fit rectifiers and deploy batteries. Based on Schallenberg (1981)*

The ‘war of the currents’, fought at this time almost personally between Thomas Edison and George Westinghouse in the U.S., favouring DC and AC technology respectively, is an early example of path dependency in electrical networks. The alternating current eventually established itself as the dominant design, both in the U.S. and the UK, further reinforced through later projects such as the UK national grid, taking advantage of the ease with which AC voltage could be stepped up or down and therefore transmitted over long distances (Lehtonen and Nye, 2009). This favours large scale power plants in remote locations and also lead to their more efficient operation, since the aggregated load profiles of the enlarged grid became smoother and the need for battery storage diminished. (Baker and Collinson, 1999; David and Bunn, 1988; David, 1992)

Despite considerable improvements in battery technology, stimulated by other sectors, batteries never returned to their wide spread application found in early DC networks.

More recently, the advent of an increasing share of DC loads (LEDs, computers and other mobile devices) and distributed DC generation has led to a renewed interest in local DC networks, such as the ‘Project Edison’ (Williamson et al., 2011). Proponents of such solutions claim cost and energy savings, as well as the potential to better integrate with AC systems through load shifting and integration of storage.

4.1.2 Pumped hydro storage in the nuclear age

Following the Electricity (Supply) Act from 1926, the advent of the national grid in 1930 and an increasingly diversified load profile led to several decades without any further

deployment of electricity storage. The scale of power stations increased steadily and storage could readily be provided from coal stocks. The system bore little resemblance to the early DC networks, and it was from a very different angle that storage would see a renaissance in the second half of the twentieth century. The rise in nuclear power station deployment in the 1960s and '70s opened up an opportunity for storage to provide flexibility to this base load technology, and—potentially more importantly—provide backup in case reactors had to suddenly come off the system. (Boon, 2010)

‘[With a] substantial programme of nuclear plant on the system, there would be a powerful economic case for an associated storage component of, perhaps, 10–15% of the plant on the system.’

Wright (February 1980)

In fact, the installation of nuclear power stations—or just the *expectation* of their installation—has been a considerable factor in the commissioning of pumped hydro storage. Deane et al. (2010) identified a correlation between nuclear deployment and pumped hydro in the United States. A very similar trend can be observed for the UK and Europe. Figure 4.3 shows the installed capacity for both nuclear and pumped hydro per decade since 1950. After consecutive decades of growth, suggesting a degree of technological co-evolution, the 1980s brought about a downturn with no further deployment in either technology in the UK by the 1990s.¹

Among many reasons for the decline in nuclear installations are two major historical events: the safety concerns following the 3 Mile Island (1979) and Chernobyl disasters (1986), and a ‘near universal decision to change from centrally planned and regulated utilities to a market based [...] structure’ (Price, 2011a). The latter, especially in combination with the emergence of North Sea gas in the UK, has had a fundamental impact on how large scale projects, such as pumped hydro, are viewed and costed.

In the 1970s it was expected that the UK would require a pumped-storage station around every 10 years (Holmes, 1980). In practice no further sites would be built over the next 30 years. And although the expected deployment of nuclear power did not come to fruition, the built pumped storage sites still operate today and provide system services. Their operating strategy was able to adjust away from relying on providing backup for plant outages and more towards ancillary services. (Boon, 2010)

A possible revival of nuclear energy coincides with a renewed tentative interest in pumped hydro storage.² In Europe 15 new installations have been proposed with a combined capacity of 7 GW (Deane et al., 2010). In the UK, Scottish and Southern Energy have consulted on new sites for pumped storage in Scotland (Murray, 2009).

¹Installations post 1990 take place primarily in eastern European countries, namely Slovakia, Slovenia and Romania, but also France

²No causation implied. In practice this interest seems more likely to be motivated by developments in wind power deployment

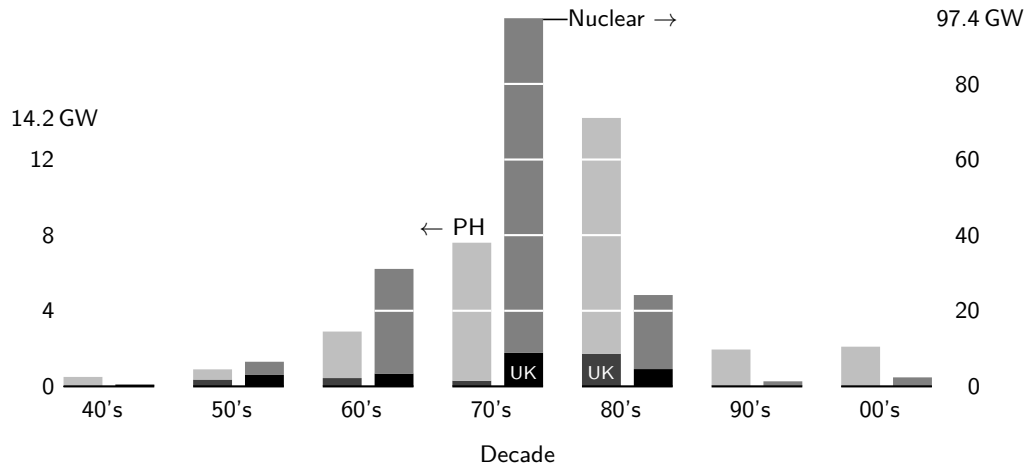


Figure 4.3: New build of nuclear (right bars) and pumped hydro (left bars) for the UK and Europe (excl. Russia). Nuclear build peaks in the 1970s followed by the maximum build of pumped hydro in the 80s. Reduced new build of nuclear coincides with a reduction in pumped hydro build. Sources: IAEA (2011); Deane et al. (2010); MacLeay et al. (2010)

4.1.3 Project motivations

Interest in storage application is said to move in ‘waves of enthusiasm’ (Price, 2011a). And each cycle brings with it a slightly different set of motivations. Some of the core reasons do however remain unchanged over the past 40 years. Efficiency, cost and integration of nuclear are commonly referred to, and even the expected integration of renewables, such as wind, and electric vehicles has been cited as far back 1980 (Wright, February 1980).³ More recently ‘decarbonisation’ has been added to the agenda (among them Cooper et al. (2011); DTI (2004a) and Boston (2010)).

The first case of system integrated storage in the UK since construction of the national grid was the Ffestiniog pumped hydro site in Wales in the late 1950s. The business case was based on cost and capacity requirements. These have largely remained the central points in the justification for pumped hydro projects. Over the following decades the assessment gets more refined. By the 1980s the assessment of potential ‘cost savings’ includes not only avoided investment in other plant, but also the operation of the system, where storage could add value by displacing costly options to provide reserve and response over very short timescales.

By the turn of the century studies of the value of storage in the U.S. would consider no less than nine types of applications in different combinations, and by 2010 this number

³See also Hernen (1977); Wright (February 1980); Baines et al. (1985); Douglas (1990); Baker and Collinson (1999); Davidson et al. (2000); Price et al. (2000); Price (2000); Eckroad (2002); EPRI (2003); Butler et al. (2003) and Bathurst and Strbac (2003)

had grown to 21 (see EPRI (2003) and EPRI (2010)). Despite the increased sophistication, it is still cost and capacity requirements that underlie the rationale. Cost now includes a wider remit of efficiency and displaced alternatives, and capacity is broken down by the ability to respond on different timescales. The commercial assessment remains ‘production’ focused throughout. The system benefit of charging storage with surplus renewable energy or otherwise constrained electricity for later use is referred to in principle, but not quantified.

In the wake of 11 September 2001, security was also raised as one of the considerations. Resilience against ‘man made attack or natural disasters’ could be increased with sufficient amounts of storage (Price, 2011a).

4.2 Case study of storage deployment

The previous section touched on three phases in which storage developments were taking place. Phase 1 between 1890 and 1910 consisted of batteries in small DC networks; phase 2 spanned from the 1950s until the 80s and featured pumped hydro storage alongside nuclear power developments; and phase 3 is the present interest in storage development driven by the prospect of fundamental system changes as part of a low carbon transition.

This section focusses on two specific cases of storage deployment, which were selected from the limited number of UK based examples. The criteria for selection include a sufficient degree of scale and public interest in the project, as gauged by the level of press coverage and commentary. Furthermore, projects have been selected to cover different regulatory environments. To achieve a high level of insight for present and future storage uptake, cases have been selected as close to the present day as possible.

The two projects under review are the Dinorwig pumped hydro installation in northern Wales and the Regenesys flow battery commercialisation project.

These projects were specifically selected to expose the influences of their socio-technical environment, the regimes in place at the time and the landscape pressures acting upon it. A potentially significant difference between the two projects is that Dinorwig was planned and built under the CEGB at a time of a centralised UK energy system pre-privatisation, whereas Regenesys—although receiving government support—was managed by commercial actors in a market post-privatisation.

It is commonly agreed that the centralised system favours large scale deployment projects in general (see Helm (2008)). The specific impact of this distinction on the motivation of individual actors relating to storage projects will form part of this analysis.

Both projects set out to deploy proven technology, but their aim was for ‘world firsts’ in their field. Pumped hydro storage sites had been in operation around the world, including the neighbouring Ffestiniog site, and the Regenesys technology had successfully been tested in the laboratory. The challenge in both cases was to deploy the technology on a yet unprecedented scale. Thus, substantial technical and project management challenges had to be faced in both instances. Participants claimed that all of these can be overcome, provided sufficient resources are made available. This study therefore is less concerned with the technical detail of the development process

and instead views their developments from a socio-technical perspective. More detail on the technical challenges encountered during the projects has been documented by DTI (2004b) and Baines et al. (1985).

The review period spans around 10 years in each case. Dinorwig was first proposed in 1971–72, and construction commenced in 1974. The official opening by HRH Prince of Wales took place on 9 May 1984. (Baines et al., 1985; CEGB, July 1972)

The exact starting point of Regenesys is less well defined. The project went through initial development and ‘proof of concept’ phases prior to commercialisation dating back to around 1989. This study will focus on the commercialisation project, which took place between 1993 and 2003.

Each project is now reviewed in turn in Sections 4.3 and 4.4, including their development and views of participants and commentators before, during and after the project. The process of both projects is then discussed from a transitions perspective in Section 4.5.

4.3 Dinorwig—the electric mountain

At the time, Dinorwig was the largest civil engineering contract ever awarded by the UK government. It followed 3 smaller installations, built in the 1950s, ‘60s and ‘70s. With 1728 MW, Dinorwig surpasses the capacity of these three existing sites combined. The capacity was dictated by transmission constraints, which implies that, had those constraints not existed, an even larger capacity might have been chosen. Selection of sites was based on the availability of ‘two adequate reservoirs with maximum vertical and minimum horizontal separation; close proximity to the Grid; good transport access; good geological conditions; and low amenity value’. Dinorwig was finally selected from a shortlist of four sites for ‘amenity, social and economic reasons’. (Hernen, 1977)

4.3.1 CEGB’s economic case for Dinorwig

Estimates of the value of the proposals to the CEGB were put forward during the planning phase and discussed in literature. The sophistication of the valuation had improved since Ffestiniog 20 years earlier, which was justified purely on a ‘capacity need’ basis as an alternative to coal (see Baines et al. (1985, p.936)). The case was now made based on the statutory obligation of the CEGB to provide a secure service:

In the late 1960s estimates of the reserve needed during the next two decades to cover the worst possible loss of generators was calculated to be about 1300 MW, to be available within 10 s, to keep within statutory obligations.

(Mandle, 1988)

The response time thus became a central feature of the design and cost-benefit analysis. Douglas identifies and values five principal savings (Douglas, 1990): 1) load following 2) transmission capacity 3) deferred construction of thermal plant 4) reduced energy imports, improved load factors, and 5) rapid response and spinning reserve.

As the range of savings considered shows, a system wide view was taken, that would recognise the ‘benefits in the improved operation of the system’. This *total* value was said to be worth ‘well over £50m’ per year. (Mandle, 1988)

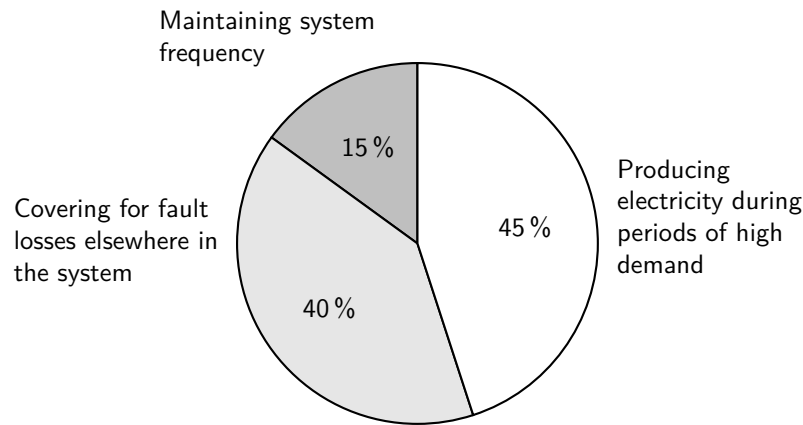


Figure 4.4: *Relative share of anticipated Dinorwig benefits to CEGB. Data: Holmes (1980)*

Holmes gives an insight into the CEGB’s thinking at the time of how these values would accrue. As shown in Figure 4.4, the largest share of 45% stems from production of peak time energy, and a further 40% from covering system faults such as nuclear power station failures, which were a more common concern at the time. Only 15% of the value is expected from frequency services. The distribution of these three sources of revenue has, however, changed over time. Power stations have become more reliable, such that the revenue from ‘system faults’ makes up a smaller share. The dash-for-gas, which saw deployment of additional capacity following the privatisation of the UK electricity industry in the 1990s, further put pressure on revenue from peak time energy. The loss in these two value streams has been compensated by a ‘proportionally higher than expected’ share in ancillary services, which now makes up roughly even shares with the other two sources of revenue. To access this lucrative market a specific arrangement is in place today between First Hydro and National Grid, whereby Dinorwig provides short term operating reserve (STOR). (Boon, 2010; Holmes, 1980; Baker and Collinson, 1999)

The of annual savings of £50m anticipated by Mandle (1988) compares very favourably with the initial cost estimates made by the CEGB in 1972 of £75m. But even when the build costs rose to over £400m, a commercial case could still be made, be it over a longer period. The appropriate amortisation period was a subject of debate at the time. Over a 30 year life with a 5% discount rate, the benefits could add up to anywhere between £500m and £1bn (in £1985) (Douglas, 1990, p.346). Some commentators argued that the 30 year time horizon was too short sighted, since many of these projects

offer a longevity in excess of 40 or 50 years (Baines et al., 1985, p.956). This view, supported by several commentators, highlights one of the most notable differences in approach between the costing pre- and post-privatisation. We will return to the role of engineering and economic lifetimes in the discussion in Section 4.5.

4.3.2 Project challenges

The main project challenges were inflation rates, the geological challenges of the work and the sheer scale of the project.

Cost forecasting in the late 1970s was made difficult by high levels and volatility of inflation. Cost estimates published in the early 70s therefore appear naïvely low, and led to political criticism that the cost spiralled out of control. However, the £75m quoted in 1972 are equivalent to over £270m in 1984 prices, following a period of substantial retail price index (RPI) rises (see Figure 4.5). F. W. Coates (Atomic Power Constructors Ltd) complains that ‘Inflation has played havoc with comparisons of cost’. The actual build costs were thus much debated. Initial figures citing in excess of £425m were later corrected to capture the time value of expenditures, which reduced the total system cost to around £410m (see Baines et al. (1985, p.933 and p.955)). This value is equivalent to around £1bn at 2010 prices or £560/kW. Whilst high inflation can favour capital intensive projects, such as this one, the level of inflation remained low once the site commenced operation, as shown in Figure 4.5.

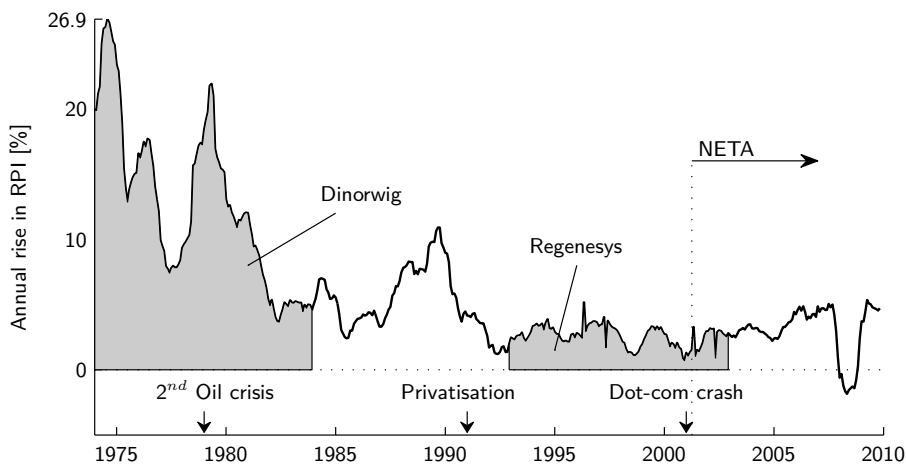


Figure 4.5: Annual retail price index (RPI) increase during the Dinorwig and Regenesys project and selected historical events coinciding with the projects. High inflation made costing over the duration of Dinorwig project especially challenging, whereas Regenesys enjoyed low and stable interest rates. Based on data from Office for National Statistics (2011)

Furthermore, the economic context of the UK during the build period led project leaders to complain that the CEBG was ‘beset with difficulties’ (Holmes, 1980). A

major concern for project managers were industrial disputes, which posed a substantial challenge to the CEGB more widely at the time. The CEGB was also aware that the neighbouring site in Ffestiniog encountered public resistance in the 1950s to the construction of pumped hydro reservoirs on a scale ‘not seen with nuclear power’ (Baines et al., 1985, p.936). Care was therefore taken to engage the local community, employ local people (many of them miners who lost their jobs as the result of the Dinorwig slate mine closure), and to make concessions towards the amenity of the site. The latter included measures to move transmission links and services under ground to ensure minimal visual impact, despite increases in cost. (Hernen, 1977)

4.4 Regenesys: the world’s biggest battery that never was

4.4.1 Technological optimism

At the time of conception of the Regenesys project in the early 1990s, technological optimism amongst commentators and project participants was rife. Commentators referred with excitement to novel storage technologies and predicted significant reduction in cost making them commercially attractive in ‘only a few years’. Further, such systems were expected to ‘revolutionise future central power station economics worldwide’. (Baker and Collinson, 1999)

After National Power and PowerGen had been privatised in 1991, the energy market at the beginning of the Regenesys project was a duopoly. Competition was limited, but cost reduction rose as a priority for the two market participants. The prospect of the introduction of NETA was seen by some commentators as a significant opportunity for storage to emerge as a new player in this market. It was felt by some that the vertical integration of services had disguised the true value that storage could bring to the system. Now, fundamental changes in the unbundling of electricity markets would allow the benefits of storage to be more clearly identified. Storage would be able to provide and charge for a new a range of services, including ancillary services, which Regenesys specifically aimed to address.⁴ (Price et al., 2000; Baker and Collinson, 1999)

The new market arrangements would see the introduction of more customisable arrangements, such as bilateral contracts, in place of bidding pools. These changes were expected to create ‘genuinely new market opportunities’, not only in the UK, but worldwide. This new market would extend beyond trading in electricity markets:

The regulatory climate in electricity utilities worldwide is changing, such as to focus attention on environmental factors, asset utilisation and customer service, three areas in which storage can make a very valuable contribution.

Baker and Collinson (1999)

At the same time Baker and Collinson warn that the commercial viability needed to be proven through carefully targeted applications demonstration schemes.

⁴The fact that Dinorwig was operating in the ancillary market with significant success was noted well before the introduction of NETA in 1999 by Baker and Collinson

Regenesys was just such a demonstration scheme. 'Regenesys' is the registered trademark of a regenerative fuel cell system, which had been developed by Innogy Limited, a wholly owned company within the npower division of National Power (Price, 2000). After the technology had been proven viable on the laboratory scale, a 1 MW pilot plant was constructed at the Operations Training & Evaluation Facility (OTEF) located at Innogy's Aberthaw Power Station in 1997. This pilot proved 'extremely successful'. (Nuttall, 2004; DTI, 2004a)

As a result of the initial success, the decision was taken to build a 10 MW plant, comprising 120 modules with a total capacity of 100 MWh (about 1% of Dinorwig's 10 GWh, yet substantial by battery standards). The plan was formulated in 1999 and the completion at the site in Didcot was expected before the end of 2000. Innogy's confidence in the the commercial potential was such that it floated Regenesys as a separate venture (Regenesys Technologies Ltd.). At the time there was even speculation that the technology could end up being worth more than the company's power station business (Lee, 2004).

Interest also came from the U.S., where the Tennessee Valley Authority (TVA) was faced with a \$5m (around £3m) upgrade to the substation and the sub-transmission system. They opted instead to invest around \$30m (£16m) in Regenesys technology and install a 12 MW/100 MWh system. (Grant and Hoagland, 2002; Lee, 2004)

However, technical difficulties delayed the project and the completion date for the UK project, which by now had been relocated to npower's Little Barford plant in Cambridgeshire, was revised to early 2004. In May 2002 Innogy's npower division became part of RWE, which in 2003 decided that Regenesys did not fit the 'core business'. A partner was sought to take the project forward. No such partner was forthcoming and the decision was taken to discontinue the project in 2003. At this point the site and a considerable amount of demonstrator equipment had been built and was now left unused. The TVA project was unable to complete, claiming to be 85% finished. (Price et al., June 1999; DTI, 2004a; EPRI, 2003; Lee, 2004)

4.4.2 The value proposition

Several references to the need to aggregate different value streams are made by project participants and commentators in publications during that period (see EPRI (2003); Grant and Hoagland (2002); Price et al. (2000); Price (2000); Davidson et al. (2000); Baker and Collinson (1999); Price et al. (June 1999)). Due to the commercial nature of the project, it is understandable that no specific figures for the expected value of these streams are cited.

The expectations held by project participants were clearly high and their valuation of the business reflected this. To potential investors the value was presented as around £1bn, which one potential investor referred to as 'fantasy', given that no product had been launched yet (Loughhead, 2011).

Studies to establish the value and feasibility of battery energy storage were conducted at the time. Sandia National Laboratories carried out such a study in 2002 on 2.5 MW / 10 MWh systems. However, the aim of Regenesys was specifically to operate

at larger scales (≥ 100 MWh) and Innogy opted not to take part in the study. (Corey et al., 2002)

Nevertheless, it was the intention of the Regenesys programme, alongside the technology development, to promote the benefits of the technology and to establish the economic value. The efforts in these work streams was said to be ‘significant’. Thus, as part of this ambition, Innogy did collaborate with the Electric Power Research Institute (EPRI) in 2003 and shared expected cost information for the year 2006 as well as ‘mature’ prices. The cost for the preferred Regenesys configuration of 10 MW with 100 MWh of storage, can be deduced as around £7.5m or around £5.6m once mature. The mature value is equivalent to around £560/kW in 2006 (£630 in 2010£). With this cost assumption and depending on application, EPRI established positive net present values for the technology, depending on the assumed cost of alternative solutions. It was seen as most competitive for applications requiring eight hours or more of stored energy. (EPRI, 2003)

The site at Little Barford was seen as a demonstration project and would itself not be economically justified. Although a number of benefits could be identified (including arbitrage, load following and voltage control, as well as a proprietary arrangement with National Grid to provide ‘black start’ capabilities) the plant was not located in such a way as to maximise these benefits. It was rather intended as a demonstration of the technology. (EPRI, 2003; Price, 2011b)

Expectations for the scale of the market opportunity were high. Every year 10–15 GW of electricity storage installation were anticipated, based on the displacement of new capacity alone. (DTI, 2004a)

4.4.3 The sudden end of Regenesys

RWE publicly stated that their decision in 2003 to withdraw funding was ‘strategically motivated’.

‘While ongoing testing has proven the technology, we will not be committing the capital expenditure needed to take it to market’

RWE Spokesperson, The Guardian (16th December 2003)

However, given that the capital cost of the Regenesys project had already largely been sunk, it is questionable if RWE would have foregone a revenue stream, if they indeed believed in the profitability of the technology. The absence of any buyer for the technology suggests that either it was valued too high or the trust in the technology was not yet sufficient. Joe Hoagland’s (senior manager at TVA) response represents the sentiment of many at the time, but also illustrates the problem: ‘[We] would not buy Regenesys, but I hope somebody could pick it up’.

Confidence in the technology had been high, and those working on it were ‘surprised and dismayed’ by the project’s sudden end. (Lee, 2004)

Steve Joseph, from Sheffield University, who had been working on the project expressed his frustration about the withdrawal of funding, when he stated that ‘no technical problem can ever be resolved at a price that satisfies the commercial people’. (Lee, 2004)

‘Though unproven, the Regenesys technology may be viable. [...] Engineering difficulties [...] might be adequately addressed with sufficient time and investment of resources.’

TVA press release, Nuttall (2004)

The TVA statement that the technology ‘*may* be viable’ is not exactly a ringing endorsement for a technology they invested £16m in. While the technical risk was described as ‘manageable’ by many (Nuttall, 2004; DTI, 2004a), it was also suggested that the commercial risk/return ratio was judged to make the proposition not viable. Here lies the clash between the engineering achievement of the project and its commercial failure. Even Nuttall, who argues in favour of research and development in storage technologies, concedes that RWE probably made the ‘right business decision’. Price suggests that liberalised markets want lower risk and in the early 2000s they could get that by investing in CCGT instead (Price, 2011b).

4.5 Analysis from a transitions perspective

This section returns to the analytical framework to provide structure to the comparison of the two cases reviewed above and to test to what extent the multi-level perspective and its implied mechanisms for technology uptake are applicable to storage. Where appropriate this section seeks to generalise the specific finding of each case study to establish the broad conditions faced during their respective periods. To this end the review of battery storage in early DC networks from Section 4.1.1 will also provide some comparison.

First, the broad context of the case studies is compared. Then, the conditions that created niches for storage are reviewed, before the conditions in the socio-technical regime are analysed and contrasted. Table 4.2 provides a high level overview of the key niche and regime dimensions.

4.5.1 Comparison of project contexts

The context of the UK in the period 1973–83 and 1993–2003 is different in many ways and some of the key differences are summarised in Table 4.1. The former period spans the ‘winter of discontent’ with wide-spread industrial disputes, when Britain was referred to as the ‘sick man of Europe’. Interest rates were high, and many state owned businesses were said to be in need of privatisation, in order to improve their efficiency.

The picture in the latter period, by contrast, saw a confident economy with low interest rates, building up to what was later termed the ‘dot-com bubble’, in which many businesses with little or no short term revenue prospects attracted large investments. The bursting of this bubble, causing a mild recession, also led to the disappearance of cheap

Table 4.1: *High-level comparison of landscape pressures and regime conditions that favoured or disfavoured the Dinorwig and Regenesys project.*

Dinorwig		Regenesys	
Favourable	Unfavourable	Favourable	Unfavourable
access to finance and public funding	industrial disputes	public funding	changing regulatory regime
long term planning (30 years)	volatile interest rates	low and stable interest rates	uncertain commercial prospect
vertical integration	geological scale of the project	world leader in development	changes in ownership and strategy
stable regulatory regime	environmental restrictions	technology deemed viable and valuable	lack of cheap finance (end of project)
			competitive market with tight margins

and abundant finance, at a time when the the need for such finance for the Regenesys project was the greatest.

The bursting of the ‘dot-com bubble’ can be seen as a major factor in the external economic environment that disfavoured Regenesys. Apart from this, the economic conditions surrounding the Dinorwig period can be described as largely less favourable.

What made up for this disadvantage was a stability that arose from the state owned nature of the CEGB throughout the project. Plans were prepared and executed with a long term perspective (30 years or more), without the same dependance on financial markets as would be the case in a privatised context. Even by CEGB standards, the Dinorwig project was ambitious in its scale and its financial exposure in today’s terms was an order of magnitude greater than that of Innogy (£1bn compared to £100m).

Regenesys on the other hand, saw several changes in ownership and experienced a turbulent time of fundamental regulatory changes. The introduction of NETA—anticipated as a driver for the uptake of storage—and the emergence of a more competitive market, breaking up the duopoly that existed during the conception of the project, led the changes in strategic alignment of the investors. The commercial prospect was no longer sufficient within an increasingly competitive market operating on tight margins.

4.5.2 Niche creating conditions

Niches have been postulated as particular protective spaces, which allow efforts to ‘go in all kinds of directions’ (Geels, 2002). This broad sense of technology exploration has not been observed in any of the above cases. Even in the DC period, which saw significant innovation efforts, the alternative choices remained limited (development focussed on either lead acid or alkaline batteries).

The nuclear period created a niche for pumped hydro specifically, due to what could be termed its ‘unique selling point’: rapid response in cases of nuclear type failure. The result was therefore not a diffuse development of radical innovation with small scale concepts, but a planned and deliberate construction on a large scale. Pumped hydro technology itself might have gone through a process of innovation, some of which took place in other sectors, such as water management and turbine design. Its adoption into the electricity sector was, however, down to very conscious decision making at a central level. Instead of the multitude of small arrows protruding upwards from the niche level in Geels’ classical MLP diagram on page 70, pumped hydro was pulled up by the socio-technical regime with one single arrow.

For Regenesys the conditions that would have created a niche are less clear. Participants accept that the market for the technology still needed to develop. In the meantime the development relied on funding from commercial and public bodies, who would justify their support with longer term prospects. This funding arrangement creates an artificial commercial niche, rather than a niche application. As the subsequent developments have shown, this niche is vulnerable to collapse, once backers lose faith in those longer term prospects. As with pumped hydro, one of the defining features of niche developments is not fulfilled. The project stands as a lone example, rather than part of a vibrant, radical and diffuse wider effort seeking to address a ‘gap in the socio-technical regime’.

The DC networks provide a good example of a niche application in the MLP sense. The load levelling challenge was so profound that even batteries with poor performance would be able to enter the market. Once deployed they could improve technically and commercially and reinforce their position.

As these three examples show, niches can take very different shapes for storage and may not necessarily stimulate the ‘diffuse development effort’ implied in the multi-level perspective.

4.5.3 Changes in the socio-technical regime

The configuration and role of the socio-technical regime in relation to storage experienced fundamental changes over the period reviewed here. The dimensions of the socio-technical regime and some landscape characteristics for each period are compared in Table 4.2.

What all phases of development effort have in common is the *anticipation* of a game changing technology future. Batteries attracted research effort, not in the first place for grid applications, but for the far more lucrative market of electrified transport –

a market that was not to materialise. Pumped hydro also got much of its attention based on future plans. This time expecting the wide deployment of nuclear power – an expectation that would also prove wrong. And flow batteries were developed in the hope that they could (among other things) support a more renewables based system – a future that still remains to be realised.

Market arrangements changed between and within the periods reviewed. Whereas the commercial case for DC batteries could be made within the confines of a single generator, the case and the market structure during pumped hydro deployment covered a larger number of components and considerations within the remit of a vertically integrated CEGB. At the time of Regenesys the expressed hope among proponents and other commentators was that a ‘new regulatory regime’ would finally bring about the ‘true value’ associated with storage. This view was prominent in the period preceding NETA. The breakup of vertical integration—so it was believed—would make more value streams accessible for storage, which were currently ‘disguised’ from the market.

Similar sentiments are currently expressed in relation to the electricity market reform process (EMR) and specifically the proposed capacity mechanism. The new market mechanism is expected by some to ‘unlock’ the potential benefits of storage and overcome the hitherto underrepresented benefits it could bring to the wider system (see Cooper et al. (2011); DECC (2010d); UKERC Meeting Place (2011a) and IMechE (2012)).

However, over a decade after the introduction of NETA, the ‘improved market conditions’ have not brought about a favourable investment environment for storage. Ironically, vertical integration, which once was blamed for obscuring the market for storage, is now believed to be lacking as an aggregating function for the wide range of benefits accruing for different stakeholders across the energy landscape. In the absence of vertical integration, valuing the ‘common good’ characteristics has become harder (Price, 2011a). Although the ‘big six’ utility companies in the UK are vertically integrated, in that they operate across the entire value chain, bar transmission in England and Wales, it appears that the functional separation of different sub-regimes may lead to a lack of appropriate aggregation of value for storage. Section 6.2.1 will return to the question of possible sub-regimes and their relationship with storage.

As shown in Section 4.3.1 the timescales over which projects are assessed commercially has changed considerably, too. Whereas for Dinorwig the engineering lifetime, i.e. the longevity of the physical structures and equipment, was used (estimated as 30 years), Regenesys would have to deliver over a much shorter economic life, dictated not by the ‘life of the equipment’, but by expected returns and risk portfolios of commercial actors.

An interesting contrast exists in the response to changes in the socio-technical regime post deployment. Whereas batteries became obsolete within the AC dominated national grid, pumped hydro maintained a role, despite the absence of further deployment of nuclear power. This suggests that some types of storage may be more resilient to changes in their socio-technical and landscape context than others.

Table 4.2: *Socio-technical regime environment over the past century*

		DC networks ~1900	Nuclear ~1970	Low carbon ~2000
Prevalent technology	Techno-	Lead Acid / Alkaline	Pumped hydro	Flow batteries
Niche conditions		Load levelling	Backup for nuclear	Operational savings
<i>Socio-technical dimensions</i>				
Technology		EV (anticipated)	Nuclear (anticipated)	Wind (anticipated)
Infrastructure		Local networks	Centrally owned/operated national grid	Split between SO/TNO, utilities and DNOs
Sectoral policy		Innovation led	Centralised planning	Liberalised energy market, regulated networks
Industrial networks		Entrepreneur developers	Centrally commissioned contractors	Market based, bilateral contracts
Markets		Privately owned businesses / startups	Centralised planning	Duopoly / NETA, Utility oligopoly
Culture		Innovation, revenue focus	Security focus, long term planning	Conservative, cost focus, short term
Techno-scientific knowledge		Held by innovators	CEGB, Contracted in	Utilities, developers, academia

4.5.4 Transition types

The small sample of cases considered here already suggests that different dynamics led to the uptake and failure of storage technologies over time. The narrative, common in early adoptions of the MLP, that niches are the primary origin of transitions, may therefore not be adequate in some cases of storage uptake.

The critique of the MLP in Section 3.3.4 referred to Berkhout et al. (2003), who noted an ‘undue emphasis’ on niche processes in the applications of the MLP. They make an important distinction of fundamentally different types of transitions and how these affect the transition pathways. Berkhout et al. (2003) propose a taxonomy of four ‘ideal types’ of transition:

1. Endogenous renewal;
2. Re-orientation of trajectories;
3. Emergent transformation; and
4. Purposive transitions.

Geels and Schot (2007) incorporate these types into the MLP and developed 5 transition routes: reproduction, transformation, substitution, de-alignment / re-alignment and re-configuration. These are listed and explained in Table 4.3 and an illustration of how they relate to the different levels of the MLP is shown in Figure 4.6.

Table 4.3: *Transition routes and the process of transition for five types of transition. Geels and Schot (2007); Bennett (2010)*

Transition type	Process of transition
Reproduction	Endogenous change within the regime; no critical interactions with landscape or niche levels.
Transformation	Change arises from interaction of an evolving landscape with the socio-technical regime; no critical interactions with niche levels.
Substitution	Novelty occurs in a stable regime where it is initially unnoticed but diffuses by linking with the socio-technical regime. The speed depends on landscape factors.
De-alignment / re-alignment	Interaction between the three levels opens up the regime to competition between an incumbent technology path and other options until one dominates.
Re-configuration	Replacement of a set of interlocking technologies by an alternative array that have become linked in hybridised niches. Emergent properties engage landscape changes.

Based on the review in this chapter it is possible to characterise the transition types encountered in past storage transitions. For some of the cases discussed here one needs to consider two transitions. One that drove uptake of storage, and one that terminated its use or changed its role once built.

For batteries in DC networks, their uptake can be described as part of a *re-configuration*. Batteries, originally intended for electric vehicles, became instrumental in shaping the development of early DC networks. They shaped the expansion and viability of DC stations and networks. Later they would be displaced in a process of *substitution*, when alternate-current networks rendered their services obsolete.

The processes that brought about pumped hydro were different. The technology was brought about by the existing regime, without this regime having to undergo fundamental structural changes. It thus fits the model of *reproduction*. The changing landscape affected the way pumped hydro operates within the system by way of *transformation*, without requiring further innovation from niches.

Attempts to bring storage to market in order to aid the long term transition towards low carbon future systems constitute a *re-alignment* of the existing system. Tensions in the regime level as a result of (anticipated) landscape changes are supposed to allow niches to deliver new technological solutions. Existing technologies are not to be directly replaced, but rather complemented by storage. This type of transformation in-

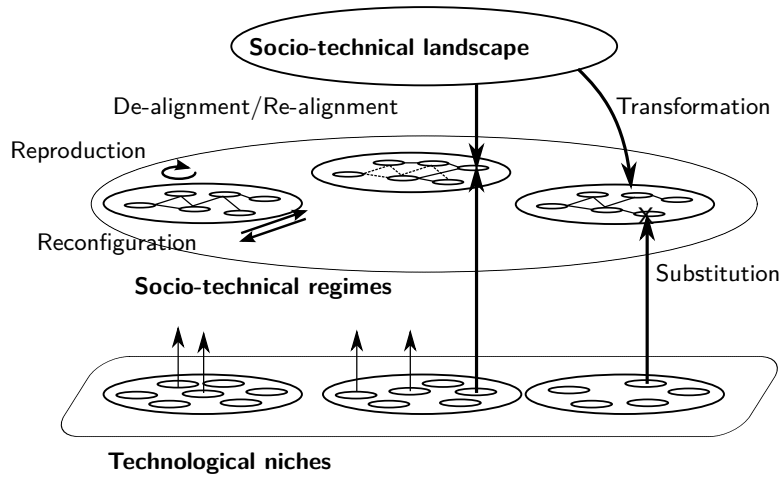


Figure 4.6: Transition routes originating at niche, landscape and regime level.

volves all three MLP levels. Evidently, landscape pressures had neither led to sufficient tensions within the socio-technical regime to stimulate widespread innovation, nor for the Regenesys project to establish itself in the socio-technical regime of the time (RWE regarding it ‘not core business’).

Socio-technical landscape and regimes have changed gradually since the end of the Regenesys project, such that the growing number of innovation projects today still face a *re-alignment* as the underlying transition mechanism.

Without deliberate intent, the cases reviewed here serve as examples of all five of the transition types developed by Geels (2002). This is testament to the complexity involving storage transitions. Their purpose and key actors can differ fundamentally and successful transitions are subject to a large number of external factors.

4.6 Discussion

The review of historic cases of storage uptake has shown that the circumstances under which storage has found a role in the system has changed markedly over time.

Niches developed in different forms, not necessarily driven by the technical performance of storage, but for pertinent external pressures that seemed to make the adoption of the technologies ‘unavoidable’. Similarly, the discontinuation of storage, once it had established itself inside a regime, was primarily driven by changing landscape, rather than a failure to improve technologies further. Batteries have undergone dramatic im-

provements in performance, reliability, size and cost, since their DC network heyday in the late nineteenth century. Yet, the advent of the national grid and a subsequently more diversified system prevented wide spread battery deployment for grid applications from regaining this role for over 100 years.

For some technologies the socio-technical regime is said to be a ‘stabilising force’. For electricity storage, however, with its deeply context dependent functionality, changes in the regime can lead to abrupt changes in its role. New functions and value propositions can emerge, such as the provision of ancillary services for pumped hydro energy, and old ones, such as load levelling for DC batteries can disappear.

Based on these cases, technical performance and cost alone seem to be insufficient guides for technology uptake. This thesis therefore aims to give appropriate weight to the contextual factors, such as the socio-technical regime and the landscape pressures upon it, when assessing the role for storage in the future.

The scale of the three projects reviewed here, supports the notion that the socio-technical regime is also instrumental in shaping technologies. Early batteries were developed on a small scale, analogous to the scale of DC generators. This reflected both technical feasibility and the scale on which investments could be financed. Pumped hydro, on the other hand, was deployed in ambitious, large scale projects, alongside ever larger coal and nuclear power stations, driven by national strategy and in the context of a prevailing consensus that ‘big is beautiful’. Post liberalisation, the Regenesys project returns to what can be termed the ‘utility scale’ of storage. In each case a single dominant regime took charge of the project, rather than collaborative consortia. However, the regime in the Dinorwig case includes generation and the network, whereas by the time of the Regenesys project the network was no longer part of the generation regime. The diverse range of benefits had already been appreciated by the CEGB, and due to their vertically integrated nature, could contribute in full towards the internal commercial justification of the project. Post liberalisation the alignment of the project motivation and the utilities priorities no longer matched in the same way.

The alignment of the socio-technical regimes with respect to storage services will therefore receive particular attention in this thesis.

4.6.1 Relationship of regimes with storage

In early DC networks generators themselves saw the need for storage and drove deployments. As networks expanded the role for storage was no longer merely an subject for ‘generators’ but concerned the overall system operation, including reserve scheduling and network capacity requirements. Its function, thus, became more vertically integrated. At this time the CEGB also was vertically integrated and could make the case for storage on generation and system operation grounds. This vertical integration was no longer present in the case of Regenesys. By then, network and system operation functions were separated from generation. The alignment of RWE with the ‘whole system’ function of storage was not sufficient for their continued involvement to be judged worthwhile.

To recognise the role of different functions of storage in future systems it may therefore be necessary to distinguish between different sub-regimes within the electricity sys-

tem. In response to suggestions that ‘socio-technical regimes are often presented as too homogeneous or monolithic’ (Genus and Coles, 2008), Geels (2011) proposes the use of sub-regimes, which will be adopted here to the electricity system. For the purposes of this study the electricity system is subdivided along three district regulatory and cultural rule sets, into an electricity *generation* and supply sub-regime, a *network* and system operation sub-regime, and a sub-regime of electricity *consumption*. Other sub-regimes such as heat and transport can be expected to strongly influence these sub-regimes as part of a transition towards a low carbon electricity system, and may deserve more explicit consideration in future studies.

The sub-regimes, shown in Figure 6.1, are distinct from one another physically, and also in terms of their distinct sets of rules. This is most noticeable in the type of regulation they are subject to. The electricity *generation* and *supply* sub-regimes operate in regulated, but otherwise broadly competitive markets. The *network* sub-regime constitutes a natural, yet regulated, monopoly. The demand side is mostly unregulated and largely de-coupled from sending price signals back to ‘the system’. This has led to different cultures, skill sets and practices developing in these sub-regimes, which affect their relationship towards new technological solutions and the profitability of those solutions.

The differentiation between these three sub-regimes is intended to provide better visibility of tensions and preferences that could influence the uptake of storage.

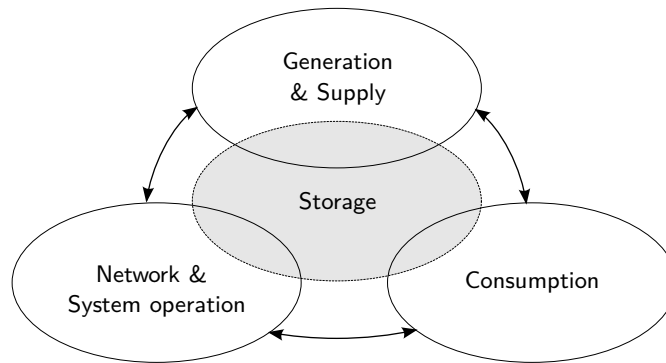


Figure 4.7: *Socio-technical sub-regimes in the electricity system with distinct regulatory and cultural rules. Their interfaces (arrows) represent physical, monetary and service flows. Storage functions would overlap with aspects of all three sub-regimes.*

4.6.2 Protected niches for storage

Past transitions which have been analysed in literature, often led to the narrative that transitions originate in niches (Verbong and Geels, 2007; Geels, 2002). As the examples in this chapter have shown, storage has had periods when such niches existed and deployment subsequently took place. However, storage has failed to become a sustained part of the current socio-technical regime, as has been the case in other studies where niche tech-

nologies became ‘dominant designs’. In the case of storage, landscape changes led to the end of storage deployment at the end of the deployment phases around 1910 and 1980. In the third phase, it can be argued that the socio-technical regimes were not willing—for commercial as well as strategic reasons—to provide sufficient niche-protection.

Grid storage does not suit the narrative of transitions towards ‘dominant designs’. This thesis suggests to view storage as a ‘facilitating technology’, highly dependent on the context in which it operates. The development of dominant designs is more relevant *within* a storage regime, where competing storage technologies rival each other for the delivery of similar or overlapping services. This study, however, focuses on the role of storage within the system more generally, and here the historic failure of storage to establish itself as *part of* existing socio-technical regimes raises questions as to whether creating protected niches is sufficient to deliver on any strategic ambitions to deploy grid storage in the UK.

4.7 Conclusions

This chapter sought to test the applicability of transition theory as part of the analytical framework for the analysis of future transitions of electricity storage. Three historic periods of storage deployment have been reviewed, drawing on the multi-level perspective as an analytical tool.

Each period has been found to exhibit distinct motivations for the deployment of storage and the prevailing socio-technical regime strongly influenced scale, type and success of deployment.

The differences between these historic cases support claims in the literature that different types of transitions need to be differentiated. The five transition types proposed in the literature all appear to have taken place at different stages in past storage uptake or phase out. Most recent attempts to bring storage to market were identified as a re-alignment transition, which has been suggested as a possible mechanism for the development of future transitions. Re-alignments involve all three levels of the MLP. This thesis will therefore require a broad perspective, to capture niche, regime and landscape developments that could affect the role of storage going forward.

The applicability of the framework proposed in Chapter 3, which set out not to view the future role of storage merely as a question of technology development, is supported by the findings of this chapter. Improvements in battery performance have, for instance, not helped this technology to maintain or regain its role for load levelling. Even though a niche application facilitated the establishment of widespread battery use, changes in the system context led to a substitution of its role.

In response to these findings, the following chapters will apply the analytical framework with particular emphasis on understanding the socio-technical regime, its evolution and its tensions in relation to storage, alongside the techno-economic drivers as experienced by private investors. Three sub-regimes of *generation*, *network* and *consumption* emerged from the discussion in Section 6.2.1. These will be adopted in the analytical

framework to explore differences in their relationship to storage and possible tensions between them.

Changes to the structure of the regime level, such as brought about by landscape changes, like the construction of the national grid or liberalisation of markets, fundamentally changed the technical role of storage. They also affected which group would drive its deployment. Distributed generators, centralised operators and utility companies all showed an interest in storage at different periods. Chapter 6 will therefore return to the question of which group may drive future uptake of storage.

The cases further suggest that niches, even if they lead to initial technology uptake, do not necessarily lead to the establishment of sustained roles. The presence of protected spaces may be a necessary, but not a sufficient condition for storage to establish itself in socio-technical regimes. Niches and their role in the uptake of storage will be returned to in the context of support mechanisms for storage in Chapter 7.

In the following chapter the techno-economic drivers for generic storage characteristics are explored for selected future scenarios. These provide some of the context for the relationship of stakeholders to these characteristics, which is dealt with in Chapter 6. Insights into preferences and barriers perceived by different stakeholders allow this thesis to better understand potential tension within the socio-technical regimes, which could translate the techno-economic drivers into technology uptake.

Techno-economic analysis of the commercial value of electricity storage

INVESTMENT IN STORAGE is critical to its deployment, and understanding the uncertainties facing investors is an important component in understanding their decision making processes. This chapter therefore sets out to understand the factors that impact on the commercial value of storage. A time resolved techno-economic model, built on historical wind and demand data, will be developed, discussed and used to identify the sensitivities of the commercial value of storage to investors. Many such modelling approaches have been undertaken with varying degrees of detail and complexity as discussed in Section 2.3. The model presented here is simple in some regards (such as representation of network constraints), but yet sufficiently detailed to explore some of the central sensitivities of the value of storage at the national level, in a more detailed way than has been possible with previous models.

5.1 Model overview

The characteristics of the UK wind resource and its impact on the electricity system are relatively well researched (Gross et al., 2006; Sinden, 2007). Further studies have explored the use of storage in connection with renewable energy systems (van der Linden, 2006; Solomon et al., 2010, 2012; Exarchakos, 2008; Wilson et al., 2010; Weber, 2005), often with a focus on isolated systems. This study specifically chooses to model the integration of storage as part of the grid connected system, as suggested by Korpas and Gjengedal (2006); Barton and Infield (2004) and Anderson and Leach (2004). This approach can give new insight into the relationship between storage operation and system operation at the national level and resulting values for particular ‘types’ of storage.

Two broad approaches have been taken to modelling UK electricity systems. As discussed in Section 2.2.1, system studies tend to employ a holistic and system wide perspective with only coarse temporal resolution. Other studies attempt to understand system balancing with high penetration of wind and issues arising from ramp and slew rates of wind and errors in wind forecasting. These studies require high temporal resolution and therefore tend to simulate short periods of time and make static assumptions for system context. (Black and Strbac, 2007, 2006; Pelacchi and Poli, 2010; Barton and Infield, 2004; Bathurst and Strbac, 2003)

The model in this study fills a gap by positioning itself between the two approaches above. It draws on six years of historical data with high temporal resolution (half hourly to hourly).

Both wind and solar PV are modelled in some detail. To avoid unnecessary complexity and for computational reasons many other aspects of the energy system, which are not essential for this model, are simplified. The model is built on the principle of an idealised energy market, which dispatches energy on a least short run marginal cost basis.

Figure 5.1 gives an overview of the model structure. Time resolved data for meteorological resources and power demand form the basis for the decision to charge (buy) or discharge (sell) storage. The operating strategy is to provide arbitrage, by buying at low prices and selling at high prices, without other sources of revenue.

For analytical simplicity, the UK network is assumed to be a single bus system (a ‘copper plated island’), meaning that demand can be met by generation, independent of its physical locations and free of network constraints or losses. For the purposes of storage assessment this assumption provides a worst case, since transmission and distribution constraints can be expected to make storage more favourable during times of congestion between regions. Recent modelling by Strbac et al. (2012) further suggests that transmission constraints are unlikely to contribute significantly to the value of storage. Compared to the cost of storage, reinforcing transmission networks is relatively cheap. The same does not hold true for distribution networks, which will be discussed separately in Section 7.1.

The model does not perform asset allocation. It sets out with a given plant mix based on the scenario being simulated. The only change to this plant mix is that peaking capacity can be displaced by storage capacity. For high penetrations of storage one would expect that the plant mix could be re-optimised, which would require a systems model approach and is not part of the capabilities of this model. For small levels of storage penetration the resulting error is expected to be small compared to other uncertainties discussed in Section 5.6.

The model in Figure 5.1 can be used in two different modes. In the technology agnostic form, the economic parameters of the storage system can be omitted and the values generated are *gross values*. These are expressed as £ per kW of storage per year. These figures are generic and can be applied to a range of technologies of varying cost and life expectancy. A pumped hydro installation could for instance be characterised as follows:

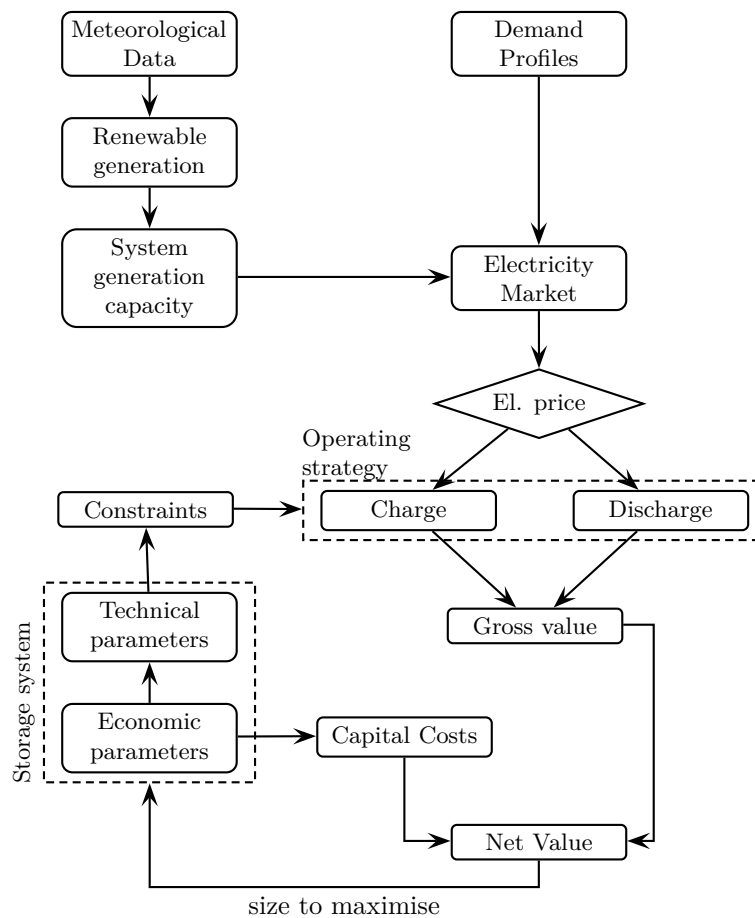


Figure 5.1: Flow chart of the techno-economic model. A time series of storage charge and discharge is built up from renewable resource and demand data. The NPV is calculated from costs of a given storage system and the revenues from operation within the constraints for power and energy capacity.

Economic life	n =	20	years
Discount rate	r =	10	%
Discount factor	a =	8.51	
Capital cost	CapEx =	560	£/kW

If the gross value is above annualised cost of £65.77 per kW per year ($CapEx/a$), this technology becomes viable.¹ Technologies with a shorter expected life would need to deliver higher annual returns.

This approach fulfils the aim of being technology agnostic and is used in Section 5.3 to characterise the generic trends behind the gross value of storage within energy mar-

¹Operating and maintenance costs may also be incurred and should be deducted. For the purposes of this study such costs are assumed to be negligible.

kets. What this approach does not allow, is to optimise the storage configuration. In Section 5.4 the energy and power related costs of selected storage technologies will therefore be included in the economic parameters, and the solver selects the best scale and configuration for each by maximising the net present value (NPV) of storage. The NPV method has been chosen over a levelised cost approach, to ensure that investment risks arising from changes in revenue can be better reflected. (Anderson, 2007)

5.1.1 Storage representation

Storage economics

The economics of a storage plant are mostly analogous to those of a conventional plant, with the notable difference that the primary energy (E_{in}) is traded in the same market as the final product (E_{out}).

For a storage system to be economically viable within a wholesale market, a positive NPV has to be achieved from

$$\sum_t (1+r)^{-t} (\pi_{out} E_{out} - \pi_{in} E_{in}) - C \geq 0 \quad (5.1)$$

where, π_{in} and π_{out} is price of electricity at the time of charging and discharging respectively, and C is the capital cost of the storage installation. The amount of energy charged and discharged is developed as a time series in 30 min intervals. The power flows are constrained by the power of the storage system, while the amount of energy flowing in and out of storage is limited by the storage level in that interval and the storage capacity.

The profitability of a storage investment therefore depends not on a ‘spark-spread’, as given by the difference between gas and electricity prices, but the spread between the price of electricity at the time of charging (π_{in}) and discharging (π_{out}). We shall call this the π -spread

$$\Delta\pi = \pi_{out} - \frac{\pi_{in}}{\eta_{sys}} \quad (5.2)$$

for a system with a round trip efficiency of η_{sys} . The total amount of energy delivered from a storage installation is

$$E_{out} = c \times E \times DoD \times \eta_{out} \quad (5.3)$$

where c is the number of charge/discharge cycles per year, E is the installed storage capacity, DoD is the mean depth of discharge per storage cycle and η_{out} the discharge efficiency. For a given amount of energy output, the energy required to charge the system is

$$E_{in} = \frac{E_{out}}{\eta_{in} \times \eta_{self}^{\Delta t}} \quad (5.4)$$

where the product of charge efficiency (η_{in}), discharge efficiency (η_{out}) and self discharge losses with storage duration from $\eta_{self}^{\Delta t}$ make up the total round trip efficiency of the system

$$\eta_{sys} = \eta_{in} \times \eta_{out} \times \eta_{self}^{\Delta t} = \frac{E_{out}}{E_{in}} \quad (5.5)$$

The capital cost of a storage system (C) is calculated from the energy related costs (C_E) and the power related cost (C_P) for a given technology. Some scale independent fixed costs (C_{fix}) may also apply, but these are assumed to be small in comparison and will be neglected here.

$$C = C_{fix} + C_E \times E + C_P \times P \quad (5.6)$$

The choice of discount rate (r) can severely affect the relative attractiveness of projects with high upfront costs or high running costs. Furthermore, the discount rate may need to reflect the economic risk and the cost of finance. Network infrastructure, for instance, is perceived as low risk, since both technology and processes are well established. Furthermore, returns are regulated and thus bear low risk. Generation assets, conversely, seek investment in a market environment that demands higher interest rates. For storage this study uses a moderate discount rate of $r = 6\%$ as a default, which places it between the social discount rate laid out in the Green Book and typical commercial rates. The economic lifetime of 20 years also fits between these two positions. Initially these parameters are used to allow a comparative study between the technologies considered here. The impact of changes to these values is considered in the sensitivity analysis in Section 5.6.1.

With the discount factor (a) given by the economic life time (n) and the discount rate (r)

$$a = \frac{(r + 1)^n - 1}{r(r + 1)^n} \quad (5.7)$$

and the π -spread definition (5.2), the condition 5.1 can be combined to

$$\Delta\pi E_{out} - \frac{C}{a} \geq 0 \quad (5.8)$$

As shall be shown later, the implicit assumption (common for conventional plant) that $\Delta\pi E_{out}$ is consistent over years, requires further scrutiny, because utilisation changes depending on demand patterns and the renewable resource of each year. Secondly, the π -spread depends on system efficiency. Unlike for coal or gas plants, where standard efficiencies are used to calculate spark-, dark- or clean-spread, storage technologies are more diverse, as shown in table 5.6. The economic importance of efficiency depends on the expected price of electricity. From (5.8) and (5.2) the minimum efficiency condition for a positive NPV can be written as

$$\frac{\pi_{in}}{\pi_{out} - \frac{C}{aE_{out}}} \leq \eta_{sys} \quad (5.9)$$

which suggests, that for a system operating on low cost excess electricity, the efficiency can be somewhat lower. It should be noted, however, that with low efficiency, more storage capacity is required to deliver the same E_{out} and thus the system costs increase. The exact relationship between storage capacity and the energy delivered from storage depends on the environment in which the storage system operates. The time resolved approach described in Section 5.1.1 will be used to gain further insight into the importance of efficiency for the overall value of storage.

Storage time series

Storage is represented as a time series of energy flows for 30 min periods (Δt). Positive flows feed into storage, whilst negative flows represent energy removed from storage. The flow, $f_{(t)}$, is constrained by the power P_{str} of the storage system

$$-\frac{P_{str}}{\eta_{out}} \leq f_{(t)} \leq P_{str} \times \eta_{in} \quad (5.10)$$

The amount of energy flowing in and out of storage in each time period is further limited by the storage level at the time, $S_{(t)}$, which is constrained between 0 and the storage capacity E .

$$f_{(t)} = \begin{cases} \min\left(\frac{(E-S_{(t-1)})}{\Delta t}, \Delta P \times \eta_{in}\right) & \text{if } \Delta P > 0 \\ -\min\left(\frac{S_{(t-1)}}{\Delta t}, \frac{-\Delta P}{\eta_{out}}\right) & \text{if } \Delta P \leq 0 \end{cases} \quad (5.11)$$

where ΔP is the external grid request to provide load ($\Delta P > 0$) or power ($\Delta P < 0$). From this flow the storage content can be developed as a time-series with

$$S_{(t)} = S_{(t-1)} \times \eta_{self} + f_{(t)} \times \Delta t \quad (5.12)$$

The flow can be seen as a storage internal process. What the external energy system experiences is the load delivered or taken by storage ($P(t)$):

$$P(t) = \begin{cases} \frac{f_{(t)}}{\eta_{in}} & \text{if } f_{(t)} > 0 \\ f_{(t)} \times \eta_{out} & \text{if } f_{(t)} \leq 0 \end{cases} \quad (5.13)$$

The gross value of storage is the sum of all transactions where the energy consumed is charged at the market price ($\Pi(t)$) at the time and energy delivered is rewarded as

$$V_{str} = \sum_t P(t) \times \Delta t \times -\Pi(t) \quad (5.14)$$

The representation of wholesale market prices is explained in Section 5.1.2 and relies on a division of the electricity supply system into broad classes of generation as described below.

Generation capacity classes

To obviate the need to construct a complex market allocation model, which is not necessary for the exploratory analysis carried out here, the energy system is modelled around four generic types of generating capacity. These are characterised by their operating strategy and ability to dispatch energy. The following list describes their position in the merit order.

Uncontrolled / variable capacity: Most renewable technologies are characterised by high capital and low running costs. They will therefore aim to dispatch their energy

whenever possible. With additional policy incentives for generation, some of these technologies might even choose to generate at negative electricity prices. Other than curtailment, their output is not influenced by the system.

Inflexible / baseload capacity: This capacity chooses, for technical as well as economic reasons, to operate at high and consistent load factors. Baseload generators, as defined in this model, are therefore the sum of output that would stay on the system, even during a temporary drop in electricity prices.

Flexible / mid merit capacity: These technologies can respond to changes in demand more quickly and cheaply than the storage technologies considered here. This can include flexible portions of the baseload generators, i.e. their spinning reserve.

Peaking capacity: Capacity that is required on the system to ‘keep the lights on’. These may well operate under unfavourable commercial conditions. Their load factors may be low and the need to respond to sudden changes in demand could require fast ramping. In the absence of capacity payments, these plants depend on the financial incentive of temporally high electricity prices to be kept on the system.

Different forms of capacity can be part of the same physical asset. A plant may for instance run part of its capacity in base load, but reserve some capacity to respond more flexibly to price signals.

An example of the generation and demand profiles over a three week period is shown in Figure 5.2. During high wind periods, peaking capacity operates little and storage charges during low demand periods, when prices are lowest. Storage discharges at low wind periods, either by supporting ramping up or reducing peak load.

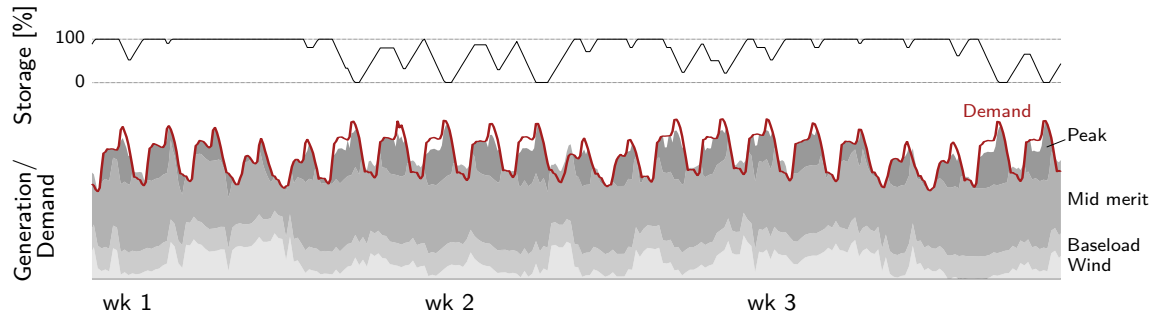


Figure 5.2: Generation and demand profiles with the resulting level of electricity held in storage. Illustrative example for three weeks in August. Base case scenario with 30 GW installed wind and 10 GW 6 hour storage.

5.1.2 Representation of wholesale price setting behaviour in a competitive electricity market

The wholesale price at which storage charges and discharges is calculated based on work by Green (Green and Vasilakos, 2010a, 2007, 2010b) and Eager (Eager, 2010; Eager et al., 2010). The price setting approach assumes that peaking plants are price setters. During periods of high demand, fewer participants remain with spare generating capacity, which puts these actors in a stronger bidding position to mark up the wholesale price. One can equally reverse the perspective and argue that peaking plants only operate during periods of high demand and thus have to mark up the offer price sufficiently to recoup the capital expenditure on their investment. The lower the load factors for these plants becomes, the higher the markup during these periods has to be. In the absence of such price spikes these plants are not economically viable, retire and risk supply shortages and blackouts.²

The same principle, which drives up prices during supply shortages, can be applied at the opposite end of the price duration curve. If demand is low and plant with high short run marginal cost are no longer operating, any further reduction in generation requires plant with low short run marginal costs (and thus little incentive to curtail output) to reduce generation. The bidding position is now reversed in that bidding takes place on the price at which these actors are willing ‘not to generate’. As in the example above, the less capacity remains, the stronger the bidding position for those remaining actors and market prices can depart significantly from the marginal cost—this time the prices are driven down and could even become negative. The symmetry between marking up and marking down of wholesale prices allows for a single function to describe both phenomena.

The function to calculate the uplift U , which describes the factor by which wholesale prices exceed the short-run marginal costs of generation, consists of a proportional term (κ) and an exponential term (α)

$$U_g(t) = 1 + \kappa \times e^{-\alpha \left(\frac{C_g - P_g(t)}{C_g} \right)} \quad (5.15)$$

where g denotes the class of generator in the merit order (e.g. peaking plant, or wind). The multiplier in the exponent is a measure of the ‘slack’ in the system. C_g is the installed capacity of this class and $P_g(t)$ denotes the output of this class at time t . Analogously, during periods when demand is low, C_g is the capacity remaining on the system and P_g is the curtailment required from this class.

The short run marginal cost of generation is the cost a generator experiences for delivering an additional unit of energy, or the amount saved by not doing so. From this uplift function the wholesale price Π at time t can be calculated from the marginal cost $\dot{\pi}_g$ as

$$\Pi_g(t) = \dot{\pi}_g \times \left[1 + \kappa \times e^{-\alpha \left(\frac{C_g - P_g(t)}{C_g} \right)} \right] \quad (5.16)$$

²The extent to which uncertainty over future earnings can inhibit resource adequacy despite such price signals has been studied by Eager (2010) and is discussed in (Grünwald et al., 2011b).

Table 5.1: Merit order of short run marginal costs for broad generation classes. Based on Green et al. (2011) and MacDonald (2010). (ROC=value of renewable obligation certificate)

Merit order (g)	Plant type	$\dot{\pi}$ [£/MWh]
1	Wind	-ROC
2	Base load	8
3	Mid merit	20*
4	Peaker	30*

* A premium of 10£/MWh applies for CO₂ abated plant.

The uplift function is only applied to the extremes of the merit order. Mid merit plants are bound by the marginal costs of their ‘neighbouring’ plants in the merit order stack. Their minimum bid is their own short run marginal cost and the maximum markup they can realise in a competitive market is the short run marginal cost of the next more expensive plant ($\dot{\pi}_{g+1}$). Between these two points a linear relationship of output and wholesale price is assumed.

$$\Pi_g(t) = \dot{\pi}_g + \left[(\dot{\pi}_{g+1} - \dot{\pi}_g) \frac{P_g}{C_g} \right] \quad (5.17)$$

If one assumes a system with n classes of plant, the price function can be written as a combination of 5.16 and 5.17 as

$$\Pi(t) = \begin{cases} \dot{\pi}_g \times \left[1 + \kappa \times e^{-\alpha \left(\frac{C_g - P_g(t)}{C_g} \right)} \right] & \text{if } g = n \\ \dot{\pi}_g \times \left[1 + \frac{\dot{\pi}_{g+1} - \dot{\pi}_g}{\dot{\pi}_g} \frac{P_g}{C_g} \right] & \text{if } 1 < g < n \\ \dot{\pi}_g \times \left[1 + \kappa \times e^{-\alpha \left(\frac{C_g - P_g(t)}{C_g} \right)} \right] & \text{if } g = 1 \end{cases} \quad (5.18)$$

Table 5.1 lists the generation classes by merit order of their short run marginal costs and their installed capacity.

The values for κ and α are calibrated against observed market data. They are neither universal nor do they constitute values grounded in economic theory. Studies employing this approach, including Redpoint (Redpoint, 2007) and Pöyry (Cox, 2009), use empirical data to calibrate the uplift function, using *observed* values from electricity price settlements in the present market. The price setting taking place in the market is the result of complex operations and involves a hard to quantify element of human decision making. Changes in market power, for instance, could affect the behaviour of traders in the market and change the uplift function. A degree of caution is therefore

necessary when projecting from presently observed price uplift behaviour onto future systems. The impact of changes in assumptions on price uplift are examined in Appendix A.1.2, which concludes that modest increases (up to around 9%) to the value of storage can be expected if the competitiveness were to increase, while a less competitive market environment with a flatter price uplift could reduce the value of storage in some instances by around 30%.

In this study the value for α is calibrated against price duration curves in literature published by Cox (2009), Green and Vasilakos (2010a) and Eager (2010). An α of 4–4.5 broadly agrees with these studies. The κ value is established following the principle outlined above, stating that the price uplift must be sufficient to keep the peaking plants commercially viable. This condition is translated into a 95% confidence by the investor that the net present value of the investment is positive. To test this condition a normal distribution of probable future values is assumed, with fuel prices as the source of uncertainty. The gas price projections are based on DECC estimates and listed in Table 5.2.

Table 5.2: *Gas price forecasts for 2030 based on DECC (2011a)*

Estimate	Cost [£/kWh _{th}]
Low	12
Central	24
High	34

From the distribution of net present value the value which will be exceeded with 95% confidence can be written as

$$V_{CI_{95}} = \bar{x} - z_{90}^* \times \sigma \quad (5.19)$$

where $\bar{x}$ and σ are the mean and standard deviation of the net present values for a peaking plant respectively. z^* denotes the boundaries of the confidence interval. For a 90% confidence interval $z_{90}^* = 1.645$ (Simon, 1986), such that the lower boundary excludes 5% of the distribution and the confidence of future NPV to be above this level is 95%. The uplift function must be tuned for this point on the probability distribution to coincide with an NPV value ≥ 0 . Figure 5.3a shows how changes to the κ value of the uplift function shift the price duration curve and thus change the NPV expectation for peaking plants, displayed in Figure 5.3b.

The price uplift functions for increasing levels of wind are shown in Figure 5.4. High levels of wind spread the price duration curve at both ends, with extreme values reaching up to £10,000/MWh on some occasions.

This approach provides a simple, yet powerful method to model price volatility for storage to operate in. It does assume that the fundamental price setting dynamics do not change: peaking plants remain price makers and storage acts as a price taker.

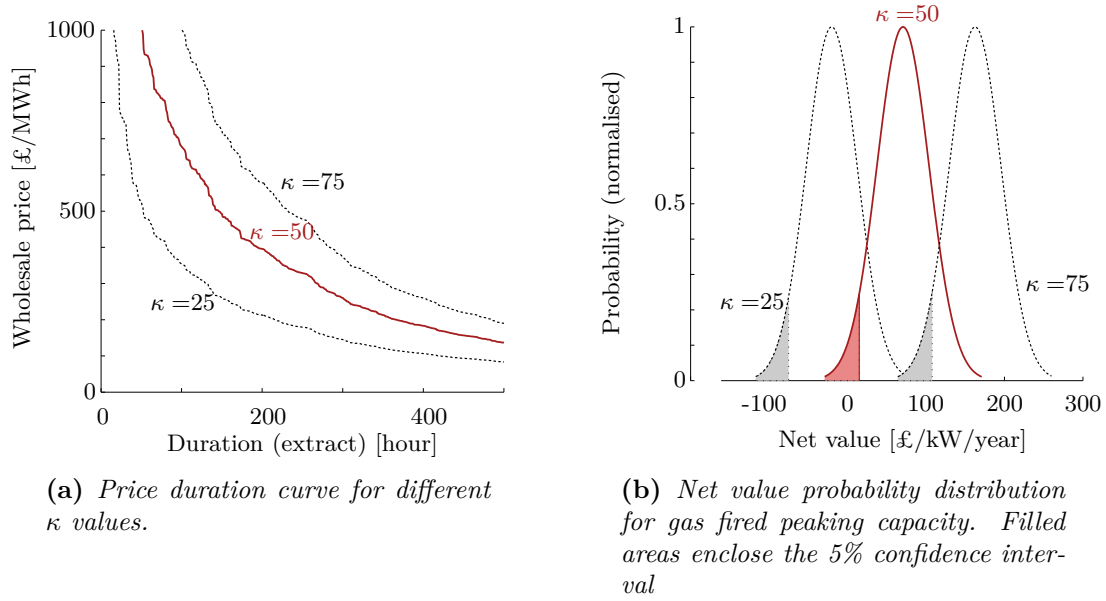


Figure 5.3: The κ value of the uplift function shifts the price duration curve and thus the revenue for peaking capacity operating in this price zone. Here, with $\kappa \geq 50$, the confidence in a positive NPV is $\geq 95\%$.

Furthermore, the scenarios and their plant mix feeding into this model were derived without consideration of the possible integration of electricity storage. It is therefore conceivable that storage, rather than added as an afterthought, should be included in the scenario development, which could shift the optimal plant mix. Such holistic feedback of storage on the plant mix is beyond the scope of this study.

For high penetration of storage this approach may require refinement, if absolute values are to be derived. In this study the evaluation is more focused on trends, for which the assumptions are expected to be sufficient.

5.1.3 Model implementation

The model has been constructed in Matlab R2011b, building on the standard libraries and toolboxes. Several optimisation steps are performed as part of the techno-economic analysis. Combining all of these optimisation steps into a single objective function would create a multidimensional and therefore challenging optimisation problem. Instead the problem has been decomposed where appropriate.

Some of the optimisation steps are independent from each other and could be performed as a one off, such as the distribution of the wind power portfolio. Others, such as the tuning of the price uplift function and the gross value optimisation of storage are interdependent and are therefore performed iteratively.

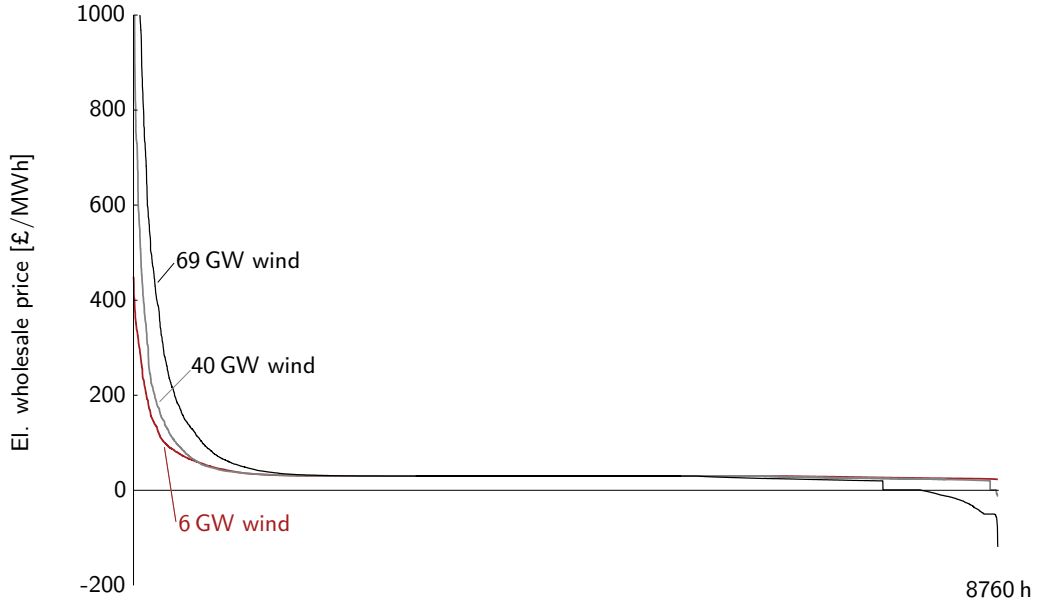


Figure 5.4: Price duration curves for different levels of wind deployment. Graph is capped at £1000/MWh. For high wind cases prices can reach up to £10,000/MWh at peak hours.

An overview of the optimisation steps is given in Table 5.3. The computation times refer to a 1.8 GHz Intel Core i5 processor with 4 GB 1.6 GHz DDR3 memory. Of these four discrete optimisations the price uplift and gross value optimisation are dependent on each other and both need to be solved for a given run. In some repetitive optimisations κ values are recorded as a look up table. This avoids simultaneous solving of the combined, higher dimensional, problem and thus speeds up the computation time from in excess of 10 minutes to less than 20 seconds per run.

Table 5.3: *Optimisation steps and solvers used as part of the techno-economic assessment.*

Optimisation	Objective Function	Method / Comment
Wind site allocation (Appendix A.1.1)	$\min_s D_w = D(t) - \sum_s W_s(t)$	Iterative solver algorithm for 16 sites (s) with 8760 time steps (t). This optimisation is only performed once, which allows for a slow solver algorithm to suffice. With an exit condition of less than 1% change on at least 3 consecutive iterations, the processing time amounted to around 2 minutes.
Price uplift (Section 5.1.2)	$\min_{\kappa} V_{CI_{95}} = [NPV_{pk}(\kappa) - (z_{90}^* \times \Sigma_{NPV})]^2$	Seeks the price uplift factor κ at which the marginal generator has a 95% confidence of a NPV greater than zero. Performed independently the optimisation with the unconstrained nonlinear optimisation function (fminsearch employing the Nelder-Mead Simplex Method) converges in less than 3 seconds.
Gross value (Section 5.3)	$\min_{f(t)} -V_{str} = -\Pi(t) \times f(t)$	The flow in and out of storage ($f(t)$) is itself a function of the wholesale price ($\Pi(t)$). The optimisation is therefore a nested process: for a given price profile the storage operation is optimised by setting a price threshold for charging and optimising the corresponding sales/discharge price using the same solver as for the price uplift. Buy and sell thresholds are iteratively optimised until the termination tolerance of $1e^{-4}$ is reached. From the new demand profile (including the flows in and out of storage) a new price profile is calculated on which the objective function is evaluated. For a one year profile with 8760 data points, the gross value (excluding the price uplift optimisation) converges in approximately 20 seconds.
Scaling storage power and energy (Section 5.4.2)	$\min_{P_{str}, E_{str}} -NPV = C_P(P_{str}) + C_E(E_{str} - \Pi(t) \times f(t, E_{str}, P_{str}))$	Storage power and energy are optimised concurrently as two combined and constrained nonlinear optimisation functions (both Matlab fminsearch functions). The bounds are set and adjusted to expected ranges to speed up the convergence. Depending on these ranges an optimisation for one year of data with 8760 readings can take between 4 and 20 minutes.

5.2 Model inputs and validation

5.2.1 Input data

Scenarios

The core scenario for this study is based on the DECC Grassroots scenario, which is described by DECC as

A (tacitly) high fossil fuel price pathway where the public embraces high energy demand reductions and multilateral innovation drives reductions in renewable technology costs, bringing them on an economic par with other forms of low carbon generation.

Etheridge (2011)

This scenario comprises a high share of renewable generation, which of interest, because it allow this study to explore the relationship between high levels renewable generation and the commercial value of storage. The generation mix of this pathway is shown in Figure 5.5.

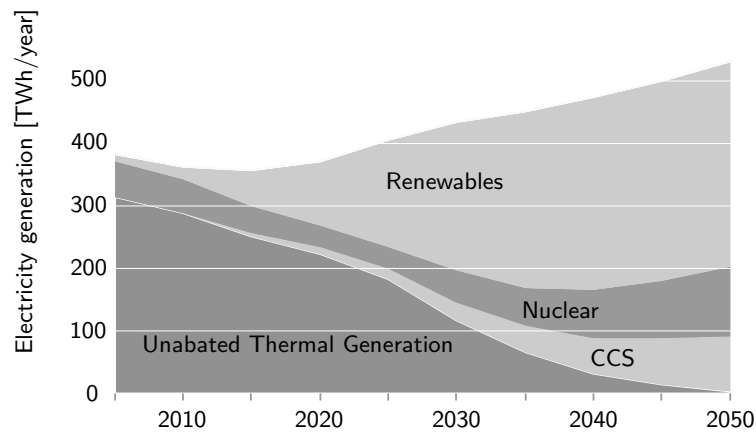


Figure 5.5: *Electricity generation by plant type in the Grassroots scenario. Based on DECC (2010a)*

Other scenarios develop very different pathways. Two technology options that could deliver carbon reductions aside from renewables are nuclear and CCS. Two pathways, favouring these options have been adopted for use in this model. The relative share of each generation class is shown in Table 5.4. The nuclear pathway has the highest share of base load capacity. The marginal costs of generation in Table 5.1 have been adjusted for the CCS scenario to account for higher running cost of abated plants. Both mid-merit and peaking capacity carry an additional £10/MWh.

The capacity mix is not re-optimised by the model in response to the presence of storage. For small amounts of storage this is expected to have a minor impact on results. As the penetration increases, wholesale market prices become more affected (flattened), and thus changes the relative attractiveness of base load and peaking plants and so may necessitate re-allocation. This is not part of the scope of this study. Cases with high penetration of storage should therefore be treated with some caution.

Wholesale prices act as the sole source of revenue in the model. Network constraints are not necessarily well represented through wholesale prices, since they apply nationwide and can therefore not directly reflect transmission or even distribution constraints. It is conceivable that a constrained system will see greater price volatility, since fewer plant are available to provide services under constraints. If, for instance, a north south constraint limits supply from Scotland to England, power stations south of the constraint are in a position to charge more for their electricity. The location of plants on the system is, however, not included in the model.

Intermittent sources

The penetration of intermittent renewable sources of electricity is seen as central to the case for the deployment of storage. The model therefore has to represent the timing and scale of the dispatch of such sources with a high degree of accuracy. Two approaches can be considered to develop time series of intermittent sources: statistical representation and historical data. Both have found application in relation to intermittent sources (Sinden, 2007; Coker, 2011; Cox, 2009).

The former has the advantage of high flexibility and adaptability. Parameters can be manipulated to simulate particularly windy or unusual weather constellations and interregional correlations of profiles, and thereby ‘stress test’ the system. However, it is difficult to establish the validity of such data without extensive analysis against historical data. Furthermore, correlations between weather and electricity demand have to be established and statistically included in the simulation, as these could affect the

Table 5.4: *Capacity mix for core scenarios in 2030. Based on DECC (2010a) and Strbac et al. (2012)*

Plant class	Share of conventional generation [%]		
	Grassroots	Nuclear	CCS
Baseload	14.7	35.4	12.9
Mid merit	53.7	24.0	53.3
Peaking	31.6	40.6	33.8
Renewables	60.0	9.4	18.0

value of storage.³

Historical data, while limiting the range of analyses that can be performed, have the advantage to include any correlation between regions and, if combined with historical demand profiles, any correlation with demand, too. This study therefore builds upon historical data for the period 2003–2009.

Extensive historical data are available from the British Atmospheric Data Centre (BADC) server (UK Meteorological Office, 2006). The selection and distribution of power between wind sites has been diversified, such that the requirement for storage is minimised. The solver algorithm iteratively redistributes the relative distribution of a given amount of wind power across a set of GB sites. On each iteration the amount of demand that can be met from this portfolio (without having to be curtailed) is calculated. The solver seeks to maximise this amount by incrementally refining the optimal distribution. The process is terminated when the reallocation of capacity becomes less than 1% of the total wind power. The allocation of sites is shown in Figure 5.6. Out of a shortlisted 16 sites, only four are selected by the solver to optimise the diversity of the wind resource. Appendix A.1.1 gives more details of the selection process and the resulting wind profiles. The relatively small number of sites required to reach optimal levels of diversity has since been confirmed by Green and Staffell (2012), who approached diversity as an optimisation of financial performance of a portfolio of wind sites.

Demand profiles

For consistency with the data on intermittent sources, demand profiles are also based on historical data and cover the same period of time. As with the wind data, historical demand data avoid the need for sometimes arbitrary parameterisation. This does however limit their use in some significant regards.

Most data available for the UK are highly aggregated and do not allow the representation of local phenomena. This limits the scope to represent network constraints and also blurs different roles for storage in areas with distinctly different profiles throughout the year, such as commercial areas with high air conditioning loads in summer, and residential areas with high heating and lighting loads in winter. This is a shortcoming of the data, which could not be overcome.

Information on historical UK electricity demand is available from the National Grid (National Grid, 2010). A duration of 6 years (2003–2009) with half hourly resolution of these data is available for this model.

The demand data have a mean of 36.3 GW and a peak of 59.9 GW. Demand is scaled to suit the demand growth projections of the scenario. Changes in profiles, especially relating to the uptake of new technologies, such as electric vehicles and heat pumps can not be incorporated into aggregated historical demand data without a bottom-up representation of demand, which is not available in this study.

The demand profiles for the 6 year period can be found in Appendix A.1.4.

³see Appendix Figure A.10 for correlation between wind resource and demand based on the data used in this study

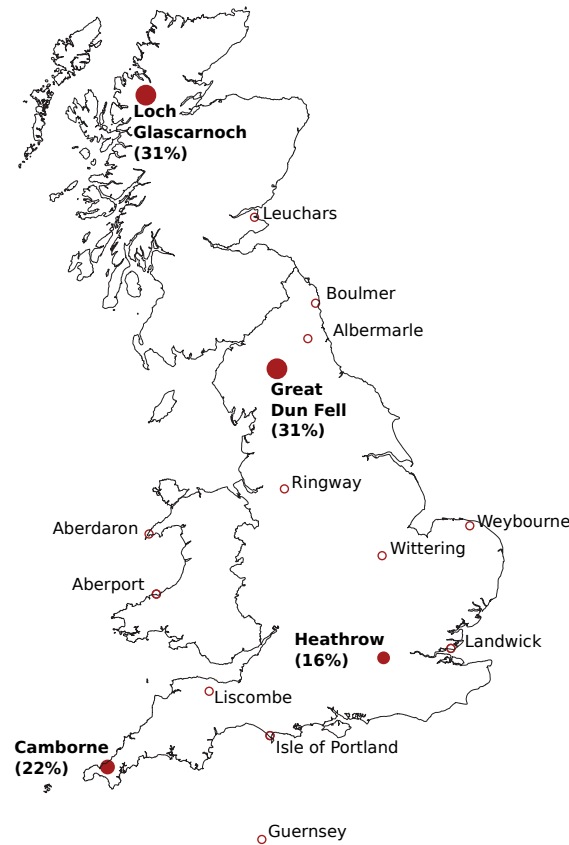


Figure 5.6: Location of Met Office land based weather stations providing hourly wind speeds. The locations selected for optimally diversified wind resource are marked in bold with their respective share in brackets. Map: Ordnance Survey ©Crown copyright 2010.

5.2.2 Validation and model limitations

The techno-economic model has undergone several stages of iterative development and improvement, based on feedback from stakeholders, emerging research questions and in particular after detailed discussions as part of the Strbac et al. (2012) study. The modelling approach has been subjected to peer review at several stages through seminar presentations (Grünewald, 2010a,b,c,d,e)), working papers (Grünewald et al., 2011a; Grünewald, 2012) and discussions with experts in the field. During each stage of development the code was subjected to a series of tests and validation procedures. These are explained in more detail in Appendix A.2.

Model validation was performed in the following sequence:

Mathematical integrity Testing whether the model converges within specified ranges for key input parameters. Includes tests with small changes ($\pm 10\%$) and extreme

inputs (-65536, 0 , 65536).

Data validity Testing input data for consistency by comparing data subsets (e.g. all January weekdays) and other sources of data. Large datasets have further been subjected to visual analysis (see for instance Appendix A.1.4 and A.1.1).

Output validity Ensuring that model outputs are consistent with functional expectations and in agreement with observed trends.

Results of all three stages of validation are shown in Appendix A.2.

The data validity testing included a comparison between different sources and types of wind data. External data sets for offshore wind profiles have been compared to the data developed for this model and results for model sensitivity are shown in Appendix A.1.3.

Given the exploratory purpose of the model, output validation with measured experimental data is not always possible. Instead, model output has been compared with key past conditions for which results are (at least in relative terms) known.

Section A.2.1 includes two cases from the historic review in Chapter 4: DC batteries and the Dinorwig project. The load profiles during batteries deployment in the late 19th century lead to high values when applied to this model, and the conditions anticipated during the build of Dinorwig are broadly consistent with the value proposition stated by the CEGB at the time (modelled value: £713/kW, cost estimate: around £560/kW). The present marginal value of additional storage is low ($\leq$ £2/kW/year), which is also consistent with the investment level experienced today.

These historic validation ‘snapshots’ are complemented by a systematic parameter analysis. Here, expected outcomes are recorded *a priori* for a range of parameter changes and contrasted with observed model outputs. Results are shown in Appendix A.2.2.

The validation exposed some limitations in the applicability of the model, but broadly confirmed its adequacy for the purposes of this study.

Omission of network constraints

A significant simplification of the model is the representation of the GB network structure as a single bus. This decision was taken to keep the model complexity manageable within the practical limitations of this study.

The absence of a network model means that the simulation is blind to the effect of local network constraints, which could further add to the value of storage in affected regions, implying that the estimated values of storage from the model are relatively conservative. The Strbac et al. (2012) study also chose to simplify the network infrastructure to a system with initially two and later five regions. They concluded that the impact of transmission representation on storage is minor.⁴ This is not to suggest that transmission constraints do not add significantly to the value of storage, but rather that

⁴Based on Ofgem approved figures for overhead transmission line costs of £35k per km.

the cost of reinforcing transmission networks is so much cheaper than storage, that the former would be chosen over the latter in most cases.

For distribution networks the situation is different. Here the reinforcement costs can be such that storage might be considered as an alternative solution. The explicit evaluation of these values through a network model, would require both detailed disaggregated demand data and the network topography for a specific region. The results are therefore highly location specific (see KEMA (2010b)) and do not lend themselves to the general evaluation of the role of storage attempted here.

For storage technologies that can be connected at the LV distribution level, Strbac et al. (2012) find a consistent value of around £50 per kW installed. This value can therefore be seen as a conceptual undervaluation of distributed storage applications in the absence of a detailed distribution network model.

Islanded system

The model does not include any interconnects to neighbouring countries. This is an omission due to the added complexity which the representation of neighbouring energy systems would have required.

Interconnects are argued by some to act as an alternative to storage, citing possible connections to the pumped hydro capacity in Norway and increased links with mainland Europe (UKERC Meeting Place, 2011b). The effect of interconnects on energy markets are complex with some counterintuitive effects, such as increased prices in markets connecting to the GB network and—in some instances—even increased need for storage, due to additional arbitrage opportunities.⁵ Strbac et al. (2012) concluded that, while interconnects can reduce the market size for storage, the effect on the value of storage is less pronounced.

Simplified representation of dispatch

The translation of scenarios into generation classes is somewhat subjective, yet changes to the assumptions made can have a significant impact on the value of storage, as will be shown in Section 5.3.6. The plant mix is therefore not altered when making relative comparisons between model runs.

The abstraction of treating the electricity system as a simple ‘economic wholesale market’, ignores a great many subtleties in the way electricity systems function in practice. Scheduling of reserve capacity, dealing with planned and unplanned plant outages, errors in demand forecasting and any location specific considerations are not included in the model. Some of these are instead considered in the socio-technical discussion.

⁵Interconnects with Ireland were shown by Strbac et al. (2012) to lead to a higher value of storage in the UK as it would be able to ‘export’ storage services via an interconnect to the more volatile Irish market.

Sensitivity to demand profiles

The integrity of the demand profile data has been tested and appears reliable. However, demand profiles might change in future as a result of systematic changes in user behaviour and adoption of new technologies. Electrified transport and heating could have a pronounced effect on future profiles. Projections of their impact can be contradictory. Some claim that they exacerbate the need for storage by adding proportionally more to peak load than to average load (Dyke et al., 2010), others see them as part of the solution by providing inbuilt storage (Kempton and Letendre, 1997; Ault et al., 2008). In the absence of a consensus, this study works with recent historic profiles and returns to the effect of additional flexibility in the demand profiles in Section 5.5.2.

A further limitation of the demand profiles is the lack of regional disaggregation. While the transmission between regions may not be a significant source of revenue, as discussed above, regional demand patterns may nonetheless be less smooth than national profiles. The effect of less diversified profiles may thus lead to higher values for storage and specifically favour particular regions for early adoption. Such data has, however, not been available for this study.

5.3 Gross value of storage

This section reviews the results from the techno-economic analysis for future UK scenarios. First, generic results on the gross value for storage are presented, before in Section 5.4 selected technologies are analysed to assess the prospect for bulk storage in the UK.

5.3.1 Storage value increase with wind deployment

Intermittent generation increases the volatility of electricity prices, which could add to the value proposition for storage. Figure 5.7 shows the increasing gross value of storage for the base case scenario with increasing amounts of wind.

At present levels of wind the value is not sufficient to stimulate further investment, and even at around 20% of total installed capacity (16 GW of wind) values do not increase substantially. At 32 GW of wind deployment, the gross value begins to exceed £100 per kW per year, which is roughly the level of present technology options. With further expansion of wind capacity the value increase begins to level out.

As explained in Section 5.1 the model cannot perform any re-optimisation of the plant mix. For consistency the results shown in Figure 5.7 have the same underlying generation mix. Peaking capacity is reduced as the wind capacity increases, but only by a small amount, in line with the capacity credit of wind, to maintain security of supply. The value of storage may further benefit from a reduction in base load and mid merit capacity for high wind scenarios.

The relative difference between the value of 10 GW and 2 GW storage reduces with increasing levels of wind, pointing towards a larger market for storage. The effect of diminishing value with increasing capacity is discussed in the following section.

The standard deviation of the gross value with high levels of wind reaches $\sigma = 14.2$.⁶ The gross value for 2 GW storage in a 64 GW wind case therefore corresponds to a 3σ range of £82.5–167.7/kW/year. This means that by the same condition as for peaking capacity the value that can be assumed to be exceeded with 95% confidence is around 20% lower than the mean values shown. Other uncertainties may further depress the cost target.

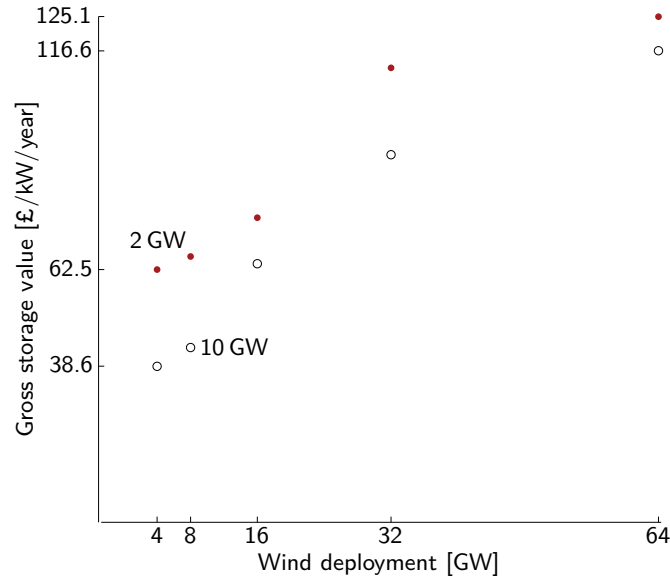


Figure 5.7: Increase in gross value of 2 and 10 hour storage with increasing wind deployment.

5.3.2 Diminishing marginal value

Storage is often said to suffer from ‘self cannibalisation’: the more capacity is installed the less it is worth, because by levelling prices it diminishes its own value (House of Commons, 2012, p.18). To some extent this is true of any product. Oversupply leads to falling prices. This section explores the dynamics that make this effect particularly pronounced for storage.

Figure 5.8 shows the reduction in value with increasing capacity for a fixed point in time with a given amount of wind installed. The value of storage reduces in two ways. First, the average value, which is the value based on the entire installed capacity drops off for simulations with larger storage capacities. Only so much storage is needed and in the example shown, 20 GW of storage flatten the prices to a point where the efficiency losses outweigh the trading margins.

⁶Result for six years base case scenario with uplift function re-optimised for each year.

The average value assumes that the entire fleet of storage is invested in and operated as a single monolithic unit. In practice, a certain amount of storage capacity might already be present on the system. The potential investor of additional capacity is therefore less interested in the value of this already installed capacity, but needs to know what the *marginal* value of any *added* capacity is.

To establish this value the model can be run consecutively. First the installed storage capacity P_{str} is simulated to establish the dispatch schedule of storage and other plants. From this the average value for this storage capacity (V_{str}) and the new price profile ‘post storage’ is deducted. A second run with a marginal increase in storage capacity of δP_{str} leads to a small change in the overall value of storage, which is now V_{str}^* . The marginal value of additional capacity can thus be approximated as

$$\dot{V}_{str} = \frac{V_{str}^* (P_{str} + \delta P_{str}) - V_{str} P_{str}}{\delta P_{str}}. \quad (5.20)$$

For very small values of δP_{str} the marginal value can become sensitive to minor fluctuations in the value of storage.⁷ Figure 5.8 presents marginal values based on a $\delta P_{str} = 0.1$ GW. The average value for the combined fleet of storage capacity tends to be higher than the marginal value of an additional unit of capacity and both reduce with further deployment.

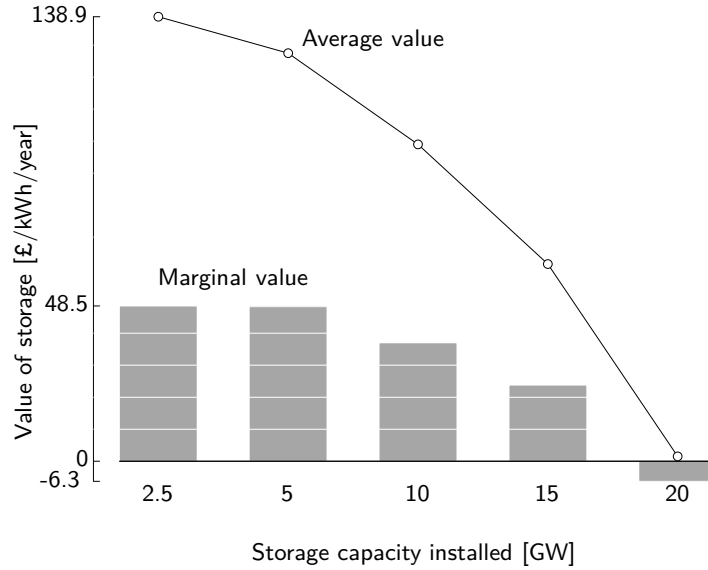


Figure 5.8: Declining marginal value of storage with increased deployment. Example shown for 40 GW wind case with 2 hour storage duration and 2 hours foresight.

⁷Small errors in V_{str} and V_{str}^* can cause errors in $\dot{V}_{str}$, which is based on the small difference between potentially large values

The reason for the diminishing value with increasing capacity is that the first unit deployed, by definition, has access to the most valuable operating options. The second unit has access to the remaining, lower values. Should this value be close to or lower than its cost, it would not be deployed, even if the average net value of the entire storage capacity was still positive. Incremental investment can thus lead to lower deployment than a lump investment.

The implications of these results on investor behaviour and uptake of storage will be discussed in more detail in Chapter 7, which deals with potential routes for uptake of storage and specifically the role of average and marginal values in Section 7.1.2.

5.3.3 Value of storage duration

A similar effect to the reducing value with increasing storage capacity (in terms of rated power) applies to the energy capacity (i.e. the maximum amount of energy that can be held in storage).

In the previous examples the energy capacity (E_{str}) scaled linearly with the size of a storage installation (P_{str}), by defining a storage duration (d) in hours.

$$E_{Str} = P_{Str} \times d \quad (5.21)$$

Now, a given storage capacity in a given context is given different storage durations and the marginal increase in value is measured. Analogous to the marginal value in the previous section, this value is a measure of the value at which increasing the energy capacity of a storage system begins to add to the value of the system.

Figure 5.9 shows how the highest values can be achieved with relatively short storage durations. The additional value of increasing the energy capacity to longer storage durations falls sharply.

This is not too surprising, if one considers that a longer storage duration cannot be cycled as often as a smaller one. Furthermore, it is short durations that can capture the most volatile ‘spikes’ in the price profile. The added value from longer duration storage has to come from trades in the remaining, smoother price profile.

Despite the reduction in marginal value, Section 5.4 will point towards commercial opportunities for longer storage durations.

5.3.4 Storage efficiency

High round trip losses are cited by stakeholders and in literature as a barrier for storage. The impact of storage efficiency has therefore been simulated explicitly to understand under which conditions storage efficiency could be an inhibiting factor and what levels of efficiency are required.

Figure 5.10 shows two simulations of storage with 10 GW and 6 h capacity. In Figure 5.10a the installed wind capacity is lower and the value of storage increases almost linearly with efficiency gains. For every percentage point gained in efficiency the value of this storage capacity increases by around £1.6 per kW.

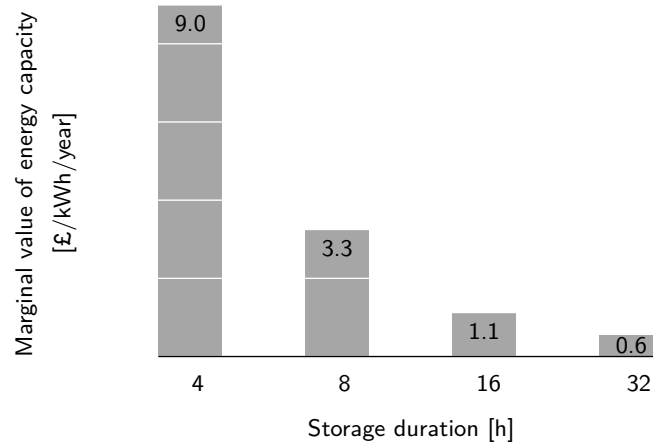


Figure 5.9: *Diminishing marginal value for increasing storage durations. Based on Grassroots scenario with 10 GW of storage.*

The picture changes in Figure 5.10b, where a higher share of wind is deployed. The overall value of storage is naturally higher, yet the value of additional efficiency is reduced. Even a system with 40% efficiency is only 27% less valuable than a perfect system with 100% efficiency. Marginal gains of improving efficiency are especially low for systems with already high performance. Above 70% efficiency improving by one percentage point is worth less than £0.5 per kW. Or conversely, if the costs can be reduced by more than this amount by sacrificing efficiency, the value of the technology would improve.

Why does efficiency, which is presently an important aspect of improving UK emissions, not matter more when it comes to storage in systems with high levels of renewables? The answer can be found in the shape of the price duration curve of future systems. With high levels of wind the spread between high and low prices increases. High prices get higher, low prices get lower. Storage, which seeks to charge at low prices, deals with surplus amounts of energy. Energy that would otherwise have to be curtailed. The alternative to storing it is therefore to lose it, which is equivalent to a conversion efficiency of zero. Even a modest conversion efficiency therefore improves the overall efficiency of the system.

Furthermore, a storage system charging inefficiently at low prices still achieves a high mark-up when selling at high prices. What is not considered at this point is the cost of the additional energy capacity requirement if the discharge efficiency is low.⁸

⁸In order to sell the same amount of energy with half the discharge efficiency the amount of energy ‘in store’ must be twice as large.

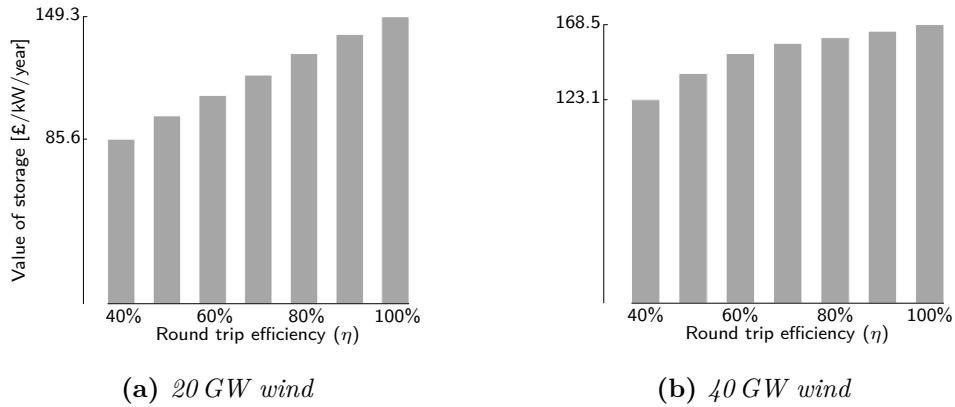


Figure 5.10: Higher efficiencies have a minor impact on the value of storage in high wind scenarios. Case: 10 GW with 6 hour duration in base case scenario.

5.3.5 Operating strategy and foresight

Unlike a ‘real world’ operator of storage, the modelling environment allows this thesis to test different operating strategies and compare the results.

The advantage a ‘model operator’ has over the ‘real world’ operator is access to perfect foresight. The standard operating strategy is to start with a best-guess buy and sell price for a simulation period. The solver then seeks to improve on the starting value by first optimising the buy price (less sensitive) and then the sell price (more sensitive). These prices still apply across the simulation period. Results can be further improved if at each point in time the option value of delaying a charge or discharge action is considered. Would a higher sales price be possible if the operator waited another one, two or four hours? This decision requires foresight.

Figure 5.11 shows the gain in value when the operator is assumed to have this foresight. Systems with short storage duration (high power, little energy) are most sensitive to the level of foresight. These systems fill up and deplete quickly and choosing the best period to do so therefore carries high value. Waiting until the better price is available can often be the right strategy. For systems with greater energy capacity the added value of foresight is somewhat lower. Since these systems do cycle more slowly and therefore capture a broader range of prices, they are less dependant on the precise timing of their operation.

Another trend evident from Figure 5.11 is the diminishing value of additional foresight. To some extent this is related to the cycle rate of the storage capacity. For a full reservoir that typically cycles every 12 hours, the price development beyond the next cycle is of no consequence to the scheduling of the present capacity and nothing is gained from further foresight. Between one and four hours of foresight improvements in value of up to 22% can result.

The extent to which such gains can be realised in practice is uncertain and the simulation of foresight is computationally expensive. Unless explicitly stated, simulations are therefore performed without foresight by default.

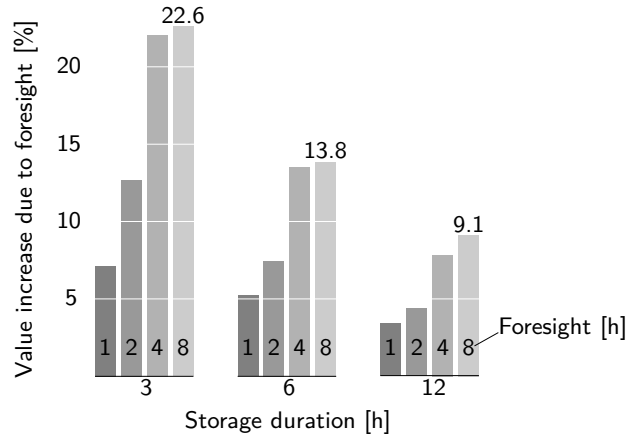


Figure 5.11: Increase in value of storage relative to a reference case without foresight. Systems with short storage duration are most sensitive to the level of foresight. More than 4 hours of foresight only yields minor improvements.

5.3.6 Storage in nuclear and CCS scenarios

The primary driver of the value of storage in the examples so far has been the effect of intermittent wind on wholesale prices. However, some scenarios include only modest shares of wind. Here one scenario that achieves carbon reductions through a higher share of nuclear power and one scenario that relies on CCS to meet carbon constraints are considered alongside the Grassroots scenario.

Figure 5.12 applies the scenarios described in Section 5.2.1 to 10 GW of storage with 6 hour duration. Not surprisingly, the value in the Grassroots scenario is highest.

The nuclear scenario with a high share of base load capacity still shows a somewhat increased value of storage compared to present levels, however not on a par with the high wind scenario. Storage has the potential to charge with relatively low cost energy during low demand periods, but the price spikes are less extreme, since peaking capacity operates on higher load factors.

In the case of CCS the situation is highly unfavourable for storage. The marginal cost of generation are generally higher with less arbitrage potential.

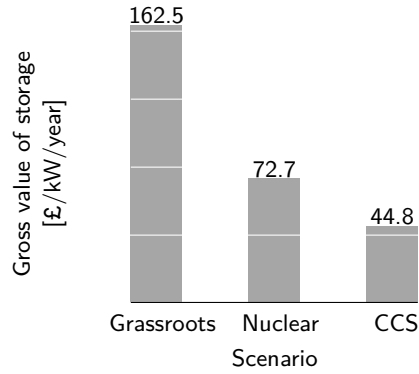


Figure 5.12: *Sensitivity to changes in scenario assumption. The high renewables Grassroots scenario yields the highest value. The CCS scenario is least suitable for storage. Examples shown for 10 GW 6 h storage.*

5.3.7 CO₂ reduction potential

The model is not designed to optimise the system for carbon reduction and the objective function does not include emissions as one of its parameters. As stated in Section 2.2.1, emission reduction is also not the primary motivation for policy makers in considering support for storage. Furthermore, the scenarios feeding into the model are already designed to meet certain carbon constraint targets and additional reduction may not be ‘necessary’. Nevertheless, the potential of storage to further reduce emissions (or perhaps more importantly, reduce the cost of achieving increasingly tougher targets) is of interest in this context.

Figure 5.13 shows the impact of storage on overall emissions in a scenario with 40 GW of wind. These figures assume emission factors based on MacLeay et al. (2010) as shown in Table 5.5. The average emissions apply to the entire fuel based generation across the year. Wind is assumed to have no emissions.

Table 5.5: *CO₂ emission factors. Based on MacLeay et al. (2010).*

Class	Symbol	Emissions factor [t/GWh]
Peaking	e_{pk}	915
Mid merit	e_{mm}	598
Average	e_{mean}	400

The reduction in output from peaking capacity and mid merit capacity is calculated

for each storage configuration and the emission reduction is calculated as

$$\eta_{CO_2, str} = \frac{(E_{pk_{ref}} - E_{pk_{str}}) \times e_{pk} + (E_{mm_{ref}} - E_{mm_{str}}) \times e_{mm}}{\sum E_{ref} \times e_{mean}} \quad (5.22)$$

where E is the total energy output from a given class. The suffix $_{ref}$ denotes the reference case without storage and $_{str}$ are outputs after storage has been added to the system.

The simulation presented in Figure 5.13 suggests that the first 10 GW of storage deliver only modest emission reductions of well below 5% under the operating strategy simulated here. Higher capacities of storage with longer durations can displace larger shares of peaking capacity and thereby increase the CO₂ reductions. In this scenario the reductions reach a saturation point at around 30 GW of storage. Additional capacity can even lead to lower emission reductions as round trip losses (simulated here as 25%) begin to outweigh the gains from displacing high emitting plant. Storage durations of 12 hours and more only deliver marginal increases on the results for 6 hour storage.

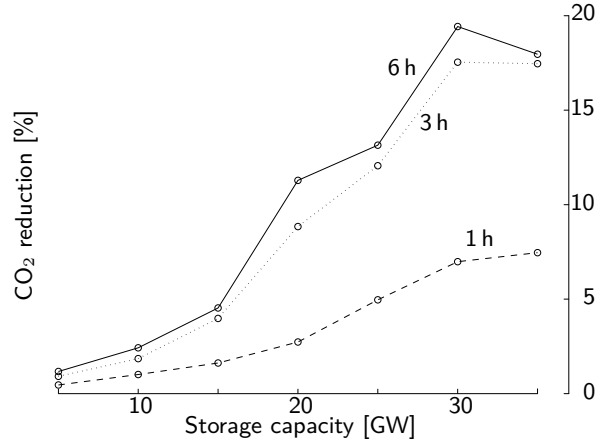


Figure 5.13: CO₂ reduction potential of storage in a 40 GW wind scenario. Only with very high storage capacity and long durations can significant CO₂ reductions be achieved based on the operating patterns underlying this simulation.

5.4 Review of technology options

This section briefly suspends the technology agnostic approach, so that the implications of the generic findings above can be put into context. Section 5.3.3 showed a sharp decline in value for longer storage durations. Does this trend suggest that longer storage durations should not be considered? A small number of storage applications that are suited to longer storage durations are simulated to test how they might perform within these scenarios.

5.4.1 Economic characteristics of storage technologies

The costs of different storage technologies vary significantly, with particular discrepancies between the capital costs related to power and to energy storage potential, as shown in Figure 5.14. The range represented by each technology's surrounding box reflects differences in assumptions on type and scale of application, learning rates and in some cases a lack of robust cost data due to the limited experience with these technologies.

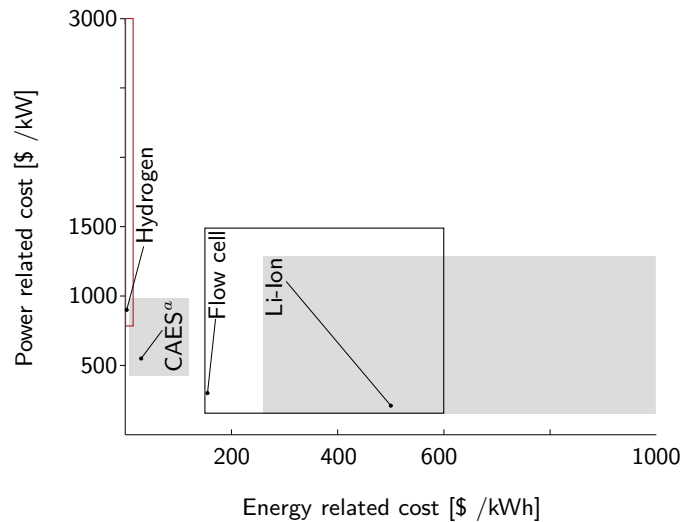


Figure 5.14: Costs for power storage technologies, split into power and energy related costs. The boxes represent the range of estimates found in the literature. The central values assumed in this study are indicated with the pointer for each technology. Data based on Amos (1998); Cavallo (2001); Eckroad (2002); Townsend (2009); Schoenung (2008); Haubrich (2006); Electricity Storage Association (ESA) (2010). ^a Compressed Air Energy Storage.

Because this study considers long term and large scale deployment options, the cost estimates tend to be from the lower end of the ranges shown in Figure 5.14. Table 5.6 gives an overview of some of the technical and operational characteristics of selected technologies.

Both compressed air energy storage (CAES) and hydrogen storage rely on suitable geology, with underground salt caverns offering the cheapest option. The energy related cost of these technologies depends on the state of development of these sites. (Evans and Holloway, 2009; Plaat, 2009; Howard B. J. Stone and Richardson, 2009)

So far, storage duration was used as an abstract concept. Figure 5.15 shows how different storage durations affect the system cost for technology options with distinctly different energy and power related costs.

With increasing storage duration, Li-Ion batteries, flow cells, CAES, and hydrogen become least cost installation options in that order. The efficiency of these systems

Table 5.6: Storage property assumptions for selected technologies. Based on Amos (1998); Cavallo (2001); Eckroad (2002); Townsend (2009); Schoenung (2008); Haubrich (2006); Electricity Storage Association (ESA) (2010)

Property	Li-Ion	Flow	CAES	H ₂	unit
Energy cost (C_E)	500	70	25	4-8 ^a	\$ kWh ⁻¹
Power cost (C_P)	225 ^b	600	550	1200	\$ kW ⁻¹
Efficiency (η_{sys})	90	75	72	35	%
Lifetime (L)	600	1500	6000	1800	cycles ^c

Technologies considered: Lithium-Ion (Li-Ion), Flow Batteries (Flow), Compressed Air Energy Storage (CAES), Compressed gaseous hydrogen (H₂). ^a Depending on the state of development of underground storage facilities. ^b Lithium-Ion (Li-Ion) batteries have an energy to power ratio of about 0.45 h. Costs are a function of either C_E or C_P . ^c A cycle is defined as 80% depth of discharge (DoD)

decreases in the same order (Li-Ion have the highest efficiency, hydrogen the lowest). Li-Ion batteries, which can not be scaled independently for energy and power do not reduce in cost with longer durations.

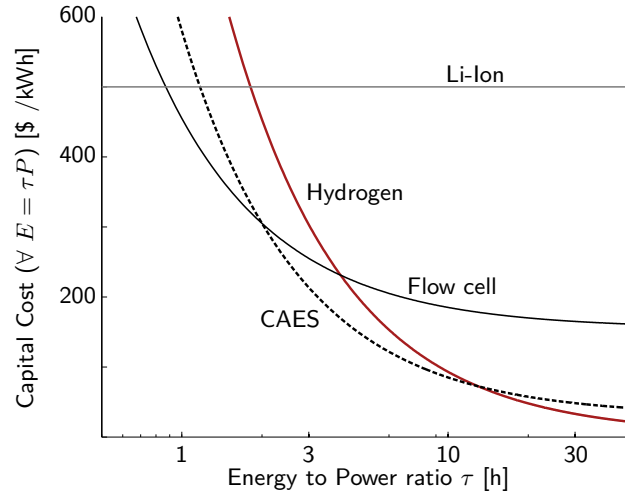


Figure 5.15: Capital cost of storage technologies for a given storage duration (τ). For long storage durations technologies with low energy related costs become least cost solutions.

5.4.2 Net value for selected technologies

The technology agnostic approach produces gross values for storage, since the technology costs are not known. Here, the model optimises the scale of energy capacity and power capacity for a given storage technology independently and it is therefore possible to

optimise the net present value (NPV) by deducting the system costs. For this, 6 years of historical data are extrapolated over a 20 year period. The penetration of renewables is steadily increased, to simulate the performance of each of the selected technologies in turn. Figure 5.16 shows the resulting mean NPV. The error bars represent the standard deviation observed between individual years.

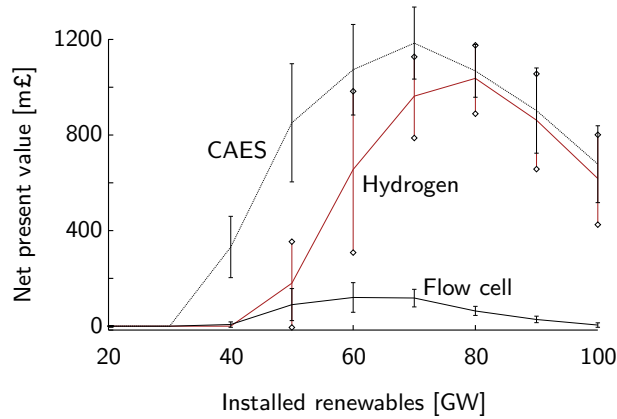


Figure 5.16: Mean NPV for storage technologies based on historical data for 6 years. Error bars represent standard variation between different years of data.

With less than 30 GW of renewables, none of the large scale storage technologies appear economically viable. However, as the amount of variable generation increases, the economics of storage improve. CAES is the first technology to provide a positive return under these assumptions at around 40 GW of total installed renewables. For larger penetration of renewables hydrogen also becomes a contender. As the amount of renewables increases further, the returns for storage start to diminish. In these cases ample supply of excess electricity is available, but not enough periods occur in which the stored electricity can be fed back into the system economically.

The configuration of the storage system is optimised for maximum NPV. In a system with 60 GW of installed renewable generation (around 50% of total capacity), a flow battery system is sized to 21 GWh of storage capacity, whereas CAES and hydrogen would ideally be sized at 69 GWh and 314 GWh respectively. The power for such systems is only modest and ranges between 1.5 GW (Flow Battery) and 3.9 GW (CAES). Due to their technical and cost characteristics, these technologies perform a predominantly energy based service.

As with the gross values in Section 5.3.1 the results in Figure 5.16 do not imply a transition over time. They represent the economics for the optimum amount of storage in a given system with changing levels of renewables. Challenges in realising these long term values will be discussed Chapter 7.

5.4.3 Load factors for storage

Load factors for this type of storage application are by definition low. Firstly, for about half the time the system has to be available for charging. Secondly, for any system with high storage duration, the load factor is further reduced, because the number of charge and discharge cycles is limited.

Figure 5.17 shows load duration curves for a system with different power ratings over a 12 month period. A storage system with a discharge capacity sized at 4% of the national peak load would operate at full load for less than 15% of the time and an additional 5% in part-load. For installations whose size exceeds 8% of the national peak load the load factor further reduces sharply.

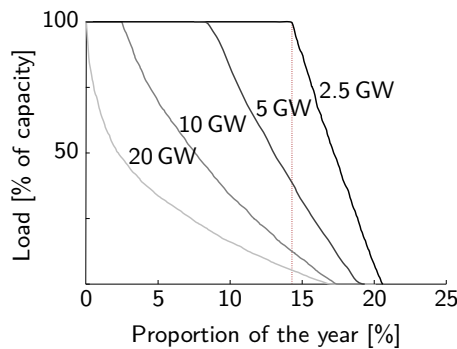


Figure 5.17: Load-duration curve for the storage discharge side over a 12 month period. For small storage capacities of 2.5 GW storage operates at full capacity for around 14% of the time. Larger installations of storage lead to significantly reduced load factors.

5.5 Alternatives to storage

Storage is not the only way to deal with future challenges of intermittency. Three alternatives to storage are commonly cited:

- Curtail wind and build flexible generation
- Build interconnectors and reinforce networks
- Enable a flexible demand side

As discussed in Section 5.2.2 this model is not equipped to model networks or interconnectors. The following sections will focus on flexible generation as an alternative to storage and consider the impact of a more flexible demand side on its value.

5.5.1 Comparison with CCGT

It has been suggested that for utility companies to embrace investment in storage technologies, the case has to be made with respect to the current business and regulatory model for the sector. Presently supply and demand are balanced generation with thermal reserve plant and by reducing or curtailing excess power generation (including wind if necessary). The thermal reserve plant of choice is CCGT, which towards the end of its life could even be converted to open cycle operation. (Mack, 2010; Denholm et al., 2010)

The condition storage has to meet to become a viable alternative to CCGT plants is to deliver a higher NPV. The future levelised costs of gas plants are not known and depend on prices for gas and CO₂ emissions. The NPV for both technologies can be derived from (5.1) as

$$\begin{aligned} NPV_{CCGT} &= \sum_t (1+r)^{-t} (\pi_{out} E_{out} - \pi_{gas} E_{in}) - C_{CCGT} \\ NPV_{str} &= \sum_t (1+r)^{-t} (\pi_{out} E_{out} - \pi_{in} E_{in}) - C_{str} \\ NPV_{str} &\geq NPV_{CCGT} \end{aligned}$$

where π_{gas} is the gas price.

If their levelised costs were equal, both would dispatch at the same position in the merit order, i.e. they would be competing for the same market. For arguments sake, we shall further assume that the operation and maintenance costs and the costs related to the power (C_P) are identical for both systems. Thus, storage carries higher capital costs related to its energy storage capacity (C_E).

Rewriting the energy delivered in terms of a load factor (L) and the energy to power ratio of storage again as τ , results in the following condition

$$\left(\frac{\tau C_E}{aL \times 8760h} + \frac{\pi_{in}}{\eta_{str}} \right) \leq \frac{\pi_{gas}}{\eta_{CCGT}} + \pi_{CO_2} \quad (5.23)$$

where η_{CCGT} is the efficiency of the CCGT plant and π_{CO_2} is the cost of emitting or capturing CO₂ per unit of output energy. The efficiency and costs can be estimated based on literature values and the load factor is derived with the model.

Since many of the input parameters are uncertain, this Monte Carlo approach has been chosen to reflect the distribution of possibilities. The relationship in (5.23) compares the probability for storage to offer a higher investment value than CCGT, based on the load factor. In the absence of a stochastic model, the load factors have been assumed to be normally distributed. The standard deviation within the data available has been established as 1.37 with a mean of 14.64%. Other parameters are assumed to be evenly distributed, such as the electricity price (π_{in}) between 5 and 15 £/MWh, and the values for hydrogen storage are listed in table 5.6. A Monte Carlo simulation with 100,000 sample points includes the different probability distributions.

Figure 5.18 shows the resulting probability distribution of storage having a higher NPV than a CCGT plant. The levelised running costs of CCGT include the fuel price per unit of output and any costs associated with CO₂ abatement or trading also form part of these costs. At around 56 £ MWh⁻¹ the probability of storage to yield higher

returns than CCGT reaches its 50th percentile. For utility companies to favour storage over CCGT plants either the fuel price or the cost of CO₂ would have to rise.

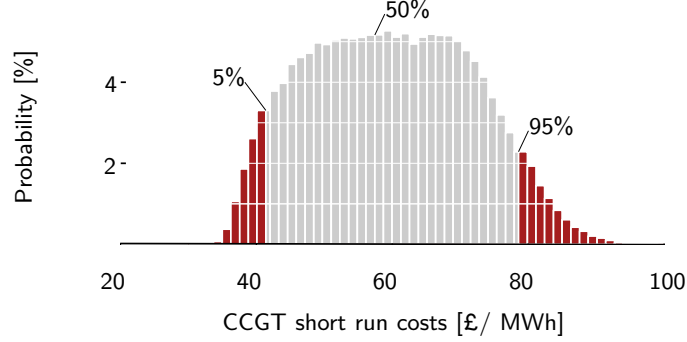


Figure 5.18: *Probability distribution of storage being commercially more attractive than CCGT plants. Only with increases in short run cost of CCGT does storage become the favourable investment option under these assumptions.*

5.5.2 Demand side response

The relationship of demand side measures with electricity storage has been investigated by Exarchakos (2008); Exarchakos et al. (2009) for the case of Greece. They found a significant sensitivity of storage profitability to the presence of demand side response (DSR). Strbac et al. (2012) also conclude for the UK that the level of DSR can have strong implications on the value of storage. The potential competition between DSR and storage therefore deserves some attention.

Section 5.2.1 argued that the complexities of temporally resolved demand profiles do not lend themselves to long term projections, which is why demand profiles have not been modified up to this point. The same challenge applies to demand response. Neither the possible future scale of availability, nor the cost of demand response are presently well understood.

DSR is therefore simulated in generically. A simple and transparent representation is used for an exploratory assessment of the response in the value of storage to different assumptions.

Following assumptions are made in the model:

- Demand can be shifted by a given number of hours (Δt_{DSR}).
- No demand is lost or gained. Demand merely shifts from one period to another. In storage efficiency terms this is equivalent to 100% efficient storage.
- All shifted demand must be met after a maximum period of Δt_{DSR} . It can not be shifted a second time.

- Demand can only be shifted to a later point in time. Preemptive increase of demand in anticipation of higher electricity prices is not considered.
- Demand responds to wholesale price signals. After DSR has taken place the price duration curve is recalculated, leaving a flattened price profile for the remaining plants.
- Demand response is instantaneous. No ramping constraints apply.

From these assumptions it is possible to represent the demand response with only three parameters: the capacity that is available to be shifted (P_{DSR}) measured in GW, the maximum duration over which the demand can be delayed (Δt_{DSR}) in hours, and a response price (π_{DSR}) in £/MWh. The response price is the demand side's 'willingness to accept' demand side measures. Above this price a delay of electricity use can take place.

In practice the demand side is a very complex set of diverse, inconsistent and dynamically changing combinations of these three parameters.⁹ They do, however, allow this study to simulate the effect of demand response on storage in generic terms. The $\pi_{DSR}, P_{DSR}, \Delta t_{DSR}$ representation is a qualitative comparison of how different assumed demand response types would impact on storage.

While the market price is below the response price no demand response takes place. Once the wholesale price reaches π_{DSR} uptake scales linearly¹⁰ between π_{DSR} and $2 \times \pi_{DSR}$ where it reaches P_{DSR} , as per

$$E_{DSR}(t) = P_{DSR} \times \Delta t_{DSR} \frac{\pi(t) - \pi_{DSR}}{\pi_{DSR}} \quad \forall \pi(t + \Delta t_{DSR}) \leq \pi(t) \quad (5.24)$$

The energy that can be shifted is constrained by

$$0 \leq E_{DSR} \leq P_{DSR} \times \Delta t_{DSR} \quad (5.25)$$

From the available demand response ($E_{DSR}(t)$) a new demand profile $D_{DSR}(t)$ is calculated based on the original demand profile ($D(t)$)

$$D_{DSR}(t) = D(t) - \frac{E_{DSR}(t) + E_{DSR}(t - \Delta t_{DSR})}{\Delta t_{DSR}} \quad (5.26)$$

such that demand that is reduced in one period increases by the same amount after Δt_{DSR} . The new demand profile is used to recalculate the new and flatter price profile on which storage now operates.

⁹For instance, fridges have reasonably well understood characteristics. Their power and delay period can be established from the nationally installed capacity and their operating profile between two temperature set points. Consumers do not get inconvenienced by changes to the cycling profile of fridges. The response price can therefore be assumed as low. More intrusive measures, such as a change in the time of service completion of a washing machine, are more changeable, within a range of 'no inconvenience caused for several hours' to 'major inconvenience from even minor delays', depending on the need for the energy service at the time. Thus, capacity, duration and response price can swing significantly.

¹⁰If the entire DSR capacity responded once the wholesale price reaches π_{DSR} , storage could take advantage of discontinuities in the price profile. Linear scale up avoids this market distortion.

Comparison between the original value of storage without the presence of DSR and the reduced value for different DSR configurations is shown in Figure 5.19 on page 144. Demand response, even when limited to a maximum of four hours, as shown here, has the potential to significantly reduce the value of storage.

If the DSR capacity was 4 GW and responded to prices above £50/MWh, the gross value of two-hour storage could reduce by over 50%. For longer storage duration, the reduction at this price level is lower, as shown for the example of six-hour storage on the right in Figure 5.19 on page 144. This could suggest that in some scenarios for DSR, storage would adopt more long-duration roles, than those simulations here without any DSR consideration.

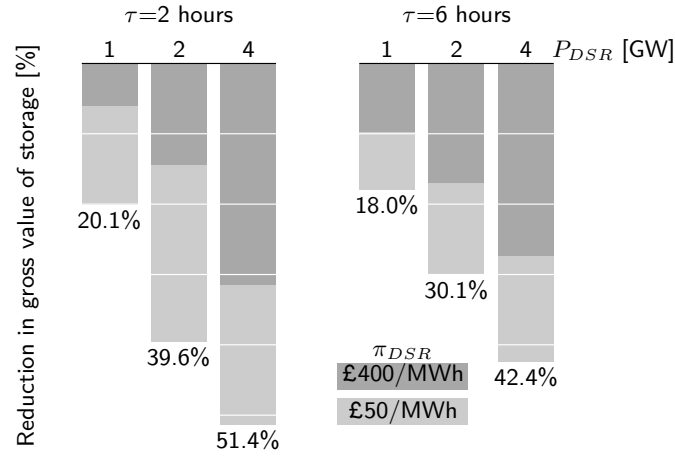


Figure 5.19: Reduction in the value of storage as a result of demand response. At a DSR resource of 4 GW and a response price of £50/MWh the gross value of storage with a 2 hour duration can halve. Longer storage durations are slightly less affected. Example for 10 GW storage in base case scenario.

For higher response prices, less demand side response takes place and the reduction in the value of storage is therefore less pronounced (darker bars in Figure 5.19).

As discussed above, neither the scope nor the cost for DSR are well understood today. It is therefore not possible to conclude how much value reduction storage is likely to lose to DSR. These findings show that DSR can have a profound impact on the value of storage, which could in some cases jeopardise its commercial viability. In part, the strong competition between DSR and storage is a result of their similarity. One stakeholder called them ‘two sides of the same coin’.

5.6 Sensitivity and uncertainty

5.6.1 Parameter sensitivity

The commercial viability of storage hinges on a large number of model parameters and assumptions. Some cases suggest that storage can become commercially viable with high levels of wind on the system. However, changes in the assumption can significantly affect the results.

The sensitivity of the commercial value of storage to changes in individual input parameters has been simulated for the example of hydrogen storage from 5.4.2. This provides a snapshot, which will inform the discussion around uncertainties in the following section. The NPV is chosen rather than the gross value, because small changes to gross value can lead to large changes in NPV, if the profit margins are small. The NPV is therefore a more sensitive indicator.

Figure 5.20 shows how sensitive the NPV is to some key parameters. Changes that are the result of a positive change in the input parameter are shown in light, negative changes are dark. As an example, increasing the power related costs in this case, diminishes the value.¹¹ This example is specific to hydrogen, which has high power related costs.

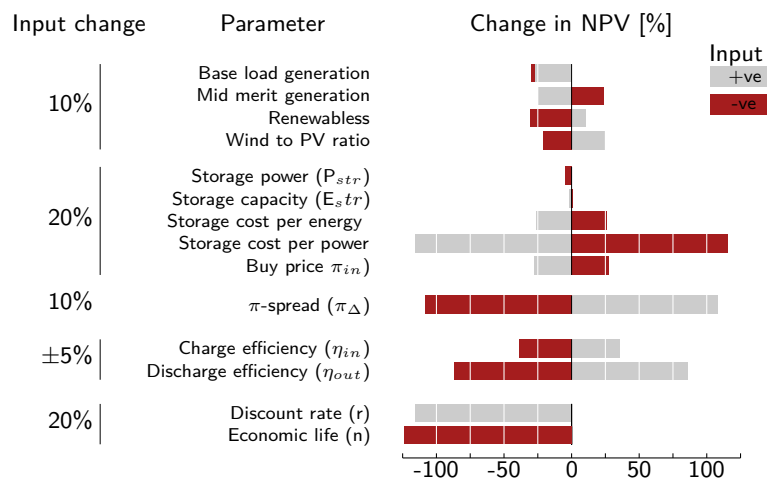


Figure 5.20: Sensitivity of NPV to key storage parameters. Parameters for a storage system have been subjected to the changes shown on the left. (in the case of efficiencies, the values have been added and subtracted). Responses to parameter increases are shown in light, parameter reductions are dark. Example for optimally sized hydrogen system in base case scenario.

A trend that applies more generally is the difference in sensitivity between charge and discharge efficiency. Discharge efficiency is the more sensitive parameter of the two. This is due to the higher value of electricity at times of selling to the grid.

¹¹Negative changes in excess of 100% turn a positive NPV into a negative one.

The trading margin (π -spread), which is the price difference between buying and selling, is among the most sensitive parameters. This value depends on the electricity price volatility, and thus the electricity market arrangements, market structure and the costs structure of the plant mix.

The economic parameters are also critical. As with most sustainable technologies, the up-front costs are high, and the returns spread over many years. A strategic long-term view is required. Discount rates of return much above 6% with pay-backs of less than 20 years are unlikely to be met by such systems.

5.6.2 Stochastic uncertainty of economic returns

Alongside the uncertainty surrounding some of the parameters mentioned in the previous section, storage is also subject to stochastic variations in demand and the availability of renewable resources. The scope for establishing the probability distribution of economic returns using historical data is limited. Nevertheless, returns on investment for each of the 6 years of data can be established. One year is the shortest period for which seasonal and most other periodic effects can be assumed to be represented. Each year is simulated with identical storage installations to compare their returns.

The results, shown in Figure 5.21, suggest that year-on-year returns can vary. Analysis of the reason for the variations shows no strong correlation with the total demand or amount of renewable resources in each year, nor does it follow any strong pattern with the difference between the two.

The returns to storage must depend therefore on the distribution in time, which these profiles follow. To establish if there is such a thing as a ‘good’ or ‘bad’ demand profile, or if returns are more affected by changes in the renewable resource, we suspend the temporal link between the two sets of data, and simulate the demand data of one year with the renewable resource data of another.

Figure 5.21 gives some indication as to the likely causes of storage performance. The six years with the temporal link intact, are ranked by storage performance along the diagonal, where six is the year with the highest returns for storage. It should be noted that the demand data between 2003 and 2009 does include increasing amounts of embedded renewable generation. However, these levels are still low enough not to affect the ranking, which is not in chronological order. The returns are represented by the size of the circles. Each column shows the returns using the the same year of meteorological data, but meeting the electricity demand of different years, and vice versa for each row. If there was such a thing as an inherently unsuitable profile, one would expect to find an overall trend towards good performance in the top right of the graph and poor performance in the bottom left corner. Similarly, if certain years were unsuitable for storage, due to the demand or the meteorological resource alone, this trend would show up as rows or columns that are consistently worse than their reference cell on the diagonal. Such a trend is not very pronounced, with some of the best results found in row 1 and column 2 (i.e. the poorest reference years).

To better understand the source of uncertainty for storage investments, the standard deviation, normalised to the standard deviation of the reference years, has been included

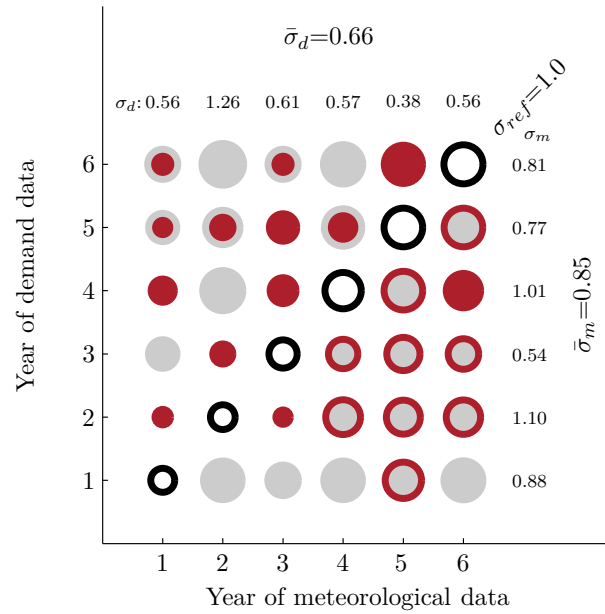


Figure 5.21: The value of storage, represented by the size of the rings, is sorted from the least to the most valuable year along the diagonal of this diagram. Around the diagonal are results from different combinations of meteorological data from one year with demand profiles from another year. If either the wind profile or the demand profile were principally responsible for the value of storage, one would expect an overall trend in one dimension or the other. The fact that values do not follow such a trend suggests that neither wind nor demand profiles alone dominate the value of storage. The colour coding illustrates the value relative to the ‘reference year’ on the diagonal (same year used for wind and demand), with red being lower and grey being higher value than the reference year. The outer rings reference along the vertical (demand) and the inner ones along the horizontal (meteorological).

for each row and column. It is apparent that the variation is on average lower across different years of demand data. Or in other words, the uncertainty of returns in a storage investment is caused to a greater extent by changes in the renewable resource, rather than changes in the demand profiles. This may not be entirely surprising (weather being more erratic than people’s demand patterns). Between the two, however, it is the influence that is largely outside policy makers’ control.

Renewable resources and demand profiles show a weak correlation, leading to slightly higher demand during periods of higher renewable resource availability. Consequently the storage utilisation for data from two different years is higher on average. For storage models this can lead to artificially inflated commercial returns from storage, when using unrelated data sets.

5.7 Discussion

From the above results five key areas of uncertainty emerge.

Plant mix Storage adds most value to systems with high levels of intermittent and inflexible generation. Conversely, its role is smaller if flexibility can be provided from other sources. Scenarios for the year 2050 with high levels of wind, nuclear or CCS suggest that the value of storage is sensitive to different different pathways.

Storage technology The model suggests that short storage durations yield the highest value. Nevertheless for longer storage durations could become viable if the energy related costs are sufficiently low. This typically requires large scale deployment. High efficiency, which adds value in early applications, becomes less decisive as a feature when wind penetration increases.

Alternative solutions The comparison between storage and CCGT has shown that storage could become commercially favourable under certain CO₂ and gas price assumptions. However, recent developments surrounding shale-gas, illustrate how difficult long term planning in this area can be (Downey, 2010). DSR is a potential competitor for storage. With the assumptions made here, DSR could significantly reduce the value and change the role for storage towards longer storage durations. It was not possible to simulate the impact of inter-connectors with this model.

Market arrangements The results assume an energy only market, with high electricity price volatility. Changes to the market structures, especially the balancing market or the introduction of a capacity market, can have a strong impact on price volatility and could change the economics for storage fundamentally (for better or worse). A system where the balancing rules are seen as ‘an evolving, flexible instrument responding to experience and events’ (Helm, 2008, p. 314), may deter investment in a technology that depends on such rules.

Stochastic uncertainty The returns from storage can vary year on year. The resulting cash flow uncertainty would be likely to increase the cost of finance and could deter investors.

This set of uncertainties could provide a valuable context for policy intervention. These could include R&D support for technology development and prototypes, which can help to identify potential solutions, to regulatory and financial support schemes, in order to hedge some of the risks and cost of finance resulting from the sensitivity of returns to external factors. The volatility in electricity prices, needed for storage to operate in an energy only market, may not necessarily be desirable for other market participants and also leads to high year-on-year revenue fluctuations for storage operators. A capacity payment (energy rather than power based) could go some way towards reducing the volatility of prices, while providing an incentive to increase reserve capacity. Such measures are currently considered as part of the electricity market reform consultation and its impact on storage should be considered (DECC, 2010b). At the

same time any specific support needs to be cautiously balanced, not to disadvantage any of the diverse alternative solutions, including the demand side, which may respond to very different measures. Chapter 7 will return to these issues.

The analysis of load factors highlights the difficulties faced by storage applications targeted at longer storage durations. As the wider benefits, such as energy security, increase with longer storage durations, the economics become more challenging, because less energy can be ‘turned over’ from the same storage capacity. It can be argued that some of the social benefits brought about by the presence of storage on the system are not presently included in its trading margin. The question of the extent to which these wider benefits justify additional policy support, is complex and receives further attention in Chapter 6.

5.8 Conclusions

A techno-economic model has been developed, tested and applied to future scenarios. The high temporal resolution of wind and demand profiles allows the model to specifically interrogate scenarios on the value of storage. The underlying scenarios were developed without detailed representation of storage and this study therefore adds to their insight into the role for storage.

With 30 GW of wind generation the value of storage reaches levels comparable to presently available technology options. The increase in value over time is balanced by a sharp drop in the marginal value of storage, which limits the market size. Short storage durations are most valuable. However, this chapter has shown that under certain assumptions large scale storage with long storage durations can become commercially viable. In scenarios with high penetration of intermittent generation, current storage technologies with low energy related capital cost can yield positive returns even at the expense of efficiency.

The value of efficiency reduces as wind penetration increases. Efficiency improvements beyond 70% yield little extra value.

The CO₂ reduction potential of storage is modest. With the assumptions of this model, capacities in excess of 20 GW and storage durations of several hours are required to achieve emission reductions of more than 10%. However, storage may ease the integration of other low carbon technologies and therefore indirectly contribute to emission reductions.

The sensitivity analysis has further revealed that the returns from storage are sensitive to a wide range of uncertainties, which may adversely affect the cost of finance and thus the attractiveness to investors. The key areas of uncertainty are the future plant mix, technology development, market structures and the stochastic uncertainty of returns.

Volatile electricity prices are a driver for the presence of storage in this model. This volatility can lead to high year-on-year variations in returns for storage, and may be unattractive for other participants in the market, too.

This chapter has reconfirmed the sensitivity of storage to external factors. Minor changes to the regulatory regime or transition pathway could severely affect the value of storage.

The following chapter will therefore expand the narrow techno-economic perspective to include wider system implications. This is done by engaging stakeholders directly through a workshop and in semi-structured interviews, to reveal their perception of the value of storage and explore potential barriers to deployment.

Future roles for storage— a socio-technical perspective

THE TECHNO-ECONOMIC analysis of Chapter 5 suggests potentially significant long term increases in the market value of storage. This by itself does not yet imply that storage necessarily enters the market to capitalise on such values. Existing and evolving practices, technologies and institutions have the potential to influence pathways, favouring some solutions over others, and potentially locking out long term options, even if these ‘could have become valuable’ in the future.

This chapter therefore expands the techno-economic perspective, by drawing on the methods introduced in Chapters 3 and 4 to assess socio-technical transitions. This involves engagement with stakeholders on perceived views and attitudes to storage, which allows this thesis, in qualitative terms, to inform the discussion on the agency such actors may bring to future transitions.

6.1 The gap between engineering and system models

Section 2.4 distinguished engineering models and system models as two broad classes of models to simulate storage within electricity systems. Engineering models focus on specific technologies and assess their techno-economic performance in a given system context. System models, by contrast, are concerned with the composition of the system at a national level and seek feasible or least cost solutions under constraints, such as carbon emission targets.

From a policy perspective neither class of model provides a complete picture by itself. The engineering perspective can estimate the value of storage for selected actors and give insight into likely micro-economic decision making processes. Should such a model appear to show that storage is not ‘commercially viable’, it is not possible to deduce whether the uptake failure is due to insufficient technology cost/performance, or the result of market failures, because these models do not readily allow for the representation of wider societal benefits.

The system model approach, on the other hand, assumes economic efficiency, which can lead to a discrepancy between what such models suggest *should* happen and observed system developments (Nelson and Winter, 2002). A number of market failure mechanisms have been put forward as explanations, including the concept of barriers to adoption, resulting from bounded rationality, informational asymmetries and other factors (Sanstad and Howarth, 1994). Unruh (2000) expands this concept to include the ‘techno-institutional complex’ as a cause of technological lock-in. Hughes and Strachan (2010b) argue that because modelling studies lack agency for their actors to influence pathways, institutional factors are not well represented within them.

This chapter seeks to address the gap between these two classes of model by exploring the agency of stakeholders with the aim of understanding to what extent market failures and institutional factors could pose a barrier to uptake for electricity storage technologies. The case of distributed electricity storage is especially interesting and challenging, due to the large number of stakeholders involved and the highly aggregated value it can potentially offer to the system in the long term. The approach builds on the stakeholder engagement method introduced in Section 3.4 and is using the perspective informed by the literature on socio-technical transitions discussed in Section 3.3.4.

The combination of these approaches provides an analytical framework to assess technologies that do not fit the established structures in the electricity system and explores tensions arising from such ‘disruptive technologies’.

Section 6.2 outlines the socio-technical perspective adopted in this chapter. It returns to the concept of the socio-technical regime and relevant sub-regimes introduced in Section 4.5.3, and introduces how these sub-regimes relate to storage. The stakeholder engagement process, which this chapter draws upon to inform the assessment of relationships between sub-regimes and electricity storage, is explained in Section 6.3. Semi-structured interviews and a dedicated stakeholder workshop have been undertaken and the process and approaches are discussed. Some results from this stakeholder consultation are presented in Section 6.4, with further reference to their insights used in Chapter 7, where they are compared and contrasted with system modelling results in Section 7.1 to identify potential barriers to uptake. The policy implications arising from perceived barriers are discussed in Section 6.5, before the conclusions and limitations of this approach are presented in Section 6.6.

6.2 A socio-technical transition perspective

The type and scope of barriers to deployment is explored here by contrasting storage relevant electricity system modelling with stakeholder perceptions of the value of storage through the perspective of a socio-technical technological transition.

Although the perspective adopted here is informed by this literature, it was necessary to adapt and expand the approach to suit the distinct characteristics of storage. Firstly, Section 4.6.2 proposed to view storage as a ‘facilitating’ technology, aimed at improving the effective working of the remaining system by providing services. It is therefore inherently dependent on other system developments and is not—unlike the focus of many

innovation and transition studies—a candidate for becoming a separately identifiable ‘dominant design’.¹ As the review of historic cases of storage uptake in Chapter 4 has suggested, even when storage is established within a given system context, it remains highly susceptible to changes to the socio-technical sub-regime.

Secondly, the vertically integrated nature of storage services across generation, network and demand, requires a cross-sectoral perspective. Aggregating value streams from stakeholders across the system poses challenges hitherto not conceptualised in the discussion of barriers to adoption. Although employed here for the specific case of electricity storage, distributed generation and especially demand side measures may face very similar ‘value aggregation’ challenges and similar approaches of analysis might be appropriate.

As part of a review of historic transitions, Verbong and Geels (2007) and Strachan and Dowlatabadi (2002) observe the successful uptake of distributed generation in the Netherlands and stress the importance of institutional factors. They argue that creating initially protected niches, allowing distributed generation to penetrate existing regimes, is more effective than mere subsidies. Furthermore, Brown (2008) and Rhodes (2010) raise the interrelations of distributed generation, storage and smart grids. A broad perspective is therefore important, when evaluating the future uptake of such solutions.

6.2.1 Present sub-regimes in the electricity system

Section 3.3.2 introduced the concept of the socio-technical regime. They are said to provide the deep structure, which stabilises the system through its embedded rules, institutions, belief systems and practices. Geels (2002) describes them as a ‘semi-coherent set of rules carried by different social groups’. During the transition of large technical systems the existing sub-regimes undergo changes internally, as well as in relation to other sub-regimes. The definition of the boundaries of ST-regimes is not always clearly defined, which has led to the accusation of ‘lack of structure’ by Genus and Coles (2008), who also remark that ‘socio-technical regimes are often presented as too homogeneous or monolithic’. Geels (2011) proposes the use of sub-regimes, which is adopted here for the electricity system. Viewed as a single regime, as has commonly been the case in studies of the electricity system, important features and tensions between sub-regimes tend to be obscured.

Subdividing the electricity system, based on three distinct regulatory and cultural rule sets, leads to the three distinct categories developed in Section 4.5.3: an electricity *Generation* and supply sub-regime, a *Network* and System operation sub-regime, and a sub-regime of electricity *Consumption*.

These sub-regimes will provide the structure to the selection and grouping of stakeholders in this chapter.

¹From the diverse set of storage solutions presently under development ‘dominant designs’ may well emerge over time. This process, however, takes place among storage technologies. The focus of this study is whether storage services can establish themselves within existing sub-regimes as a self-sustaining component of the system.

6.2.2 Relationship of socio-technical sub-regimes with electricity storage

New technologies can transform existing regimes. Of the sub-regimes in Figure 6.1, it is not yet clear which ones, if any, would adopt storage technologies as owners operators or users. It is therefore suggested that it may be useful to explore the relationship between storage and the proposed sub-regimes. Storage is treated ‘technology agnostically’ in this context and refers to grid connected electrical energy storage of any kind.² This perspective could meaningfully be expanded to include flexible demand, which ultimately can provide equivalent grid services, but this would require further conceptual and empirical analysis.

Between the existing sub-regimes interfaces provide physical (e.g. electricity), monetary and service flows, as indicated by the arrows in Figure 6.1. Unlike conventional technologies (generators, wires and loads), around which these sub-regimes have evolved, electricity storage is no natural subset any of them. In fact, its functionality overlaps with all surrounding sub-regimes and has the capacity to influence them and to create or resolve tensions within them or between them.

The following section discusses how stakeholder engagement is approached to inform the dimensions of the proposed socio-technical sub-regimes.

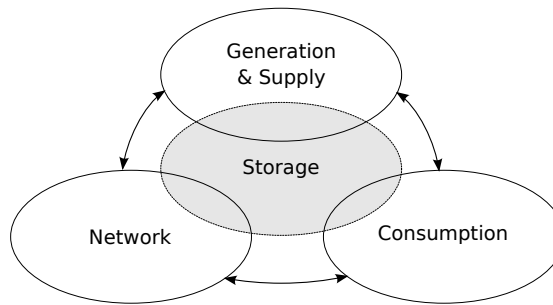


Figure 6.1: *Socio-technical sub-regimes in the electricity system with distinct regulatory and cultural rules. Their interfaces (arrows) represent physical, monetary and service flows. A storage sub-regime would interact with all three sub-regimes.*

6.3 Stakeholder engagement

Stakeholder engagement, as introduced in Section 3.4, helps our understanding of the existing sub-regime and to inform our perspective of potential tensions in the relationship of sub-regimes with electricity storage. The following two section explain the process by

²In this perspective it is immaterial whether storage is provided by conventional electricity storage technologies or other means and media to shift loads. Thermal storage and demand response can provide equivalent services from a systems perspective. See Grünewald and Torriti (2012).

which stakeholders were identified, selected and approached to take part in a stakeholder workshop and in semi-structured interviews.

6.3.1 Storage stakeholder workshop

Selection of candidates

The storage stakeholder workshop was initiated and proposed by the candidate to establish a better understanding of the interactions between stakeholders in relation to electricity storage. The initial proposal to the UK Energy Research Centre's Meeting Place led to the establishment of a steering committee, which supported the process of planning and running the event. Members of the steering committee comprised of academic experts in the field, who had previously been approached in initial interviews for this thesis, as well as two experts put forward by the review panel (see Appendix Table B.7).

The stakeholder selection process was guided by the seven regime dimensions identified by Geels (2002) and shown in Table 6.1. Organisations for each regime dimension and for the three sub-regimes plus storage were identified. To ensure broad representation of the UK electricity system, at least three organisations for each category were shortlisted. Appropriate contact persons in these organisations were put to the workshop steering committee for review. Selection of invitees sought to meet the following criteria:

- Balance across regime dimension with no more than 50% academics
- At least two candidates per dimension
- Candidates to be regarded as experts in their field (but not necessarily on storage)

Shortlisted candidates were invited in person. Where invitees were not able to attend, they were given the opportunity to propose a deputy to take their place. Two places were assigned in this way. The thirty places for which funding was available were fully allocated after two rounds of invites to a total of 55 shortlisted candidates. A list of all participants can be found in Appendix Table B.1.

High uptake is positive in that it indicates a certain willingness to engage with the subject among the shortlisted candidates. However, it is conceivable that this group might not be representative of the wider system. An unintentional selection bias toward contacts with a storage favourable agenda is possible, especially since some candidates were the result of recommendations of other contacts in the field. Although some stakeholders expressed sceptical views, the possibility of a selection bias in favour of 'storage supportive' participants cannot be dismissed. Some of the experts in the area were involved in storage applications or were in the process of considering its merits.

Fewer representatives from the demand side were involved than originally anticipated. In part this was a result of a lack of suitably representative organisations, which could be identified. Nonetheless, demand side positions were raised during the event and policy

makers and regulators, in particular, raised the importance of the demand side as a stakeholders in storage.³

The participants spanned a wide range of disciplines and did not necessarily regard themselves as ‘experts in storage’. They contributed through their insights into particular aspects, such as engineering, economics, or policy and regulation.

Workshop conduct

Consultation took place in the form of a one and a half day interactive workshop hosted at Imperial College London in May 2011, which was funded and facilitated by the UK Energy Research Centre’s Meeting Place.

The aim of the workshop was to establish and evaluate both the perceived benefits arising from the presence of storage and the barriers towards its deployment. The process aimed to invite stakeholders to share their own expectations as well as to stimulate a discussion on ‘common good’ values. Analysis of their input was intended to highlight common positions held in relation to storage and identify any underlying tensions.

To ensure a technology agnostic system focus, storage was conceptualised along the two broad categories introduced in Section 3.2.2. *Scale/location* distinguished between bulk storage connected at the transmission level and distributed storage on the low voltage network. *Time scale* captured the ratio of storage power to its energy capacity, which coarsely separates storage for short and fast services from more long duration storage applications. Prior to the workshop participants were sent a briefing note, which explained this approach and the aims of the event. The content of this document can be found in Appendix Section B.2.

³The importance of the demand side as an alternative contributor of storage, shown in Section 5.5.2, had not yet been identified at the time of the workshop and was not subject of the discussion.

Table 6.1: *Dimensions of the ST-regime and corresponding stakeholder groups consulted to inform the understanding of the sub-regimes*

ST-regime dimensions	Stakeholder group
Industry	Utility companies, network operators, storage developers
Technology	Storage developers, academia
Infrastructure	Network operators, utilities, academia
Policy	Policy makers, regulators, academia
Culture	All
Science	Academia
Market user preferences	Utilities, network operators, demand aggregators

The workshop was conducted under the Chatham House Rule, which state that:

When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.

Chatham House (2012)

References to workshop and interview statements are therefore not attributable, nor will the direct affiliation be revealed. However, for the purposes of this study it is necessary to identify contribution by broader groups. Affiliations are therefore clustered into sectors or sub-regimes to identify differences in perception. Figure 6.2 shows the share of different stakeholder groups involved in the process. To ensure compliance with the spirit of the Chatham house rule, care is taken to ensure that no such grouping has less than 3 members and anonymity is therefore protected.

Workshop format

The workshop was designed around four overarching questions:

1. What are the ‘problems’ that can be addressed with storage?
2. What types of storage are perceived to add most value for stakeholders?
3. Under which conditions is the availability of storage in the energy portfolio desirable/unnecessary?
4. Can the transition be market driven, or what form of policy support would be appropriate?

To build up towards the direct confrontation with these questions the workshop was designed in four phases. In the first phase participants were *informed* about the broader issues of concern. This was done through scene setting presentations by authoritative members of the community. Phase two sought to *engage* participants through a range of activities, including an open round table discussion intersected with prepared provocative interventions by selected participants. Phase three built on the engagement phase and aimed to *explore* the workshop questions. This phase included the working or breakout groups, in which the workshop questions were posed and discussed. The final phase was intended to *conclude* results and, wherever possible, identify consensus opinion. This was done through reporting back from breakout groups, and discussion, before the key findings were established by a rapporteur and any final comments invited by the group.

The full agenda of the event can be found in Appendix Table B.4.

This process provided a strong tool to gain insight on high level issues and interrelations. It did, however, leave unresolved any issues requiring a greater level of detail and in depth discussion. For this reason it was necessary in some cases to follow up with more personal one-to-one semi-structured interviews.

6.3.2 Semi-structured stakeholder interviews

Semi-structured interviews have been introduced in Section 3.4.2 as a method to gather explanatory and exploratory insight in a relatively flexible manner. They are used here specifically to follow up on issues raised during the workshop or as part of the techno-economic analysis and invite comments from affected parties.

Identification of interview candidates

The process of identifying and inviting participants was based on two approaches.

Organisation based: An organisation known to be a relevant stakeholder was approached to put forward a contact who is prepared to engage in the process.

Skill based: A contact with a specific skill set, track record or relevant publication was approached directly.

The majority of candidates are the result of direct referral from workshop participants or members of the workshop steering committee. In very few cases would this candidate refer to another ‘more suitable’ interviewee. In three cases the contact was established by the interviewees, who had heard about this research and volunteered to take part in the interview process.

Organisations identified during the workshop as being particularly relevant, would be followed up specifically. This was for instance the case with distribution network operators, who were represented at the workshop, but a more detailed understanding of their position was deemed relevant for this research. Another such group, which had not been considered for the workshop, are demand side aggregators. Apart from these areas of special interest, a similar spread across the regime dimensions as for the workshop was attempted. The total resulting distribution of all stakeholders involved in the consultation is shown in Figure 6.2.

Candidates are initially approached by email and purpose and timing of the interview are in most cases agreed by email, too. The initial contact introduces the subject of the interview as ‘seeking to better understand the future role of electricity storage in future electricity systems and to understand the perceived benefits of different stakeholder groups from the potential presence of storage’. It stresses that the interview is an attempt to gather perceptions rather than facts and that no expert knowledge around electricity storage is required for the interview.

The recruitment of interviewees achieved a high rate of success. Out of all 30 interview candidates identified only one failed to be interviewed.

Interview preparation and conduct

Prior to the interview, interviewees were again briefed by email that the interview would seek their opinion on the future role for storage and that no technical knowledge about storage was required. The briefing information was not standardised. Where particular

expertise was relevant, candidates would be informed prior to the interview about particular areas of enquiry (such as for instance distribution network integration in the case of DNO representatives). Specific questions were, however, not provided in advance. The purpose of the interview was presented generically as to ‘inform the candidates perspective on the future role for electricity storage in the UK energy system’.

The overall structure of the interview process and the open ended questions underpinning the interview conduct are given in Appendix Table B.8.

Table 6.2: *Interview setting*

Preference	Location	Share of interviews in this setting
1	Interviewee’s site	50%
2	Neutral venue	23%
3	Telephone	27%

Interviews are conducted preferentially at the interviewees site or a site of their choice. The primary reason for this preference was to ensure that the interviewee were at ease with their surrounding and therefore more comfortable to speak freely (Saunders et al., 2009). Locations include personal offices, meeting rooms, but also nearby restaurants. If a meeting could not be arranged, telephone interviews were conducted as a last resort (see Table 6.2).

All interviews were conducted one-to-one, with two exceptions: in one case an expert joined the meeting via a conference call, in another the meeting involved a group of three.

All candidates are informed at the outset about the intention of the interview and the research background. A table of the open ended questions that guided the interview structure is given in Table 6.3. These questions are not followed prescriptively, but rather provide the structure, which remains responsive to the specific interview development.

The consent of participants was sought for the material to be used without attribution. In some instances interviewees agreed to direct and attributed quotation with the right to review the statement.

Note taking was adapted to suit the candidate and nature of the interview. More experienced interviewees would be asked for consent to being recorded. None of these candidates refused or showed any signs of unease. It was noted however, that some candidates in these cases answer questions more cautiously for the first 15–20 minutes of the interview, before opening up. In some cases more ‘opinion related’ questions are left until after the recording ended, at which point a more informal conversation reveals personal view points. To avoid self-consciousness and guarded responses, some interviewees are not confronted with the option of a recording and hand written notes suffice.

Recordings are encrypted, transcribed and then deleted. The transcript captures the essence of what is said. Only sections of specific relevance are transcribed verbatim.

The length of interviews was planned for one hour. Face to face interviews lasted between 50 minutes and 70 minutes, often followed by some less formal conversation. Telephone interviews tended to be shorter and would not run for more than 60 minutes. The structured questions are typically dealt with within the first 45 minutes, followed by more open discussion about their implications.

6.3.3 Stakeholder participation

The breakdown of all participants in workshop and interviews is shown by stakeholder group in Figure 6.2. The largest group is made up of academics, which reflects the conceptual nature of the research subject. The demand side is the least well represented group, which, as discussed above, may be related to the fact that at present the demand side does not constitute an active market participant and therefore no formal representatives could be identified.

The number of participants does not reflect their relative importance, nor should the results be weighted in such a way or used for statistical purposes. The process was intended to be qualitative, with insight being gained through in depth engagement with each participant, rather than—as would be the case in a survey based study—through numerical trends.

Some of the results from the stakeholder engagement process are presented in the following section, which contrasts differences in perception. Chapter 7 will further draw on the insight from interview and workshop findings resulting from this process and apply them to the analysis of possible uptake routes for storage.

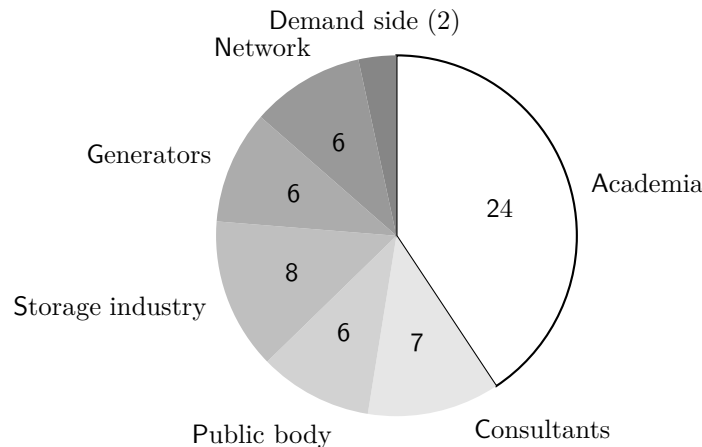


Figure 6.2: *Participating stakeholder groups in workshop and interviews. ‘Public body’ covers regulators, policy makers and research councils.*

6.4 Stakeholders perception of the value of storage

6.4.1 Preferred location and storage duration

The thirty workshop participants were given the opportunity to express their preferred location for future storage installations on the energy system and the storage duration they perceived as most valuable. The selection was collected with an iPad application, which is explained in more detail in Appendix B.2.1. Particular care was taken for participants to be able to make their contributions privately and anonymously. Before entering their choice, they select from a list of category names, which they associate with. Their ‘self-allocation’ leads to the groupings listed in Table 6.4.

The range of choices is deliberately wide. Timescales span from ‘seconds’ for frequency response to ‘years’ for inter-seasonal storage. Originally, five categories for location were offered: ‘home’, ‘distribution network’, ‘utility scale generator’, ‘transmission’ and ‘system’. Since utility scale generators tend to be connected to the high voltage network, the third and fourth category were later merged. The ‘system’ category is distinct in that this type of storage would not necessarily be located in physical proximity to existing generators.⁴

Choices were expressed as first, second and third preferences. This ‘alternative voting’ approach was chosen to ensure that participants did not have to average different preferences and would express freely which options were perceived as most desirable. The patterns did however suggest that the choices were perceived as somewhat discrete. A slight degree of clustering along the category labels did occur, as Figure 6.3 illustrates.

The overall results of all contributions are shown in Figure 6.3. The distribution covers the full width and breadth of the options provided. When interpreting the clusters one has to be mindful that the human eye is capable of seeing patterns even in random distributions. Nevertheless, a slight clustering for storage located at ‘distribution’ level or smaller and with durations between ‘hour’ and ‘week’ can also be supported with histograms (see Appendix Figure B.1).

The contributions are separated into stakeholder groups and shown side by side in Figure 6.4. Again, one must not over interpret a relatively small number of data points with such wide distributions. The broadest category with the largest number of submissions is ‘System’ and this remains highly distributed across both dimensions (Figure 6.4b).

The ‘generator’ group shows an interesting trend in Figure 6.4a, whereby short duration is performed by small scale storage and long duration storage is delivered on larger scales. Technically this combination seems very practical. Interestingly this distribution is not the overall trend for other groups. The policy group (Figure 6.4c) seems to occupy a complementary space with some short duration storage located at the system level.

The ‘storage’ group displays a clear preference for durations between hours and up to a week, with first choices predominantly towards smaller installations (Figure 6.4d).

⁴Physical location and ownership model are two separate issues. Some overlap can however not be avoided and some participants may perceive location also as a proxy for who owns or operates storage. When clarification was sought, participants were told that the category asks for their views on ‘location’.

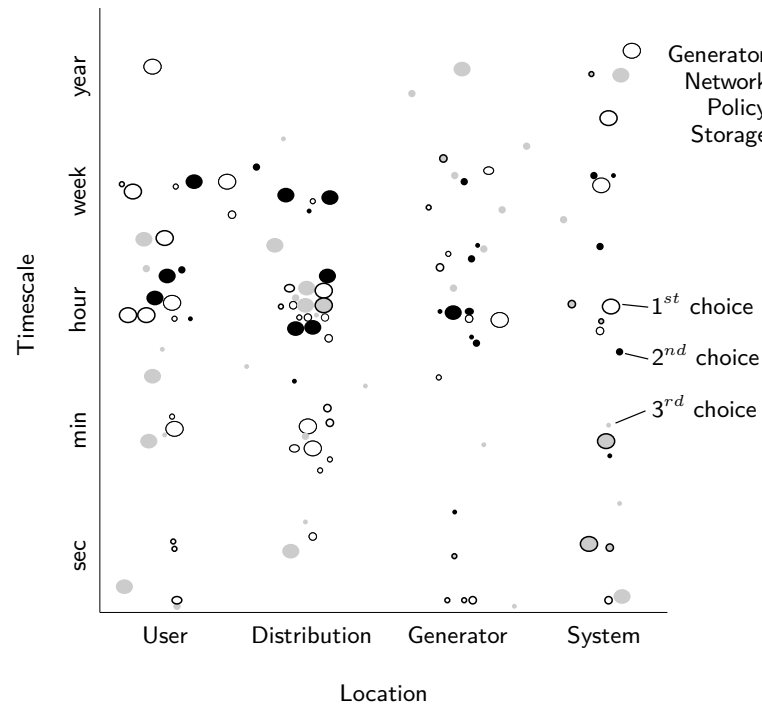


Figure 6.3: Distribution of all workshop contributions for preferred location and storage duration.

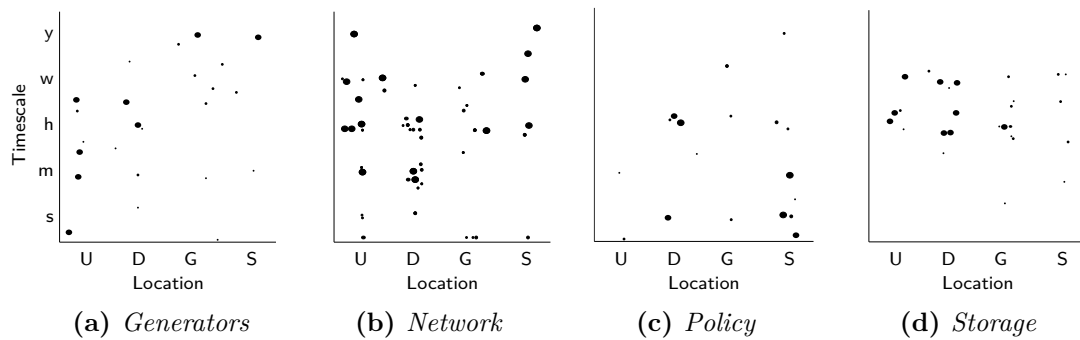


Figure 6.4: Stakeholder preference maps separated by stakeholder groups. (Locations: U=User or household level, D=Distribution level, G=located with Generators, S=System level; Timescales: sec/min/hour/week/year)

6.4.2 Stakeholder review of benefits

This process garnered insights into current practices and perceived responsibilities in dealing with system services that could practically be served through electricity storage. As part of the workshop, stakeholders contributed views on what they perceived to be the benefits arising from the presence of storage to the system as a whole. Participants received general scene setting presentations and engaged in a round table discussion on some of the major challenges facing storage. No guidance regarding the type, scale or ownership model for storage was provided, to encourage a ‘system wide perspective’, nor was any particular scenario put forward.

A total of 117 ‘benefit suggestions’ were submitted as part of this process. Appendix Figure B.4 highlights the dominant themes in the form of a word cloud. The submissions have further been grouped and assigned to broader categories as shown in Figure 6.5. The number of submissions in each category, while not statistically robust, gives an indication of the relative importance assigned to different functions storage could provide. The largest category covers system operation (33%), followed by system capital costs (23%). Consumer benefits and security/resilience also feature highly at around 14% each.

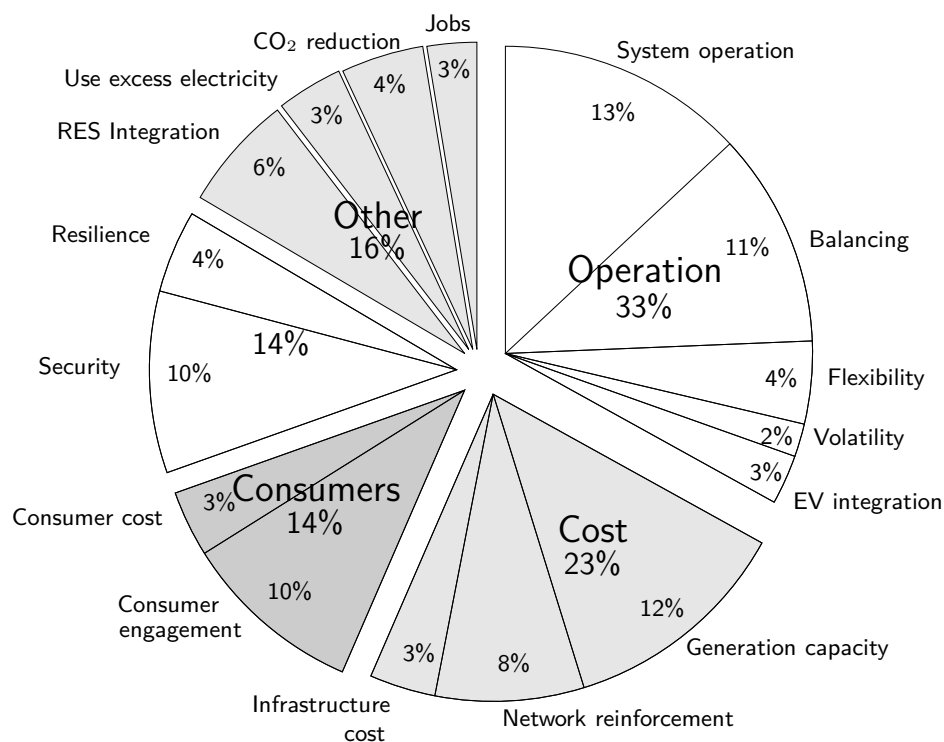


Figure 6.5: Breakdown of benefits suggested across stakeholder groups

6.4.3 Distribution of perceived importance of benefits among stakeholder groups

To address the question of how these perceived benefits were distributed among stakeholders, submissions were assigned to stakeholder groups. The grouping presented in Figure 6.6 follows loosely the sub-regime definitions for *Storage*, *Network* and *Generation*. *Consumption* is not included as a group in its own right. However, policy makers and regulators represent their interests to some extent. The storage group included both technology developers and operators, and the Network group also included participants classifying themselves as ‘independent’ or as possessing a ‘systems perspective’. The Generation group was primarily made up of utility representatives. Appendix B and Cooper et al. (2011) provides more detail about the workshop method and participant groups.

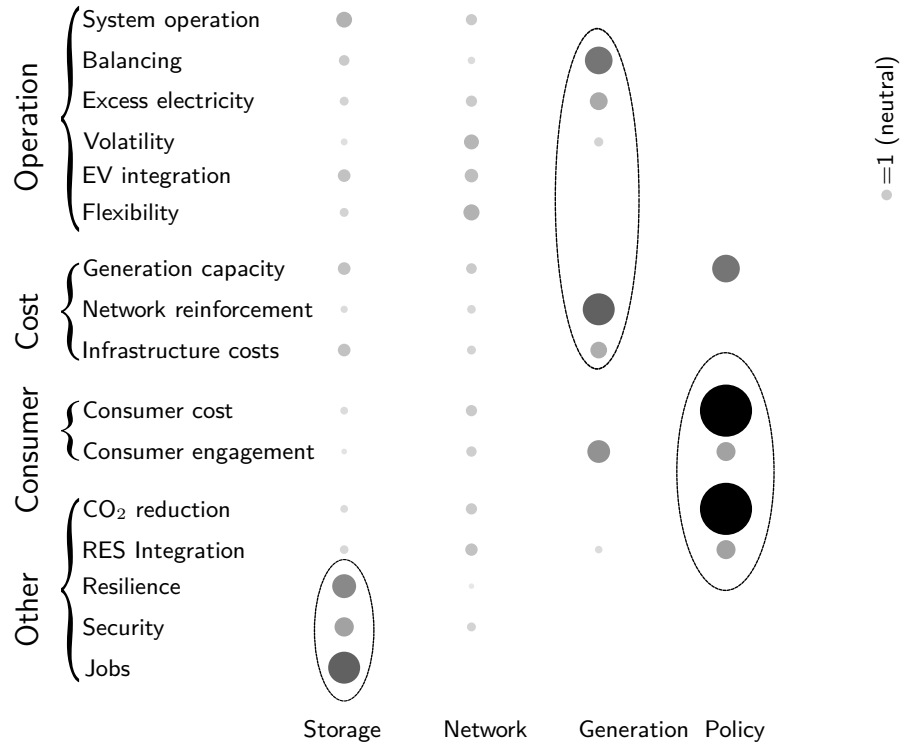


Figure 6.6: Relative importance of benefits to stakeholder groups. The size of circles is scaled by their relative importance squared (P^2)

The distribution of perceived benefits is based on the number of submitted benefit suggestions (n) for each benefit category i by stakeholder group j . The relative import-

ance of a given benefit to this stakeholder $P_{i,j}$ is calculated as

$$P_{i,j} = n_{i,j} \frac{\sum_i \sum_j n_{i,j}}{\sum_i n_{i,j} \sum_j n_{i,j}} \quad (6.1)$$

where values greater than one indicate that this benefit is more significant to this stakeholder than it is to the other groups. This metric provides a simple, yet robust comparison without the need to weight results (Pfeffermann, 1993). A graphical representation of the distribution of P values is shown in Figure 6.6. The categories are arranged in order of the number of submissions they received, with the most cited ones placed at the top.

Three clusters become apparent. One cluster for *Generation* focusses on cost and operational aspects. These were perceived during the discussions to yield potentially high value (or cost if not mitigated), which is consistent with recent modelling by Strbac et al. (2012). Interestingly, value is not necessarily only seen for this group itself. The *Generation* group cited network rather than generation cost avoidance as a major benefit. The implication of this ‘somebody else’s problem’ effect will be discussed in Section 7.1.

A second cluster, with the strongest relative preference ($P = 4.8$), falls to policy makers and regulators, to whom cost to consumers and CO₂ reduction are especially important.

Thirdly, storage developers and operators are prominent in the ‘miscellaneous’ category. This is interesting, as it shows a lack of overlap in priorities between storage related 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 only account for 17% of submissions (see pie chart in Figure 6.5).

The *Network* category does not exhibit any particular preference, which may be explained by the somewhat broader definition of the group and a more system wide perspective of network operators. The latter is supported by the semi-structured interviews.

6.4.4 Whose problem is storage?

Although the sample size cannot claim to have statistical significance, it is consistent with the plausible hypothesis that different groupings within the electricity system have different storage priorities. Such differences are not uncommon and other technologies may provoke similarly polarised views. However, in the case of electricity storage, all groups presented in Figure 6.6 are supposedly beneficiaries of storage and between them have to negotiate *how* storage is used and *who* pays for the investment and the services.

These questions were followed up in semi-structured interviews to identify in more detail the nature and origin of these differing stakeholder views and how they might affect technology uptake.

The stakeholders most commonly cited as ‘suitable candidates’ to drive uptake in storage are large scale generators, System Operators (SO), Transmission Network Operators (TNO), and DNO’s. Interviews with members of these groups, while not dismissing their interest in storage, do suggest a preference for ‘others’ to engage in investment and

operation. Utilities refer to network operators, network operators prefer to contract storage from aggregators (citing regulatory limitations), and these—in turn—point towards large generators as suitable investors. The circular dynamic of this ‘somebody else’s problem’ field around storage is illustrated with quotes and paraphrased statements from stakeholder interviews in Figure 6.7. It may therefore be necessary to consider the need for a new actor, which brings together the interests and skills of all affected parties.

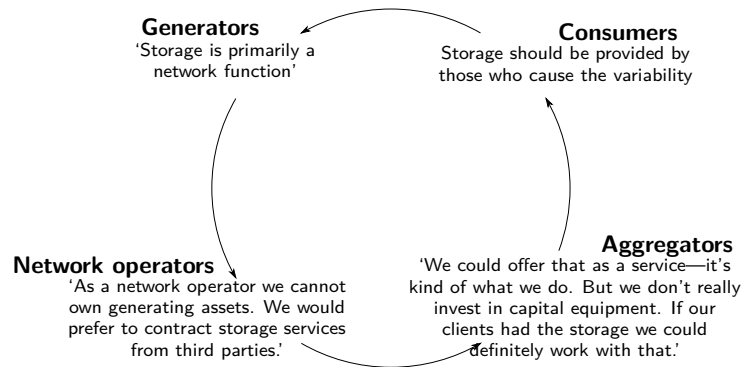


Figure 6.7: *The ‘somebody else’s problem’ field surrounding storage, based on interviewee statements from the respective groups.*

One preferred option cited by these groups is indeed an arrangement whereby a new actor (a ‘third party’) provides storage services, which can be purchased contractually. A regulatory benefit perceived by network operators is the freedom such a service provider would have in aggregating values through contracts with stakeholders from across the system. One commentator remarked, however, that this arrangement is merely exploiting a regulatory loophole, due to inconsistency between the treatment of capital and operational expenditure. DNOs contracting storage are, in this stakeholders opinion, stepping outside their remit by gaining a commercial stake in generation. A number of participants from a range of groups suggested that the direction of a stronger role for DNOs in acting as distribution system operators would be desirable, but would require careful regulation to ensure that conflicts of interest between network ownership and system operation were managed.

In the current system the expressed preference for contracting storage services from external actors points towards a trend identified by Unruh (2000), whereby regulated businesses tend to invest in ‘established’ technologies rather than ‘perceived risky alternatives’.

The mechanisms behind this institutional inertia can be exemplified for the case of DNOs. The stakeholder workshop suggested that DNOs are one actor thought to be well placed to lead the technology transition by investing in distributed storage. The follow

up interviews, however, revealed that DNOs are also thought to be ‘culturally deeply conservative organisations’ – a view that was expressed by several interviewees, including one from a DNO. While DNOs engage in pilot projects, such as those funded through the Ofgem Low Carbon Network Fund (Ofgem, 2010), the day to day operation and its deeply rooted norms and practices were accepted by some—including participants from DNOs—not to suit the concept of distributed electricity storage investment and operation.

From the interviews it can be concluded that the procedure of forecasting the timing, capacity and cost of network upgrades (transformer or wiring) is well established and understood by DNOs. By contrast, the confidence level in a certain storage investment to bring about the equivalent service quality is more complex to establish, especially if the asset has to be ‘shared’ with other parties in order to aggregate value streams. The analytical skill set required differs considerably from the present system and would have to undergo deep changes if distributed storage were to be considered alongside its alternatives in the institutional decision making process.

As an example, one interviewee from a DNO raised the process of connecting and synchronising distributed generators or CHP units to the distribution network. Such projects are said to be put forward to DNOs by commercial businesses and assessed against given criteria. The applicant is then presented with a bill based on the costs to the DNO. No dialogue between these two parties is said to take place to identify the least cost or most network beneficial configuration of such projects. The operation of such assets, which in theory could support voltage stabilisation or avoid network congestion, is said not to be considered either. Other interviewees, especially from the demand aggregation sector, supported this criticism.

If the operational benefits of electricity storage are to be recognised by DNOs, the assessment and engagement of DNOs with distributed resources in general may need to improve first. The effective integration of distributed resources, such as stand-by generation, CHP systems or demand side participation, all required higher levels of engagement from DNOs. The operation of stand-by generation may be less complex than that of storage. However, as the engagement develops, planning structures that are more amenable to the assessment of the value of electricity storage may evolve. Similarities between the analytical skills required for scheduling other distributed resources and electricity storage could lead to a cultural co-evolution of appropriate planning structures. As some of the added complexity is introduced into the decision making process more challenging operational projects can be undertaken, including active engagement, planning and scheduling of assets to minimised network costs.

So far, as one UK aggregator remarked, the benefits from demand response measures to the distribution network are not rewarded in any way, and that DNOs have to do more to ‘develop relationships’ with such new participants, if benefits are to be realised. Within the present planning structures, several interviewees felt that ‘wires and transformers’ would remain the default reinforcement choice for DNOs and that considerable institutional inertia would need to be overcome.

This institutional inertia applies to other actors in a similar way. Present actors have

evolved around a system characterised by ‘predict and provide’ supplies of electricity. Operating storage assets challenges the established culture and skill set of these actors. Trading positions need to be adjusted dynamically and several objectives must be considered simultaneously. The skill set required has been likened by one interviewee from the generation group to those for trading advanced financial products. Any actor who is to engage in storage would therefore need to be sufficiently incentivised to commit to developing such skill sets or attain them from other sectors.

A conceptual overview of the distribution of key competences among stakeholder groups is shown in Table 6.5. No single actor with a distinctly favourable set of skills emerges from this comparison.

6.5 Discussion and policy implications

Engagement with stakeholders has brought out a number of issues relating to the uptake of distributed storage in existing socio-technical sub-regimes. Modelling approaches, be they engineering or system models, tend to underrepresent institutional inertia in the uptake of new technologies during technological transitions and this process is therefore suited to complement such studies.

The proposed overlap of storage services with surrounding sub-regimes in Figure 6.1 has been contextualised. None of these sub-regimes appears forthcoming in driving the uptake of storage, other than in specifically targeted and funded initiatives, such as the Low Carbon Network Fund. Further, the need to ‘share’ storage assets to provide a system optimal mix of services led several stakeholders to favour storage being held by new ‘independent’ actors, rather than any of the incumbent participants.

Such actors face similar commercial challenges as those experienced by demand aggregators today. This suggests that policy makers should consider ease of market access as a barrier for such new entrants, especially if they are not part of incumbent organisations with established access to wholesale and balancing markets. For distribution networks, where no markets exist as such, transparency and dialogue between DNOs and other stakeholders in storage would need to be established if existing paradigms are to evolve towards a system that is flexible enough to seize technology options promising lower systems costs. Such a move might also require a change in risk profile, which balances participants’ supply obligations with cost of delivery.

It may therefore not be sufficient to only address the commercial and regulatory proposition. The workshop and interview responses suggest that cultural norms and institutional inertia among incumbents pose a significant challenge to technologies like storage that are not aligned with the present structures. Stakeholders at the workshop agreed that demonstration projects can go some way towards overcoming barriers of perception.

The stakeholder engagement suggests, therefore that without a clear ownership model for storage within existing sub-regimes, and in light of considerable institutional inertia on the part of some of the key stakeholders, new actors may be required to provide storage services.

6.6 Conclusions

The socio-technical perspective employed in this chapter provides a heuristic approach to discuss specific issues related to the uptake of distributed storage as part of the transition towards a low carbon electricity system. It does not provide quantitative results, nor can it claim to be statistically robust, due to the relatively small number of key stakeholders involved in the process. Nevertheless, the views reported here come from a broad range of stakeholders with actual or potential interest in storage, and so may offer valuable insights into the challenges faced by storage.

This chapter identified *Generation*, *Network* and *Consumption* as three distinct sub-regimes with different types and levels of regulation, rules and perceptions. Storage investors and operators have to engage with all three of them, if the system and commercial value is to be maximised.

Cultural and institutional barriers were raised by some stakeholders as a possible barrier for storage uptake. A mismatch of competences of existing institutions, which evolved around a ‘predict and provide’ energy supply paradigm, seems likely to require skill, regulatory and cultural changes to better engage with storage as a technology option.

The perceived value of storage differs between the stakeholder groups in both the workshop and the interviews. The availability of storage services would be widely welcomed by interviewees. However, when followed up in interviews, the investment is preferentially to be taken by other stakeholders. This ‘somebody else’s problem’ attitude towards storage could act as a barrier to deployment, unless benefits to those ‘others’ can be internalised and prove large enough to create a sufficient incentive for one particular group to invest.

The next chapter builds on these findings and draws further on the stakeholder interviews. It explores selected mechanisms that have been put forward by stakeholders to create incentives for particular groups to invest in storage and critically reviews their potential impact.

Table 6.3: *Steps of the interview process. Questions are reformulated to suit candidates and interview flow.*

Theme	Topic / Example Questions	Purpose
Introduction	Explain the background of research, purpose of interview, use of data. Stress that interview seeks perceptions rather than facts.	Provide context and put interviewee at ease.
Background	Can you tell me about your organisation? Could you provide me with some background to your activities in this area?	Engage interviewee on a subject within their comfort zone.
Benefits	Can you see a role for electricity storage in future systems? How would the presence of more storage on the system affect your situation? What role can you see for yourselves in relation to electricity storage in future systems?	Identify level of engagement
Operation	From your point of view, how would you like to see storage operated? Do you believe that storage operation requires regulation? Are current markets suited to stimulate the right kind of storage? How do you envisage to contract storage services? Do you foresee competing interests in the operation of storage?	Depending on candidate this theme can lead to open discussion
Investment	Who, in your opinion is best placed to invest in storage? X suggests that you may be well placed to invest—do you agree?	Explore relationships with other stakeholders. Challenge without confronting.
Barriers	What do you perceive to be possible barriers to storage deployment? How do you judge the role of regulation in this area?	Invite discussion
Open discussion	Questions emerging from discussion	Repeat and agree key notes. Chance for general comments and informal conversation.
Closing remarks	Repeat purpose and use of interview and explain next steps.	Ensure consent.

Table 6.4: Workshop stakeholder grouping by category. Participants self select the category on the right with which they ‘associate’ themselves. These are assigned to the groups on the left in the analysis.

Stakeholder Group	Number	Categories (i.e. roles in the electricity regime)
Generators	4	Utilities, renewables operators, investors in generation
Policy	5	Government departments, regulators, NGOs
Storage	5	Storage developers, storage operators
Network/System	17	Network, academic, consultant, generalist, other

Table 6.5: Relevant competences relating to storage in different sub-regimes, based on stakeholder interviews and author’s own estimates based on insight from stakeholder interviews. (FF=fossil fuel based plant, RE= renewable energy, SO=system operator)

Group	Generators		Network			Demand side
	FF	RE	TNO	DNO	SO	Aggregators
Investment profile						
High CapEx projects	high	high	high	high	low	low
Long payback projects	low	medium	high	high	low	medium
Risk taking	low	medium	low	low	low	medium
Market access						
Demand response	low	low	low	low*	low	high
Reserve provision	high	low	low	low	high	high
Balancing services	high	low	low	low	high	low*
Access to DNO savings	low	low	low	high	low	low*
Access to TNO savings	low	low	high	low	low	low*
Operating skills						
Dispatch scheduling	high	low	low	low	high	medium
Demand forecasting	high	low	low	medium	high	high
Technology development						
Innovation	low	medium	low	low*	low	medium
R&D	low	low	low	low	low	low

*=expressed interest in competence development

Analytical assessment of storage uptake: markets, niches and targeted support

THE PREVIOUS THREE chapters have employed individual components of the analytical framework to assess the potential uptake of storage technologies under varying circumstances. The commercial drivers have been explored by means of a techno-economic analysis, while the wider system benefits and dynamics within the socio-technical regime have been addressed through stakeholder engagement. The analysis in these chapters was framed by insight into the dynamics of transition processes gained as part of a review of historical transitions in Chapter 4.

This chapter draws on the insights from these different approaches and combines them to explore how storage may develop in future. Several uptake mechanisms have been proposed by stakeholders. Some of these are now scrutinised by drawing on the components of the analytical framework. The mechanisms under investigation are market led uptake, uptake through niches and uptake as a result of targeted support.

Section 7.1 revisits some of the findings from Chapter 5 on the market drivers behind storage and compares them with the results from a study on the system value of storage.

Section 7.2 focusses on niche applications as a starting point for market uptake, building on insights from the stakeholders.

The potential impact of selected targeted support measures is dealt with in Section 7.3. Selected support mechanisms, which have been put forward by stakeholders, are analysed, either qualitatively, or with help from the techno-economic model, to test their potential effectiveness and scope for unintended consequences.

Implications for the uptake routes of storage and for policy relevant considerations are discussed and concluded in Section 7.4.

7.1 Market led uptake

The findings of the techno-economic analysis in Chapter 5 suggest a highly unusual future for storage. Whereas typically technologies have to reduce cost and improve performance to become or remain competitive, the cost targets for storage seem to become increasingly relaxed and efficiency becomes less crucial the more wind is deployed. This convergence of costs and targets might seem to suggest an inevitability of deployment. As the following analysis shows, changes in technology targets may also lead to missed opportunities and tipping points in the pathway development.

7.1.1 Mismatch between market value and social value

Chapter 6 argued that market based frameworks, such as the techno-economic model in Chapter 5 are not well equipped to identify wider system benefits and may therefore undervalue the contribution of storage to the energy system as a whole. System studies, conversely, can provide insight into the potential system value, but do not necessarily expose the attractiveness of the technologies to investors. Unless perfect markets are in place, one would expect a discrepancy between the ‘system value’ and the ‘market value’ of storage. Table 7.1 gives a high level overview of the conceptual differences between market and system values of storage. The difference and the resulting welfare loss as a result of underinvestment is illustrated in Figure 7.1.

Table 7.1: *Comparison of Market and System value of storage*

Market Value	System Value
Realised by market participants by trading within available market structures	Abstract theoretical value accruing to the overall system under ideal conditions
Indicative of the attractiveness of storage to investors	Indicative of the attractiveness of storage to society or policy makers
Can be modelled for subsets of the system	Requires a whole systems perspective
Draws on existing or hypothetical market arrangements	Assumes idealised, perfect market conditions
Assumes commercially rational utility maximising actors	Assumes system optimal allocation and operation of storage, including consideration of system operation, improved scheduling of spinning reserve and other infrastructure savings, which may not be fully represented through market price signals

Figure 7.2 contrasts the results of the techno-economic model of this study with the system values of storage as established by Strbac et al. (2012). Both studies attempt to

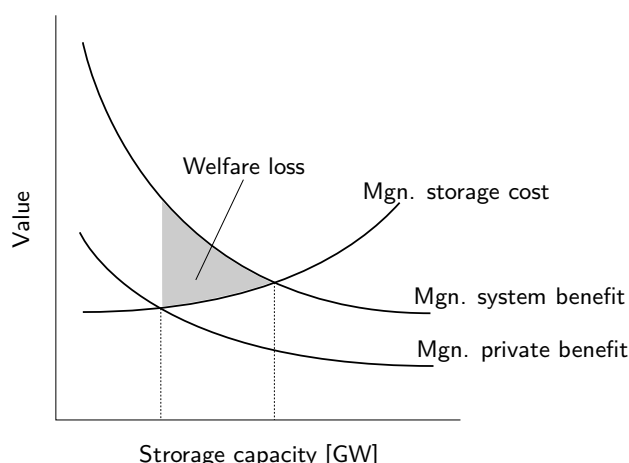


Figure 7.1: *Welfare loss as a result of underinvestment. Once marginal private benefits are equal to the marginal cost of storage no further storage is deployed, leaving a welfare loss of not realised system benefit.*

simulate an adjusted version of the DECC Grassroots scenario for the year 2030 with 69 GW of wind on the system.

The meaning of ‘value’ behind the two graphs is very different. The system value is the amount that could theoretically be saved per year across the system for every kW of storage installed, assuming system optimal allocation and operation. The market value stems from the trading revenue realised with each kW per year of operating in an energy based market. All values are gross values, meaning no costs for storage technologies have been deducted. The difference between the two graphs can be attributed to a number of reasons. It can for instance not be dismissed that a superior solver in the Strbac et al. (2012) study may find higher optima. Furthermore, the two studies draw on independent datasets for wind and demand. As Section A.1.3 on page 244 has shown, different sources of wind data and allocation of sites can impact results by around 10–20%.

These potential differences notwithstanding, some of the discrepancy of results can be attributed to systematic differences in analysis. Neither study allows for additional investment in generating assets or changes to the plant mix. However, the Strbac et al. (2012) study includes savings from displaced plant and savings from avoided network reinforcement. As Figure 7.3 on page 178 showed, the transmission savings are negligible and their omission from the techno-economic model may therefore not account for much of the discrepancy in value.

Distribution network savings are also not accounted for in the techno-economic model, since wholesale prices do not explicitly reflect local distribution network constraints. Compared to transmission network savings, distribution network savings are more significant in value, and they are therefore marked separately in Figure 7.2.

A further difference in approach is the optimal scheduling of plant, performed by the solver in Strbac et al. (2012). Whereas the market based approach seeks to minimise the cost based on a merit order dispatch, the Strbac et al. (2012) study is more sophisticated. Spinning reserve, which has to be held for fast reserve provision especially in high wind scenarios, is a costly and inefficient form of generation. It can displace other sources with potentially very low short run marginal costs and lower emissions. Spinning reserve is not scheduled based on least cost market dispatch, but by the system operator with a view to ensure security of supply in the event of unforeseen changes in load or generation. The whole system approach seeks to minimise the use of spinning reserve through storage. The exact contribution of this particular operational saving is not singled out in the results. However, the effects of the optimised scheduling are most pronounced for small levels of deployment. For larger installed capacity the difference between the techno-economic and the system model therefore becomes smaller.

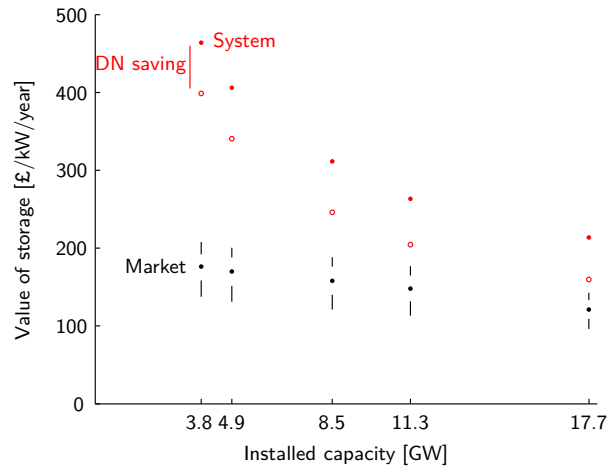


Figure 7.2: Market and system value of storage. The value for storage realised in a volatile energy market is consistently lower than the system wide value. Based on 2030 adapted Grassroot scenario with 6h storage. System values: Strbac et al. (2012)

Some of the system values, such as distribution network savings, might be added to the value of storage through negotiation of dedicated contracts as discussed in Chapter 6. Others, such as optimal scheduling of plant may be more difficult to implement as will be discussed in Section 7.3.

Wholesale prices in the techno-economic model do not recognise the location specific value of electricity. Nodal pricing might to some extent address the need for price signals that reflect transmission or distribution constraints more transparently. The scope of this study does not allow for the testing of the merit of this approach, which would require a very different model.

The value gap between the wholesale market based model and the whole-systems

model shows that the wholesale energy market alone does not capture the maximum value, nor does it therefore stimulate the optimal use of storage across the system. The implicit policy challenge is to create a market and/or regulatory framework that stimulates the desired deployment, therefore, and operation of storage, similar to that in the Strbac et al. model. The market values in Figure 7.2 suggests the lower bound (market value) and the upper bound (system value) of what such a framework might achieve.

7.1.2 Declining marginal value

The simulation of market values in Chapter 5 assumes that storage capacity is operated as a fleet and the proceeds are shared. From this perspective the average value of a given storage capacity is a valid measure.

However, investments take place incrementally. For investors it is therefore the marginal value that matters. Only if the marginal value is greater than the marginal cost would investment be forthcoming. It may be commercially viable to build 10 GW of storage, but it may not make commercial sense to build the 10th GW if 9 GW are already present.

The discrepancy between the average value and the marginal value has implications for the long term uptake of storage. Depending on whether storage is viewed as a collective asset or an incremental addition to the system, the value proposition changes fundamentally. Figure 5.8 on page 130 showed that marginal values can be significantly lower than the average values, due to the ‘self cannibalisation’ of storage.

The diminishing marginal value also affects storage over its lifetime. An investor who at times of under supply of storage has a sound business case for investment could see the value reduced and even negated if additional storage capacity or other means to provide storage services are installed. Over the planning horizon a storage investor has to consider, innovation and technical improvements could lead to additional investment, which reduces the average value of existing storage.

Even though the future average value of storage could be generally rising, a risk averse investor may not want to commit to a long term investment in a market in which the marginal value might be volatile and falling over time.

7.1.3 Value aggregation

The multitude of benefits identified by the stakeholder consultation in Section 6.4 identified a multitude of potential benefits, not all of which are rewarded in a wholesale energy market. Even if they can be monetised, several of these value streams would need to be aggregated to improve the commercial proposition of storage.

The sequence in which values build up has potentially pathway critical implications for the value proposition of storage. The wide deployment of wind energy in Scotland, for instance, creates a north-south transmission constraint, which could be avoided through bulk storage nearer the source of generation. Conversely, deployment of electrified heating and transport puts strains on distribution networks, especially in densely populated

southern regions. These trends have been quantified by Strbac et al. (2012) and an illustrative example of the development in the aggregate value in 2020, 2030 and 2050 is shown in Figure 7.3.

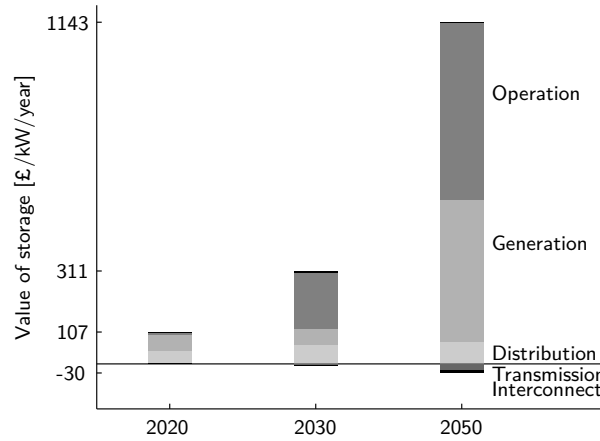


Figure 7.3: *Illustrative example of storage value composition 2020–2050. In 2020 distribution network savings provide a large share of value. In 2030 operational savings constitute the largest component, before in 2050 savings from avoided peak generation capacity become significant. Distribution network savings remain stable in absolute terms, such that their relative contribution in 2050 becomes minor. Based on adapted DECC Grassroots scenario with 10 GW, 24 hour distributed storage, Strbac et al. (2012).*

These illustrative results, based on a DECC pathway with a high share of renewables, suggest, aside from a significant increase in the overall value, that the composition of value could change over time. In 2020 savings through avoided distribution network reinforcements could make up a large part of the overall value. By 2030 their relative contribution becomes minor and operational savings from more efficient plant scheduling dominate. By 2050 the composition could change again when costly peaking plants, which in 2050 would have to be CO₂ abated in order to meet overall emission constraints, could partially be displaced through storage, which leads to savings in generation capacity.

Figure 7.3 suggests a shift from distribution network savings in 2020 towards operational and generation side savings later on. The trend among *Generation* stakeholders to perceive storage as ‘somebody else’s problem’, as observed in Section 6.4.4 on page 165 is supported by these data.

Literatures on path-dependency and technology lock-in suggest that the choices during early phases of uptake do affect the available technology options going forward. Institutional and regulatory structures form, practices and norms develop and technologies innovate in response to early adoption. It is therefore important to be mindful of the potential long term role of storage with regard to savings in distribution networks

and towards generation and operation costs. Even if the short term benefits suggest a high share of value for DNOs, the foregoing analysis suggests that engagement with other stakeholders in the development of appropriate policies may be beneficial if long term interests are to be safeguarded.

7.1.4 Phased build up of aggregate value

The techno-economic analysis in Chapter 5 suggested that the commercial value of electricity storage in future scenarios could reach sufficiently high levels to become a viable business proposition within energy markets.

However, the modelling approach took snapshots through time. This approach does not take into account how competing alternatives might be viewed by stakeholders in the lead up to commercial tipping points for investment decisions being reached. During the gradual build up of value, more established technologies could be deployed instead and dampen the build up of value for storage, increasing investment risk.

The dis-aggregated nature of the value of storage discussed above could thereby affect the timing, when the aggregated value reaches investment tipping points. Figure 7.4 illustrates with a very simple example two possible pathways. If one assumes two technology options, of which one is specifically designed to address value proposition (V_1) and the other is capable of aggregating two value propositions (V_1 and V_2), but at a higher cost. In period one, only V_1 is available and in period two, both V_1 and V_2 can be accessed.

The following choices can be made. The economic default option would be Figure 7.4a, where the dedicated least cost option C captures V_1 with a surplus of 1. By the time the second value proposition emerges, V_1 is adequately addressed and C^* enters the market to capture V_2 only. Each investment decision is economically viable at the time and a total surplus of three units accrues (1 in period one and 2 in period two).

The same costs and values apply in the example in Figure 7.4b. This time, however, the option with the potential to aggregate both value propositions is employed in period 1, despite its higher cost. In period 2 the additional value of V_2 can be aggregated and the total surplus increases to five units.

As this illustrative example shows, technologies with the potential to aggregate values, which emerge gradually over time, can potentially be delayed in their deployment, or in more extreme cases be locked out altogether, with a resulting loss in overall surplus.

A possible case of such build up of value aggregation is shown in Figure 7.3. Here it is the distribution network savings, which could potentially be addressed with storage solutions. Later on such solutions could accrue additional value through services for generators and system operators. Should, however, alternative solutions be deployed to capture the value in early distribution network applications, then this value will no longer be available to storage later on thereby delaying the timing of the economic tipping point.

However, so long as distribution network operators value storage only on the savings to the distribution network, storage does not get selected (EA Technology, 2012, p. 106).

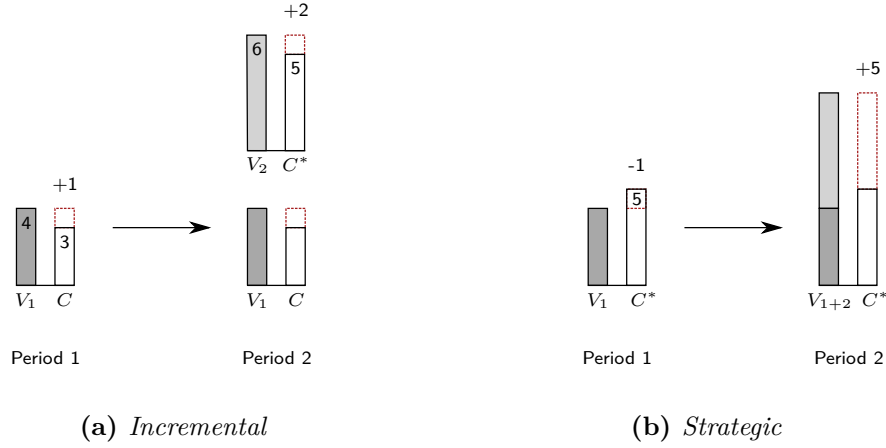


Figure 7.4: Illustrative example of value aggregation build up under incremental and strategic planning. Option C has a cost of 3 and can capture value V_1 only, whereas C^* , at a cost of 5, can capture V_1 and V_2 , which emerges in period 2. In (a) value proposition V_1 is met with least cost option C . In period 2 value proposition V_2 is met with option C^* . Each solution is economic and the total surplus over both periods is +3. In (b), option C^* is deployed at a loss in period 1, but the total aggregate value over both periods has risen to +4. Although a higher value can be captured, this option demands a ‘leap of faith’ from investors that V_2 will materialise.

DNOs are strongly regulated to avoid network constraints and minimise customer minutes lost. Remedies to constraints therefore have to be applied preferably before constraint situations arise and potentially well before other sources of revenue for storage have reached levels that put it on a commercial par with conventional ‘wire and transformer’ reinforcement. Once these alternatives have been deployed they remain on the system for decades. The opportunity for storage to aggregate distribution savings is lost. The remaining components of value would have to increase further for a now somewhat different type of storage to reach commercial viability.

7.1.5 Regulatory barriers and market failures

Opinion among stakeholders over the presence of market failures, aside from those relating to innovation, was divided. Some participants, especially from network operators, argue that there is no practical reason why storage owners and operators could not enter into bilateral contracts with service recipients. Short Term Operating Reserve (STOR) arrangements were cited as a working example of such arrangements. While in principle many stakeholders agreed with this notion, several practical complications were raised.

Dominant market structures have evolved around generation markets, such that regulatory details can prevent new entrants from competing on a level playing field in

some cases. Incidentally, the STOR market is again cited as an example, this time by a demand aggregator. STOR allows storage and demand side response to participate, yet its origin as a generation instrument is still apparent in subtle and presumably unintended details within the regulations. If, for instance, a STOR window begins at 7am, businesses, who typically bring on their load from 9am onwards, cannot commit to providing response services for the morning response period. Similar obstacles could result if regulation treated storage as another form of generation, without consideration of its practical differences and limitations.

Secondly, barriers exist around market access and licensing. The balancing market, which could provide one of the value streams for storage, currently requires a licence. UK demand aggregators regard this barrier as being sufficiently high that they do not engage in this market, yet. For bulk storage, such as existing pumped hydro installations, balancing markets provide valuable sources of revenue. Distributed storage, however, may find access to such markets more difficult. Similarly, engagement and communication channels with DNOs are said to be in need of considerable improvement if their saving potential is to be accessed transparently.

The regulatory classification of storage as a form of generator does presently prevent network operators from owning and operating storage. As discussed in Section 6.2.2, generation is only one of many storage functions. The overlapping roles for storage across generation, network and consumption regimes make appropriate classification and regulatory integration a challenging task.

Furthermore, some of the benefits are not included in current markets at all. Operators would currently not receive any value for avoided transmission losses, emission reductions or deferred distribution network reinforcement, according to demand aggregators.¹ In addition, stakeholders saw security of supply and power quality as undervalued or external benefits.

7.2 Uptake through niche deployment

Niches, as introduced in Section 3.3.3 on page 74, constitute protected spaces for technologies to develop. Their role is not confined to development of the artefact itself. Niches allow institutions, practices and actors to develop and adjust to new artefacts and their operation, and thereby create the possibility of ‘configurations that work’. Viewed from this perspective, even fully developed technologies (in TRL terms), such as pumped hydro, may require niches, if relevant structures have not yet developed.²

Section 4.5.2 on page 99 has argued, based on historic cases of storage uptake, that the emergence and disappearance of niches for electricity storage is highly sensitive to changes in the configuration of the socio-technical regime.

¹Demand aggregators therefore assign no preference to demand response measures that lead to such benefits, nor would they value storage as a additional asset in achieving them.

²The operation of pumped hydro is evidently established, with several sites operating in the present market. What is less clear is the extent to which structures exist leading to new investment in such technologies, given that all present sites date back to pre-liberalisation.

Table 7.2 provides an overview of some potential niche applications. This summary has been informed by stakeholder and expert opinions. The regimes most likely to have a key stake in each of the niche applications show that *Generation*, *Networks* and *Consumption* could all theoretically drive the uptake in future niches. One niche for each regime is briefly introduced before the potential impact of early niche development on long term uptake is discussed in Section 7.2.4.

Table 7.2: *Potential niches for early storage deployment and demonstration as cited by stakeholders. The regimes listed are associated with the niche and the value of storage in this application.*

Niche	Regime	Protective aspects	Limitations	Examples
Wind self balancing	Generation	Increase the value of wind output by shifting it to higher value periods.	Insufficient market incentive. Wind diversification through networks is a lower cost first response.	U.S. created through legislation AB 2514 (Hernández, 2011)
UPS provision	Consumption	Supply outages create an immediate high value requirement driven by disruption sensitive (industrial) consumers.	Competition of high emission, low efficiency diesel gen-sets. Operation is in the private, rather than the best system interest.	Emerging market in Germany (Schröder, 2012).
EV integration	Network	Provide localised reserve for charging hot spots	Favours high cost, high performance technologies with short durations.	Home fast charging points (Energy solutions, 2012)
DN support	Network	Potential for savings on infrastructure and avoided road works in constrained locations.	Institutional and cultural barriers	Bracknell distribution network, SSE, created through funding (LCNF)
PV levelling	Network	PV installations create localised volatility and effective electricity price gradients.	Modelling suggests that price signals are insufficient to warrant storage applications and conflicts with national priorities may occur.	Commercial products available. Level of uptake unknown.
Fast response	Generation	Suited to certain technologies	No protection through exclusivity. Competitive market with limited size. Other contenders include thermal plant, EV, DSR and wind.	Dinorwig pumped hydro station
Islanded system	All	Smaller networks face wind integration challenges sooner than larger networks. Islands tend to have higher degree of vertical integration.	Smaller networks can differ in characteristics to national grid connected applications.	Shetlands, Eigg. Supported in part through public funding.

7.2.1 Integration of electrified transport

One sector that was not included in the regime definition in Section 6.2.1 is the transport sector. Electrified transport could bring about technologies that also find applications for grid based storage. As the example of battery deployment in early DC networks in Section 4.1.1 has shown, technologies intended for one market, can ultimately find applications in other sectors. In the late nineteenth century, the appeal that drove developments in battery technology, was the prospect of a large market in electrified transport. Parallels with the present day suggest that a similar development could take place, in which vehicle batteries and grid storage batteries could co-evolve. Some stakeholders argue that the technological development stimulated in the transport sector could reduce prices to such an extent that the technology becomes commercially viable for grid applications within a few years (McCrone, 2011). Another proposed deployment route is that the mass deployment of batteries in transport applications could lead to a ‘second life’ market for used batteries in grid applications (ERP, 2011).

Rapid charging could create such an application. High power charging creates stresses on the local network, which can be overcome with a storage ‘buffer’. Thus, storage developed for the transport sector could be used to address one of the problems created by this sector. The results would be a technical co-evolution of transport and grid storage.

The additional cost of a charge point with storage leads to the value aggregation challenges outlined in Section 7.1.4. Distribution network operators could be expected to contribute towards a solution that lessens the impact of rapid charging on their infrastructure. Yet, such contributions would have to be negotiated.

In this scenario transport storage technologies would enter virtuous cycles of development with co-evolution of electrified transport and grid storage. Storage technologies from the transport sector lead the development and become more advanced. Established manufacturing and distribution infrastructures dominate solutions specifically targeted at grid applications. They therefore have an early mover advantage and could find deployment in early niche applications, with high location specific value.

The characteristics demanded of a transport storage device include high energy density and specific energy combined with high round trip efficiency and fast ramping. As the techno-economic model has shown, none of these performance criteria are specifically relevant to grid applications, and the evolution of the technology from one sector into the other could lead to unnecessarily high performance solutions at higher costs.

While these isolated cases of high value storage for specific applications may suit some readily available technologies emerging from the transport sector, the declining slope of the marginal value of storage suggests that the market for this type of technology is limited.

For storage to grow into wider deployability, the techno-economic analysis of Chapter 5 suggests that a different set of target parameters would need to be developed. Too strong a co-evolution between transport related storage development and grid based storage could thus lead to a limited scope for resulting grid based storage solutions.

7.2.2 Wind self balancing

A small number of stakeholders advocated that storage should be sited where the problem is caused: at the wind turbines or the PV array itself. PV will be discussed in the next section. The placement of storage with wind turbines is conceptually compelling and offers an opportunity for early feasibility studies and technology deployment pilots (see Aguado et al. (2009)).

Commercially, storage cited with wind turbines does not constitute a natural niche. Present policy instruments, such as ROCs, further create a disincentive to shift the dispatch of energy in time (see Section 7.3.1). However, strategic niche management could create protected spaces. Legislators in the U.S. have begun to legislate the deployment of storage (Hernández, 2011).

The result of storage physically coupled with wind generators could be that each such site is incentivised to primarily balance its ‘own’ generator. The techno-economic model suggests that less aggregated wind resources lead to a more favourable role for storage (see Appendix A.1.1). This is to say, that with a more aggregated resources, the cost of integration is lower, because less storage is needed.

As a first order integrating measure it is therefore beneficial to aggregate wind by connecting several sites on the network (see Neuhoff et al. (2008); Degeilh and Singh (2011) and Sinden (2007)). The aggregated profile becomes smoother and the role for storage subsequently reduces, i.e. the cost of integration is lower. Transmission networks, as already mentioned in Section 7.1.1, provide in many instances a commercially superior solution to electricity storage.

Combining storage with individual wind sites therefore provides a possible starting point for deployment, but not necessarily a long term optimal allocation. The total storage capacity required with this approach would be unnecessarily large and storage durations may be configured too short as a result, since aggregated wind profiles become less ‘spiky’.

7.2.3 Insuring against supply disruptions

High levels of renewable generation on the German electricity system have led to the first alleged cases of increased supply disruption. Industrial customers with high commercial exposure to process interruptions have begun to take steps to insure themselves against outages, which are said to cost them between €10,000 and €100,000 per incident (Schröder, 2012). The technologies of choice are diesel gen-sets, but storage batteries are also being increasingly deployed. Responsibility for costs incurred as a result of outages is still disputed between network operators and customers. (Schröder, 2012)

This niche creates a small, but high value early market for storage technologies, which need to be reliable, yet operate extremely infrequently. Storage durations would be configured very short and the number of discharge cycles would be low, allowing for modest life cycle targets.

These storage owners may provide the capacity, which demand aggregators say they would be interested to operate for them (see Figure 6.7). This collaboration could ensure

higher commercial attractiveness for industrial clients, while the right incentives for aggregators may steer the configuration of such storage technologies towards durations and cycle life times more appropriate for longer term use in future networks.

7.2.4 Path dependency arising from early niches

Many of the niches listed in Table 7.2 originate at the distribution level and distribution network operators were identified in Chapter 6 as one of the potential stakeholders well positioned to facilitate early adoption. The techno-economic model of this study is not equipped to explicitly simulate benefits for distribution network operators and the changes in requirements are therefore discussed qualitatively.

The primary role of storage in distribution networks is to ensure that peak demand remains below the network capacity. The value of this service is estimated by Strbac et al. (2012) to be around £50 per kW per year within constrained networks. As the load profiles in Chapter 5 have shown, the duration over which demand needs to be shifted to reduce peak load is relatively short. At the more disaggregated distribution level the demand profile can be expected to be less smooth than at the national level and the trend towards short duration storage bringing about the desired peak reduction can therefore be more pronounced. The simulation of individual household energy consumption for 50 homes suggests that future peak demands could be reduced by over 30% with merely one hour of storage duration (Grünewald, 2011). This result is consistent with Strbac et al. (2012), who identified no significant increase in value from extended storage durations for distribution networks.

This would suggest that early adoption in distribution networks might favour technologies with relatively short storage durations, which as shown in Chapter 5, also happen to have the highest cost targets, and thus suit early adoption. The above mentioned value of £50 per kW per year, by itself, is unlikely to stimulate distribution network operators to invest in storage. A study by EA Technology sees no role for storage in their modelling when only considering the distribution network benefits. (EA Technology, 2012)

Additional revenue streams would need to become available for such investments to become commercially viable. Based on the results shown in Figure 7.3 on page 178, a case could be made for strategic niche management and to provide funding to support distribution network operators in bringing a technology to market, which has potentially significant long term benefits.

Such support would need to be mindful of changing requirements from storage over time. Whereas distribution network applications might focus on high value applications served by efficient storage units with short storage durations, some of the cases modelled here suggest that, as wind deployment increases, lower efficiency storage technologies with longer storage durations, but significantly lower cost targets should be considered.

The uptake through the types of niches foreseen by stakeholders in this study may require deliberate inclusion of longer term targets for storage to suit stakeholder interests, which do not yet offer suitable niches. Targeted support may help in reaching these goals and is discussed in the following section.

7.3 Uptake through targeted support

The review of niche uptake and the comparison of market based results of this study with system values for storage in Section 7.1.3 seem to suggest that in order for societal welfare to be maximised, some strategic intervention may be necessary. This section will therefore explore selected measures and their impact on the role of storage.

7.3.1 Integrating wind

Storage representatives expressed concerns over the structure of subsidies in the present system and their effect on storage commercially. This concern has two components. The first relates to the support for nascent technologies in general:

Unlike any other new technology [storage] has to stand on its own two feet commercially from day one [...] We subsidise all the other things and not storage, which sits in the middle and could help balance it all.

Storage sector representative, Workshop, May 2011

Wind and PV are said to receive subsidies on the understanding that they have a role to play in the long term. This role for storage is not as clearly defined and therefore subsidies are not yet in place.

The second aspect of the concerns over subsidies for renewables relates to their effect on how the timely provision of energy is valued.

You have to ask, how can we create a market for time shifting wrong time energy ... Should, for instance, wind receive a different level of subsidy depending on whether it is generating at peak time or off-peak? And without penalising wind you can then subsidise storage as well.

Storage sector representative, Workshop, May 2011

This, and similar, suggestions have been put forward by storage representatives in follow up interviews and at other events (ESN, 2012).

The effect of time dependant ROC³ prices can be simulated with the techno-economic model introduced in Chapter 5. At times of surplus the price depression is less pronounced due to the lower opportunity cost of losing ROCs. This has a flattening effect on the wholesale price duration curve. The uplift of peak prices remains largely unchanged by this intervention. The value of storage on a wholesale market would consequently be reduced. However, the wind generator gains an incentive to shift the timing of dispatch.⁴

This instrument would therefore encourage a very specific type of storage, which is placed in physical proximity to wind generators upstream of the point where the output

³Renewables obligation certificates can be earned by generating electricity from eligible renewable sources and traded with licensed electricity suppliers, who are mandated to demonstrate a certain share of their generation to be backed by ROCs, thus creating a market mechanism.

⁴Assuming that the spirit of the intervention is to reward wind energy 'shifted' with storage to peak periods with higher ROC prices. For this to happen the total ROC budget would have to increase.

is metered to determine the level of ROCs awarded. From a systems perspective this allocation of storage could be sub-optimal, since wind installations are diversified in the first instance through transmission network connections. If each wind installation self-balances, the smoothing effects of comparatively cheap transmission networks are not fully taken advantage of (see Section 7.2.2).

An alternative model to overcome this constraint would be for ROCs to be upgradable by third parties. The wind generator receives a low value ROC at the time of off-peak demand. This ROC can be sold to a storage operator who is charging at the time. This storage operator can ‘upgrade’ the value of this ROC by dispatching in a high ROC value period. This approach could, however, be subject to misuse, since it can not be verified, based on the RO certificate alone, that the dispatched energy was indeed ‘renewable’.

Figure 7.5 illustrates potential misuse. In period 1 storage buys surplus wind and thereby acquires off-peak ROCs. A storage operator maximises revenue by discharging the renewable energy at the earliest opportunity in period 2, recharges on fossil fuel based energy in period 3 and can convert the high value ROCs by discharging again in period 4. This operation is especially problematic for storage systems with low round trip efficiency. So long as energy is moved from period 1 to period 4, losses only apply to surplus wind energy with low cost and environmental impact. If, however, storage is incentivised to trade between periods 3 and 4, fossil fuel based generation (which could have served period 4 directly) increases due to storage roundtrip losses.

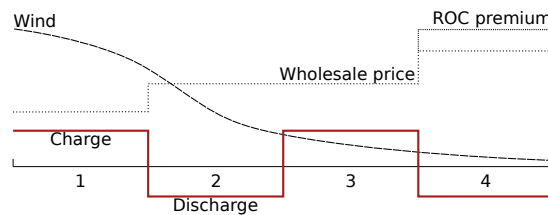


Figure 7.5: *Unintended consequence of incentivising storage with ROCs. The energy discharged in period 4, and claiming peak time ROCs, can increase overall fuel use due to re-charging in period 3.*

7.3.2 Storage for self-balancing of PV

Feed-in tariffs (FiT)⁵ for photovoltaic installations are also non-trivial in their relationship to storage. The FiT itself is in fact neutral to storage, since it is generation based, irrespective of time and whether consumption takes place locally or energy is exported

⁵Feed-in tariffs are a guaranteed price for electricity generated from eligible renewable sources independent of whether the electricity is exported or consumed locally.

to the grid. The export tariff, on the other hand, determines the attractiveness of storage. At a time when PV generation exceeds domestic demand, the options for the PV owner are to export this energy at the export rate, or to consume it and forgo the export rate. The cost of consuming is therefore the opportunity cost of losing the export rate. Without an export rate this ‘cost’ would be zero. The higher the export rate, the more costly and less attractive it becomes to ‘use’ the energy.

McKenna (2012) demonstrates the effective price resulting from the presence of PV generation for a group of dwellings based on the opportunity cost of exporting to the grid. An illustrative example is shown in Figure 7.6. In summer the effective price drop is more pronounced, but McKenna (2012) suggests that this price differential is not sufficient to justify storage investment.⁶

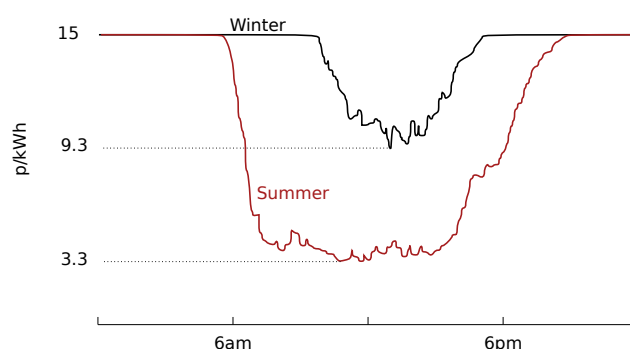


Figure 7.6: *Effective price of electricity for a group of dwellings with PV.*
Source: McKenna (2012)

The effective price profiles from Figure 7.6 have been simulated across the year and integrated into the techno-economic model. Two modes of operation are contrasted in this way. First, storage operates as previously in response to wholesale price signals, to create benchmark values. Then, the price profile is switched to the ‘effective’ prices as seen by householders with a ‘PV incentive’ through export tariffs. This changes the operating profile of storage to one that charges during the daytime, irrespective of the wholesale price at the time. It is therefore possible to deduce two types of values: 1) a ‘private value’, which is the gross benefit a householder could realise through arbitrage between the lower and higher ‘effective prices’, and 2) the resulting ‘market value’. The latter is the result of the new storage operation profile being remunerated by wholesale prices.

⁶McKenna (2012) considers Lead Acid batteries in individual dwellings with assumed efficiencies of up to 100%

Since the operation is no longer optimised to maximise revenue in this market, one would expect lower returns. As Figure 7.7 shows, the results are not only lower, but can even be negative. The graph shows four levels of wind deployment, each with 2 GW of 2 hour storage. The original market value increases in line with the level of wind on the system. If, however, the same amount of storage follows the price signals created by the PV incentive, the values are lower. The private value is independent of the level of wind at around £38/kW/year. As McKenna suggests, this value by itself may not be sufficient to invest in storage.⁷ To the wholesale market, the PV incentivised storage operation increases costs (i.e. the value is negative) and for high levels of wind the discrepancy increases.

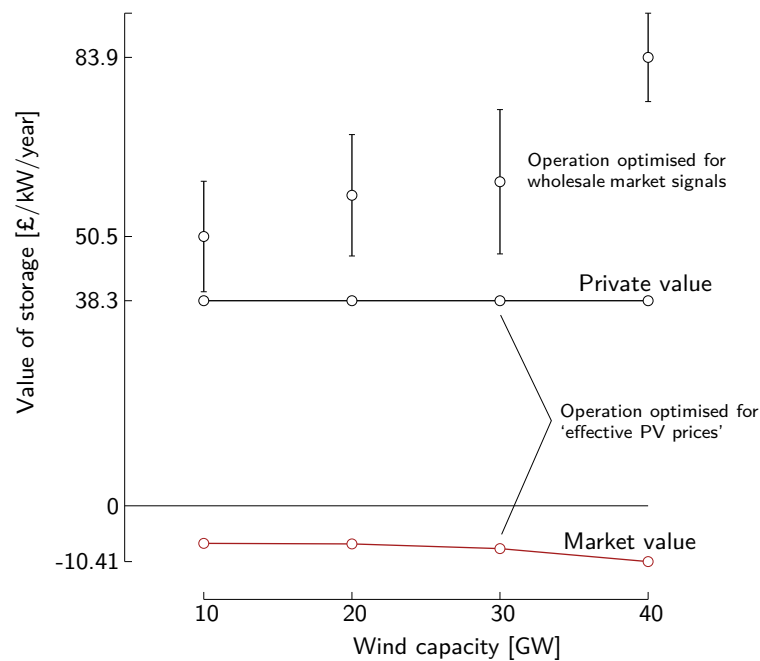


Figure 7.7: Storage can act counterproductively when following the effective price signals created by PV export tariffs. With increasing amounts of wind the discrepancy widens. The value of storage following market price signals increases, while storage operated based on local PV based incentives creates increasingly negative value. Benefits for private storage operators with PV remains unchanged.

In a high wind scenario, storage draws value especially from arbitraging from low demand periods into peak demand periods, which occur predominantly in winter. The

⁷Optimistic future estimates based on ARUP (2012) for Li-Ion batteries with a 4 year life lead to annual capitalised costs of more than £100/kW/year

PV incentive, on the other hand, stimulates storage to be most active during the summer time and charge at times of moderate demand, during the day.

The negative values in Figure 7.7 do not recognise the potential benefits to distribution network operators, who expressed concerns that high levels of PV during low demand summer periods could lead to voltage rises on their networks (see also Thomson and Infield (2007)). This example therefore illustrates one example where different interests in storage might be competing and an operating strategy that is valuable to one stakeholder could add cost for another.

7.3.3 Capacity mechanism

It has been argued by some stakeholders and policy makers alike, that a capacity mechanism could favour electricity storage and create an incentive for investment. Some interviewees cited the capacity mechanism as a sole policy instrument required to successfully deliver storage capacity to the system. The reasons given are twofold: 1) A capacity mechanism rewards the availability of energy rather than its delivery. Storage would therefore benefit regardless of its operation; and 2) one of the disincentives for investment is uncertainty stemming from price volatility. A capacity mechanism would tame volatility and thus improve investor confidence.

In this section the effects of a capacity market on wholesale prices, and subsequently on storage, are explored to test the suggestion that a capacity market ‘favours storage’.

Numerous approaches for the implementation of a capacity mechanism have been proposed (DECC, 2010d). As the detailed configuration of any future UK capacity mechanism is still undergoing consultation, a somewhat generic approach to modelling a capacity market is adopted here. The trade that is at the heart of this approach is that generation is contracted and paid for its availability during periods of peak demand. Periods of peak demand are defined here by a strike price π_{SP} . If the wholesale price exceeds this strike price the pricing system switches out of the wholesale market and capacity is provided by the strategic reserve under its obligation to the contracted parties in the capacity mechanism at a fixed rate π_{SR} .

One approach, set out in (DECC, 2010d, p. 173) is illustrated in Figure 7.8. To what extent a capacity will operate ‘market wide’ is still under consideration. An alternative approach could see a certain amount of capacity to be held back until such time as is deemed ‘system stress’ by the system operator. This could for instance be limited to extreme events, such as the five day lull in wind. For such limited and exclusive application of capacity, storage, with its relatively high capital costs, may be a somewhat less attractive option. The market wide mechanism is therefore considered here in a way that would allow it to be triggered at any time.

Following the illustration in Figure 7.8, when demand reaches a certain level the strategic reserve is called upon and the wholesale price is set at π_{SR} . This leads to a section of the price duration curve being higher than the original price duration curve. As demand rises further the two curves cross over. Beyond this point the strategic reserve is obliged to provide electricity, now at prices lower than under the previous

arrangement. The mechanism thus provides a redistribution from the highest demand periods and reallocates these across a wider number of periods in the year.

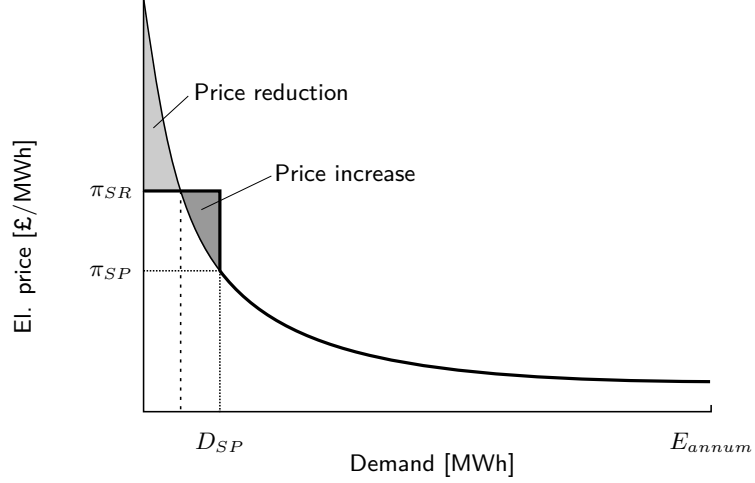


Figure 7.8: *Effect of a capacity mechanism on the price–demand curve. Under the capacity mechanism, when demand reaches D_{SP} the price steps up from π_{SP} and remains at π_{SR} . The mechanism redistributes revenue from the lighter to the darker shaded area. Based on DECC (2010d)*

The anticipated benefits include reduced price volatility and therefore greater certainty for investors about the likely revenue when operating in peak periods. Withholding of capacity in order to drive up prices is expected to be avoided under such a scheme (DECC, 2010d, p. 173).

However, the transition point at D_{SP} constitutes a discontinuity, which may distort participant behaviour. As this point is approached participants have an incentive to withhold generation in order to trip the system into the more lucrative π_{SR} zone.

Towards the upper end of demand, when the system is under most stress, the capacity mechanism now rewards plants with less than the original market price and potentially less than the levelised cost of generation in some instances. The obligation to supply must therefore be backed by a robust penalty system to ensure compliance of generators to honour their capacity commitment, since failure to do so could lead to costly black outs.

The dynamics by which the the mechanism is returned to the wholesale market are also non-trivial. Since the market mechanism has been exited, the system operator⁸ is now blind to the electricity price and cannot rely on price as a trigger. They therefore rely on supply and demand balance at the time. Generators with plants inside and outside the capacity mechanism might have an incentive to withhold output from those

⁸DECC’s preferred administrator of the capacity mechanism is the system operator National Grid

plants that do not benefit from the added price (say by carrying out maintenance on wind turbines) to keep other plants inside the mechanism for longer.

Integration of a capacity mechanism into the techno-economic model

To represent an electricity market with a capacity mechanism, only minor additions to the model are required. The capacity mechanism could be defined via the price that applies to the strategic reserve (π_{SR}). In this case the electricity prices above this value are integrated along the price duration curve. The strike price (π_{SP}) becomes the point at D_{SP} where the integral below π_{SR} reaches the same value. This way the measure remains neutral overall and merely re-distributed price markups from above π_{SR} to below π_{SR} . However, it requires solving the equation for the strategic reserve demand (D_{SR}) as the crossover point of the old and new price duration curve

$$\left[\int_0^{D_{SR}} \pi(D) \delta D - (D_{SR} \pi_{SR}) \right] - \left[(D_{SP} - D_{SR}) \pi_{SR} - \int_{D_{SR}}^{D_{SP}} \pi(D) \delta D \right] = 0$$

and deriving the strike price from the price duration function, as

$$\pi_{SP} = \pi(D_{SR}).$$

Reversing this approach is mathematically and computationally easier. For a given strike price (π_{SP}) the point on the price duration curve at D_{SP} is known. From here the strategic reserve price can simply be established as the mean of all prices above the strike price.

$$\pi_{SR} = \frac{\sum_0^{D_{SP}} \pi(D)}{D_{SP}} \quad (7.1)$$

The assumption within this approach is an omniscient system operator, who sets the strike price and the strategic reserve price such that the average price overall does not change. And since the system overall is no better or worse off, the effect is one of redistribution. The question becomes: who are the winners and losers of this redistribution?

Changes to the value of peaking capacity

The following simulations consider a 3x3x3 matrix of storage and capacity mechanism parameters. Capacity mechanisms with price of £200, £400 and £800 per MWh are simulated in the high renewables base case scenario with a storage capacity of 2, 10 and 20 GW and 1, 2 and 6 hours duration.

Before turning to the results for storage, Figure 7.9 shows the relative changes in the value of peaking capacity.⁹ In all simulated cases, peaking capacity suffers reductions in value as a consequence of a capacity mechanism. This may be counterintuitive, since

⁹These results are before peaking plants use their price making market power to ensure they remain viable. I.e. the uplift function, which would cause π_{SR} to rise, remains unchanged.

the mechanism is intended to support peaking capacity. The reason for this reduction is that peaking capacity by definition is the capacity of last resort and therefore hold the largest share of delivering the most costly demand hours (the light area in Figure 7.8). Storage capacity, even when simulated with high deployment, does not displace the need for peaking capacity. If anything, it ‘pushes’ peaking capacity further left on the price-demand curve at the expense of increasingly low load factors. Losses in cases with 20 GW storage therefore tend to be higher.

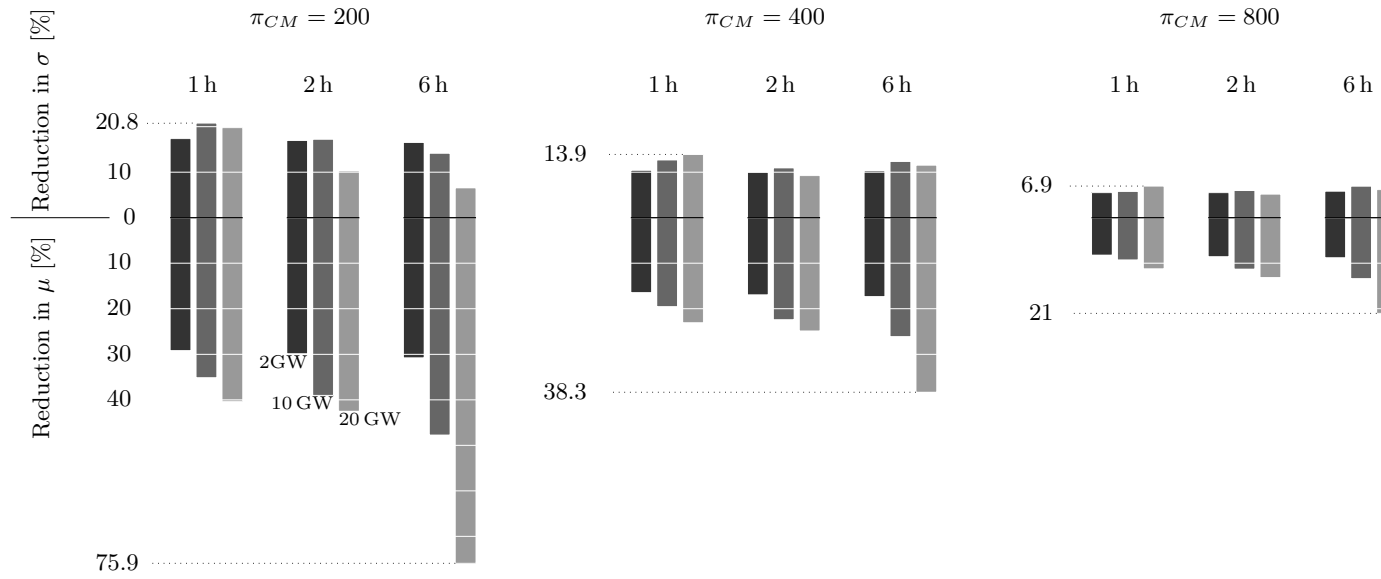


Figure 7.9: Relative changes in mean and standard deviation of the net value of peaking plants in a capacity mechanism alongside storage.

As mentioned above, the capacity mechanism is represented here as a re-distribution instrument. The redistribution taking place is from the highest price hours towards the region previously priced between the strike price and the strategic reserve price. Peaking plants, with a disproportionally higher share in the region above the strategic reserve price must therefore loose some of their revenue.

This loss is to be expected and to some extent forms part of the bargain: lower returns are the premium for higher certainty of returns. These are shown on the upper half of Figure 7.9. In all cases the standard deviation of the returns for peaking capacity reduces.

The extent of the reduction in revenue does couple with the performance of storage itself. The biggest losses, in absolute and relative terms, are recorded in cases with low strike prices and small, short duration, storage installations. Conversely, the least impact occurs when peaking plants compete with large, long duration, storage and a high strike price.

Changes to the value of storage

A noticeable difference for storage when operating within a capacity mechanism is the loss of added value from scheduling with foresight. Figure 7.10 shows how the presence of a capacity mechanism removes the added value from foresight. A storage operator seeking better prices by delaying dispatch into the future is no longer likely to capture a significantly higher price, since the highest prices are now capped.

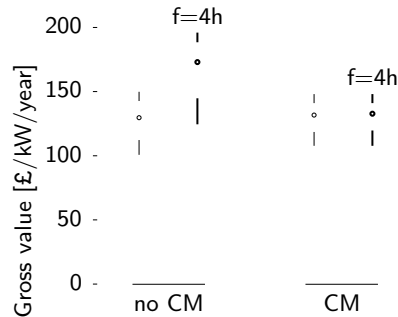


Figure 7.10: *Effect of scheduling storage with foresight. Without a capacity mechanism (no CM) improvements in the gross value of storage can be achieved through scheduling with foresight. A capacity mechanism (CM) removed the differences between scheduling with and without foresight. (Example shown for Grassroots scenario with 10 GW 2 hour storage over four years with $\pi_{SP} = £400/MWh$)*

Foresight, although modelled here with mathematical certainty, is in practice uncertain. The further the time horizon of assumed foresight spans, the less accurate this foresight is likely to become. Figure 7.10 suggests that a capacity mechanism can reduce

the highest (speculative) values that can be achieved with storage, while certainty over those values is improved (one of the stated aims of the capacity mechanism).

The results of relative changes to the gross value of storage are shown in Figure 7.12. As with generation capacity the biggest changes in value take place when the strike price is low. The higher the strike price, the smaller the part of the price duration curve that is affected and less redistribution takes place.

Short duration storage fares best, especially with small capacities. To some extent this is an unintended consequence of the new price profile. Small amounts of storage can take advantage of the price discontinuity, when the system changes from wholesale prices to the capacity mechanism. A sudden step change in price suits short duration storage.

Longer storage durations perform less well in this simulation. Their value is unchanged for small capacities, and large storage capacities with long duration can even reduce in value.

However, as with the peaking capacity, the capacity mechanism is also intended to reduce investment risk. And here the picture is more positive. This is shown for the example of the 10 GW storage with 6 hour duration, which in Figure 7.12b lost 5.5% of the gross value compared to the pre capacity mechanism results. The probability distributions of the gross value in Figure 7.11 compare both cases. The higher value without capacity mechanism also has a wider distribution.

The investment condition of a 95% confidence in a positive NPV from Section 5.1.2 on page 116 is applied again. Although the mean value in Figure 7.11 has dropped, the cost target has risen from £123 to £141 per kW per year.

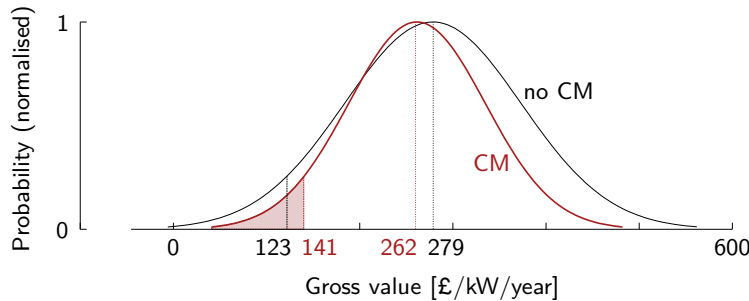


Figure 7.11: *Effect of capacity mechanism on gross value distribution of storage. A capacity mechanism reduces the mean value expectation for storage. The uncertainty is, however, reduced and the annual technology cost at which an investor can be 95% confident to make a positive return in this case increases from £123 to £141 per kW year. (Example for 10 GW 6 hour storage in base case scenario with $\pi_{SP}=400$)*

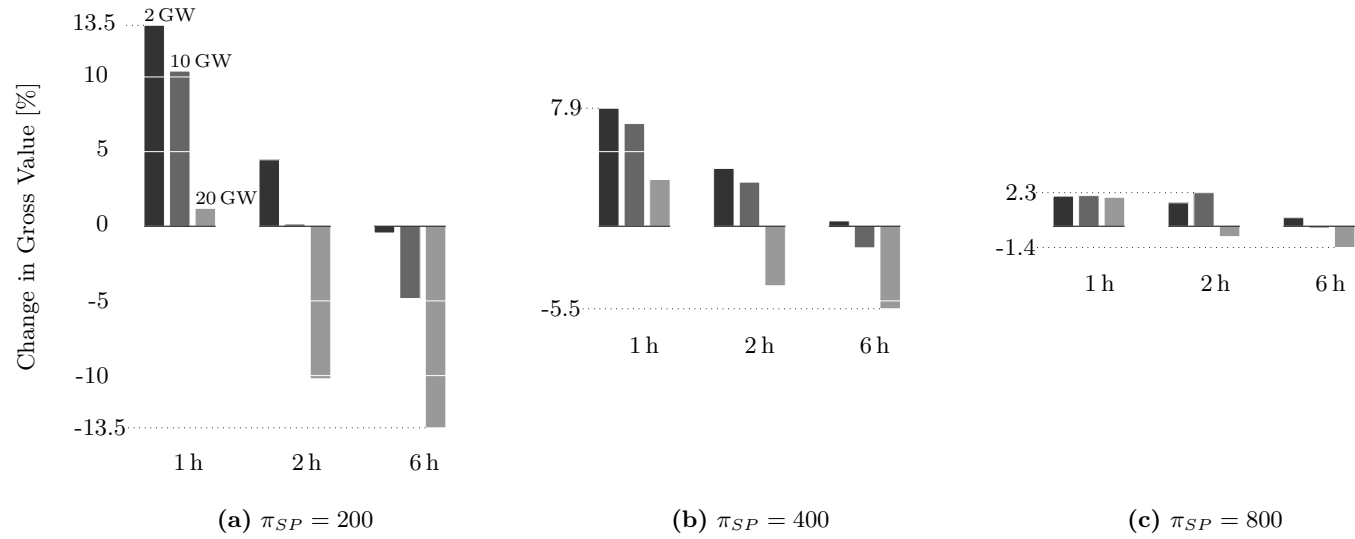


Figure 7.12: Relative changes in gross value of storage in a capacity mechanism. Larger storage capacities (2 $\rightarrow$ 20 GW) and longer storage durations (1 $\rightarrow$ 6 h) are worst affected by a capacity mechanism. The higher the strike price (π_{SP}) the smaller the impact.

7.4 Conclusions

Chapter 6 argued, based on the stakeholder consultation, that none of the existing regimes is well suited to drive the uptake of storage unaided. This chapter has further strengthened this view by combining some insights from the stakeholder process with the techno-economic simulations. It further identified several mechanisms that resulted from the socio-technical perspective, which could act as barriers to uptake.

The discrepancy between market and system values within similar scenarios supports the suggestion that the private value of storage in electricity markets does not reflect the full system or even social value.¹⁰ Parts of the difference could be reduced if—as one stakeholder suggested—access to potential distribution network saving were more accessible to market participants. Other contributing factors, such as savings in system operation, are potentially more difficult to include in market arrangements and require careful balancing of long term cost, security and emission objectives.

Aggregation of a number of value streams accruing for different stakeholders across these regimes poses a commercial challenge for storage operators. Cross sectoral and strategic planning may be necessary if the long term aggregate value is to be captured in the common interest. Failure to do so could inhibit the uptake of storage and may lead to a welfare loss.

Changing regime tensions shift the largest share of value from network operators in 2020, towards system operators and later the generation regime. If policy is to address long term developments for storage, future system operator and generator interests would need to be considered alongside near term network operator benefits.

Cases for niche uptake of distributed storage suggest that, even for dedicated high value applications, additional value streams may need to be internalised if the commercial value is to be sufficient for investment. The way in which this is done requires careful consideration. For one, supporting high performance technologies, which are already close to market and suited to early adoption, could lead to the development of a technology portfolio that is not suited to longer term interests, specifically with regard to low cost, lower performance and longer storage duration. Secondly, the operating strategy that suits one stakeholder may in some cases increase costs elsewhere, as seen in the example of PV export tariffs. Direct support for storage can further lead to inadvertent misuse and potentially even increase CO₂ emissions.

A capacity mechanism, which was seen by many during the consultation process as a ‘storage favourable’ instrument, is not necessarily a panacea. Short storage durations tended to fare better, but in part this was due to windfall revenues from price jumps when the system changes from market prices into the capacity mechanism. Longer storage durations did not benefit from the capacity mechanisms as simulated here. However, even if the mean value of storage reduced, the distribution also reduced, which could lead to higher investor confidence.

¹⁰The ‘social value’ is a potentially wider definition of value than the ‘system value’, which does not value the utility of energy services.

The review of selected uptake mechanisms for electricity storage technologies highlights the complexity of the interaction of storage with the wider system and confirms the need to consider socio-technical aspects alongside techno-economic considerations. The concluding chapter will return to the research questions of this thesis and address them with the key findings. Merits and limitations of the analytical framework are also critically reviewed.

Conclusions, policy implications and further work

THE CRITICAL REVIEW of the literature on electricity storage in Chapter 2 identified a gap in these studies relating to the future role of storage in three areas:

1. lack of a dedicated approach to represent storage operation dynamically within system studies;
2. limited understanding of changing drivers for storage over time; and
3. insufficient consideration of key actors in adopting storage solutions.

Based on these gaps, the aim of this thesis is to add to the understanding of the future role of storage in the GB system by identifying commercial drivers for the uptake of storage and their sensitivity to technical and contextual assumptions, and to put these into context by exploring wider benefits and barriers to uptake. It is hoped that the historical case studies, the techno-economic modelling, the stakeholder engagement and the subsequent analyses have demonstrated the value of these approaches in addressing this aim and generating useful insight into the potential future role of storage.

Three sets of research questions were raised in Section 2.4.2. They concerned 1) the techno-economic conditions for commercial viability of electricity storage on the GB network, 2) the wider benefits affecting the case for electricity storage, and 3) the factors shaping the uptake, configuration and operation of storage.

These research questions have been addressed through an interdisciplinary framework, which combines insights from a dynamic and highly time resolved techno-economic model, informing a long term perspective of the value of storage under consideration of different technology characteristics, as well as insights from stakeholders on possible dynamics during the transition of the UK energy system and factors affecting the uptake of electricity storage technologies.

This concluding chapter will briefly review the different methods applied in this thesis in Section 8.1, before Sections 8.2, 8.3 and 8.4 bring the main findings together to

address each set of research questions. Implications of these findings for policy makers are drawn out in Section 8.6. Finally, suggested areas for further work resulting from this study are proposed in Section 8.7.

8.1 Review of the approach adopted in this thesis

The analytical framework introduced in Section 3.5 sought to combine different disciplines to assess the role of storage with more detail and depth than the individual disciplines would have done. Techno-economic modelling and a socio-technical perspective of storage and its stakeholders inform each other. Their insights provide the basis for the transition perspective, which allows this thesis to discuss potential barriers to uptake.

The applicability of aspects of transitions theory has been tested for historic cases of storage deployment in Chapter 4. It emerged that the socio-technical regime is crucial during the transition process. Its preferences and internal tensions strongly influence the uptake of storage and a detailed characterisation of socio-technical sub-regimes therefore allows for a better understanding of the future role of storage.

Commercial drivers for storage were simulated with generic techno-economic representation in future scenarios in Chapter 5. High wind scenarios suggest commercial viability, but the results are sensitive to parameters and assumptions.

The commercial value as simulated here, neglects wider benefits, which are included through the socio-technical perspective in Chapter 6. Three socio-technical sub-regimes have been proposed and their relationship to storage has been developed based on a stakeholder workshop and personal interviews. The *Generation*, *Network* and *Consumption* sub-regimes were found to relate differently to storage. Their perceived benefits from storage do not necessarily align well with each other and none of them emerges as a likely ‘driver’ of storage uptake.

How storage could nonetheless enter the market was the subject of Chapter 7, which reviews market led uptake, uptake through niches and the effects of targeted support, based on the insights from the techno-economic model and the stakeholder work.

The combination of methods within the analytical framework has led to additional insights. Findings have complemented each other and informed and steered the analysis.¹

A challenge of the approach taken lies with the speculative nature of exploring long term system developments. While stakeholders are willing and competent to comment on the near future, they acknowledge that long term transitions are difficult to envisage with enough clarity to make confident predictions on the role different actors may play. One therefore has to assume that attitudes, practices, institutions and physical systems can change and that any analysis of such futures is merely exploratory, rather than predictive.

¹Especially the barriers to deployment would not have been apparent from a purely techno-economic perspective. Equally, the discrepancy in value between long duration and short duration storage emerging from the techno-economic analysis added to the stakeholder discussion.

Issues relating to storage are highly specific and in part new, which limits the number of experts that can be approached. Many of the interviewees do not regard themselves as ‘experts in storage’. Their input relates to the underlying tensions that storage may be able to address. The somewhat hypothetical nature of some of the discussion requires semi-structured interviews with enough depth to explore beliefs and preferences. Such interviews can only be conducted in small numbers and rely on a large degree of qualitative interpretation to reach the conclusions presented here. The insight of these experts is believed to justify the weight given to their opinions in the absence of quantitative statistical analysis of their statements.

Uncertainty over long term developments also relates to the modelling work. Scenarios, which provide the context for the simulations, are by no means ‘probable futures’. They rather aim to give a coherent narrative in which trends can be explored. As such it is not always possible to validate the model other than with a best effort to ensure its internal logical consistency, through rigorous testing. A balance has been struck to keep the model simple enough to make its workings transparent, while at the same time capturing sufficient detail to explore trends within future systems. Its main simplifications are the absence of a network model, a simplified representation of generation with coarse merit order classes and the assumption of an idealised energy market.

In conclusion, the adoption of an inter-disciplinary approach has proved highly beneficial in addressing the broad research questions set out in Chapter 2 and led to a more holistic consideration of a set of research challenges that span from technical considerations, rooted in engineering disciplines, to interactions with the wider system, for which social science disciplines have developed appropriate tools. Electricity storage may just be one example of the many challenges in relation to future energy systems which may necessitate the adoption of methods from previously distinct disciplines. Traditional disciplinary boundaries do not necessarily align with the multifaceted research challenges of transitioning an established large technical system towards sustainable, affordable and secure provision of energy. If such challenges are to be addressed effectively, the simultaneous consideration of methods from more than one discipline may become increasingly unavoidable.

8.2 Techno-economic conditions for commercial viability of grid-based electricity storage

The first research question seeks to identify the necessary conditions for electricity storage to play a role in future UK systems:

What are the techno-economic conditions for commercial viability of electricity storage in the UK?

Research Question 1

8.2.1 Generation mix

The primary driver for the increased value of electricity storage is an increase in deployment of sources with very low short run marginal cost, such as nuclear, but especially wind. The intermittent generation profile simulated as a consequence of high deployment of wind, and the resulting wholesale price volatility assumed in this study, can lead to favourable commercial conditions for storage. At present technology costs, and without additional support, storage could reach wide-spread commercial viability in large grid applications once the installed capacity of wind reaches around 30 GW. The gross value of storage in scenarios with a higher share of nuclear can be more than 50% lower and within CCS scenarios over 70% lower.

8.2.2 Storage cost

This study adopts two approaches to cost. The first is the annual gross value of storage, which is independent of technology life expectancy, and gives an upper limit for the annualised costs of a technology. The second is the net present value, which was adopted to compare technologies with specific energy and power related costs.

The simulation in Section 5.3.1 on page 128 suggests that the gross value of 2 GW storage capacity with 6 hour duration could almost double from around £60 to over £110 per kW per year with increased levels of wind on the system. The cost targets would therefore become more relaxed over time.

The counter trend is the diminishing marginal value of storage. The more capacity is installed, the lower the value of additional capacity, which could limit the forthcoming investment.

8.2.3 Storage duration

Storage duration, which in this study is the ratio between energy and power of a storage installation, also gives a measure of the type of service storage provides. Short durations tend to indicate fast charge and discharge cycles, whereas long storage durations operate to bridge longer cycles and fluctuations.

The value of additional storage duration also shows a strongly diminishing trend. In the reference scenario in Section 5.3.3 the marginal value of added storage energy capacity declines from more than £9/kWh/year for 10 GW with 2 hours duration to less than £1/kWh/year for 10 hours duration.²

However, the example of selected long duration storage technologies in Section 5.4.2 on page 138 has shown that with very high levels of renewables even these types of storage could become viable, if their energy related costs are low.

²For comparison, today's pumped hydro station in Dinorwig has 5 hours duration and an annualised capital cost of around £9.75/kWh/year.

8.2.4 Efficiency

The present paradigm that efficiency is crucial for economic viability changes as the level of renewables increases. The difference in gross value between lossless storage and a system with 40% round trip efficiency was shown in Figure 5.10 on page 133. In a scenario with 20 GW of wind the difference in value is around 42%. As the level of wind increases to 40 GW the difference reduces to 27%. The marginal gain of additional efficiency for systems with more than 70% efficiency becomes especially low in such scenarios.

While in the short term storage efficiency may be regarded as important, the long term trend suggests that technologies with lower efficiencies may still have a role to play and should not be overlooked, especially if these could lead to lower long term costs.

8.2.5 Alternatives to storage

Three alternatives to storage can be considered to provide similar services in future systems: 1) flexible generation, 2) demand side response (DSR) and 3) network reinforcement. Only the first two could be simulated in this study.

Despite the higher cost, storage can reach commercial parity with flexible thermal generation at costs well above 100 £/kW/year with 30 GW of wind on the system.³ However, the variability and uncertainty over future returns simulated in Section 5.5.1, suggests that the short run costs for CCGT plants would have to rise above £56/MWh for utility companies to perceive them as a commercially preferable investment option.

The simulations in Section 5.5.2 show a significant impact of DSR on the value and role for storage. Even moderate assumptions for DSR with a capacity of 4 GW could halve the value of short duration storage. Longer storage durations are slightly less affected.

8.2.6 Uncertainty

Despite potentially high values for storage, the wider approach taken in this study reveals several barriers to deployment. One of these, which featured throughout the modelling and stakeholder work, is the uncertainty over future revenues and hence profits.

Stakeholders expressed concerns that the revenue streams for storage are highly uncertain. Their concern was rooted in the limited access to experience based data.

Based on historic data for wind and demand profiles in Section 5.3.1, the uncertainty due to stochastic variations, could require target costs to be around 20% lower than the mean gross values. This affects projects with a short life.

Projects with long life times are more exposed to uncertainties in the development of the energy system as a whole and its regulation.

This applies especially to price volatility. Section 5.6 has shown how a 10% reduction in the difference between charge and discharge price can entirely remove the value of storage. For investors, who may try to estimate the value proposition of an asset

³Pumped hydro was estimated in Section 5.1 at around £66/kW/year

operating well into the 2020s and beyond, subtle changes to the regulatory structure governing the market arrangements could profoundly affect the business proposition.

8.3 Wider benefits from a stakeholder and a systems perspective

The second research question expands the scope of the analysis beyond the narrow electricity market perspective and asks:

How do the wider benefits affect the case for electricity storage?

Research question 2

The stakeholder workshop conducted as part of this study reveals distinctly different types of benefits from storage, as well as different groups of beneficiaries. The benefits perceived by stakeholders include:

- operational savings
- system cost reductions
- avoided network reinforcement
- benefits for consumers (cost and ‘engagement’)
- system security and resilience
- supporting the transition towards a low carbon system

Chapter 6 argued that some of the benefits listed above are believed by stakeholders to be adequately reflected within existing markets structures, while others constitute ‘common good’ characteristics, spanning across the sub-regimes, and are therefore not rewarded appropriately under current market arrangements.

The gap between the system value and the market value was illustrated in Section 7.1, and explained in part with market signals in this study not being able to deliver the optimal operation of storage. System operators may achieve additional savings through improved scheduling of spinning reserve and peaking capacity may be displaced with the right incentives. Distribution network savings also constitute an additional source of value.

External benefits further include security of supply, long term cost of further CO₂ reductions and integration costs.

Based on these findings this thesis argued in Section 7.1 that a failure to reward the external benefits could lead to a welfare loss. Present market arrangements may lead to a sub-optimal deployment levels of storage as well as to configurations of storage that potentially do not serve the best common interest. The causes and difficulties of addressing these shortcomings are addressed in the following section.

8.4 Barriers to uptake from a socio-technical transition perspective

The third research question builds on insights from research questions one and two and asks:

Which factors shape the uptake, configuration and operation of storage?

Research question 3

8.4.1 Alignment with existing sub-regimes

This study divides the electricity system along functional and regulatory boundaries into distinct sub-regimes for *generation*, *network* and *consumption*. Storage has been found to challenge the discrete nature of these sub-regimes by providing services that transcend their functional boundaries. Storage acts as demand while charging, generation while discharging, and in the process fulfils a network function arbitraging between the two (in time rather than space).

Section 6.5 argued, based on the analysis of stakeholder views, that not only actors, but the regulatory structures governing these sub-regimes may need to change if storage is to act across them more effectively and increase its value to the system as a whole.

8.4.2 Disaggregation of value

The aggregation of value poses a practical challenge for storage operators, who have to contract with several parties, as illustrated in Section 7.1.3.

Section 6.4.4 put forward several stakeholders, who expressed an interest in contracting storage services. However, no stakeholder group appears to hold a sufficiently high stake in storage to invest themselves. Generators, network operators and consumers point to each other in turn as ‘best placed’ to own storage. This ‘somebody else’s problem’ effect is played out in the near future between generators and distribution network operators, who by 2020 may benefit from the presence of storage, but potentially not sufficiently to invest themselves. System operators might gain an increasing stake in storage in the longer term.

Negotiating between these different stakeholders is not merely a matter of establishing the value of storage for each stakeholder and redistributing these values. The interests of the different stakeholders can be complementary, but at times it is possible that conflicts of interest could arise, as illustrated in the case of PV incentives in Section 7.3.2.

The regulatory and market frameworks in place for these stakeholders differ significantly. Value aggregation therefore also presents a non-trivial policy challenge.

8.4.3 Build up of aggregated value

The aggregate value builds up gradually during system transition. Any subcomponent of the aggregate value may trigger investment in alternative solutions prior to storage

appearing viable. Section 7.1.4 illustrated this process and gave an example for the case of distribution network constraints.

Only if the components of the aggregated value are accessible within the planning horizon of the investor, can the commercial proposition ‘stack up’. Generally, planning takes place over significantly shorter time periods than those considered in this study. The alternatives to storage are long lived. Generating and network assets remain on the system for decades. During this period they could turn from the commercially preferred option, into a technology that precludes storage solutions from delivering overall better value.

8.4.4 Institutional inertia

DNOs were identified in Section 6.4.4 as stakeholders, who are potentially well placed to drive the uptake of storage. However, they have been characterised as ‘deeply conservative organisations’. Their priority, in the current market structure and regulatory conditions, is on quality of supply. This is pursued with low risk, rather than profit maximising strategies. Storage is viewed by DNOs as complex, unproven and therefore potentially an unreliable technology, compared to well established, tried and tested ‘wire and transformer’ solutions.

This institutional mismatch with storage operation applies to many actors in the system. This suggests that new skill sets need to be developed or recruited from other sectors, within or outside the electricity system. Some of the competences for optimal operation of storage were likened by one stakeholder to advanced financial products.

8.4.5 Long term changes in functionality

Not only are the time scales over which storage generates savings wide ranging, the rate at which these values increase over time also differs. Distribution network savings tend to be relatively consistent, whereas operational value and capacity value increase in response to future system changes, as shown by this and other studies.

This means that today’s stakeholders, which could shape the early adoption of storage, may not necessarily take account of the types of services storage may need to provide long term. These long term changes can affect the following properties:

Storage duration Distribution network constraints require peak shaving, which can be achieved with relatively short storage durations of less than 3 hours. With long term increases in wind penetration, and if DSR were to capture short storage durations, longer storage durations would become more favourable.

Location In the short term two distinct functions for storage can be identified: 1) bulk storage of surplus wind in Scotland, and 2) Distributed storage in southern Britain to avoid distribution network constraints. In the long term, if configured appropriately, distributed storage in southern Britain could double up to integrate wind, whereas bulk storage would be unable to support distribution networks.

Technology In the long term low cost storage with long storage durations gains in value. The techno-economic analysis of Chapter 5 suggests that efficiency can be of secondary importance. This is a departure from technologies that are presently closest to market, due to high performance in more demanding applications (e.g. transport or mobile applications). High efficiency is presently required to arbitrage with small margins between peak and trough prices. Especially as the lower end of the load duration curve is depressed by low marginal cost generation, efficiency requirements could be relaxed.

As this list shows, long term planning can materially alter the type of storage that is perceived as most valuable to the system. Since the stakeholders involved can have different priorities (see Section 6.4), and take different approaches to long term planning themselves, Chapter 7 argued that the stakeholder group which leads the uptake of storage can materially affect its future role and value to the system.

8.5 Support for storage

8.5.1 Shortcomings of energy only markets

The comparison of the techno-economic approach, which builds on increasing volatility in wholesale electricity prices, with the system benefits in Section 7.1, has demonstrated that even with substantial price volatility storage may not receive sufficient investment signals to deliver its full system potential.

This was in part attributed to the limitations of the modelling approach itself. Some sources of value, such as network savings and improved spinning reserve scheduling are not included in wholesale prices, but might be internalised through dedicated contracts (see ‘Disaggregation of value’ above).

While energy markets set a public and transparent signal for investment and operation of storage, the resulting use of storage may be sub-optimal for the wider system and its stakeholders. Additional incentives may improve the effective deployment of storage.

8.5.2 Unintended consequences of storage incentives

While energy markets do not necessarily stimulate investment, they do create a clear mechanism to guide the operating strategy of storage. The scope of targeted support to improve on purely energy market based incentives has been considered in Section 7.3.

This review has shown that there is scope for well intentioned support for storage to undermine its effectiveness in reducing system costs. Three mechanisms by which storage could be inappropriately incentivised have been discussed:

1. Picking the wrong winners
2. Rewarding suboptimal operation
3. Creating perverse incentives

An example of the first case is capital support for storage. This favours technologies that are closest to market, which is not necessarily the same as being closest to the long term system interest, with changing priorities for storage capacity and efficiency.

Section 7.3.1 argued that premiums, stimulating storage of renewable energy for high demand periods, can potentially increase overall emissions. Due to the finite round trip efficiency, output from thermal plants can increase, if the incentive leads to trading margins between periods that are predominantly served by conventional plants.

The example of ‘effective prices’ resulting from PV export tariffs in Section 7.3.2 showed how local and national interest can be at odds. The overall system value can become negative, if the ‘wrong’ incentive stimulates the operation of storage.

These illustrative effects suggest considerable scope for unintended consequences resulting from the complexities of storage serving various stakeholders. Devising policy instruments in support of storage may require a cautious approach, if the intended aims are not to be reversed for individual stakeholders or the system as a whole. A balance between short and long term priorities in support arrangements may further improve the long term effectiveness of such policies.

8.5.3 Capacity Mechanism

The capacity mechanism suggested by some stakeholders as a ‘storage enabling’ instrument, produces mixed results.

Under the assumptions made in Section 7.3.3, small storage capacities with short duration may increase their commercial value, in part due to newly introduced ‘steps’ in the price profile. Larger capacities (≥ 10 GW) with longer storage durations (≥ 2 h) may reduce in value by up to 13.5% in the simulated cases, because some of the trading volatility has been lost. However, the stochastic uncertainty of revenues is reduced, which could compensate for the lower mean value and still lead to higher levels of investor confidence in some cases.

8.6 Resulting considerations for UK policy makers

The implications of the findings of this study for policy makers are twofold. Firstly, if the value that storage can bring to future systems is to be increased, mechanisms to reward storage for some of the disaggregated value it creates across the system would need to be developed. Secondly, however, the analysis suggests that the development of such mechanisms should be mindful of the competing interests at stake for a wide range of stakeholders.

This study does not provide a comprehensive review of market mechanisms to reward storage. It is evident though, from the limited analysis performed here, that incentivising storage is challenging within current market frameworks and that if the deployment of storage is left to markets alone, in their current configuration, sub-optimal system outcomes may result.

Furthermore, the examples of selected price incentives in Section 7.3 suggest that a detailed understanding of the effect of incentives on the operating strategy of storage is required, if unintended consequences and perverse incentives are to be avoided. This also applies to the integrating function that storage plays with presently distinct sub-regimes, which stand to gain from storage in different ways and in some instances may incur additional costs from the presence of storage, too. These trade-offs suggest that the involvement of a large number of stakeholders and analytical work in the development of future policy would be likely to improve the potential of storage to reduce the cost of a secure low carbon transition. Such policy might further benefit, if it were embedded in the regulatory structure across the sub-regimes of generation, network and consumption.

If an incremental approach to the deployment of storage is adopted, configurations that deliver the greatest long term value may not be developed and deployed in the best long term system interest. This relates specifically to low cost, bulk storage with modest efficiencies, which only gradually reaches its full value in long term high renewables scenarios. Yet, its absence may necessitate and lock-in fossil fuel based solutions to maintain system flexibility.

This leads to the overall conclusion that for the system benefits of storage to be maximised a strategic approach to policy may be beneficial. A long term vision for possible futures and desirable roles for storage within these futures can help to inform policies aiming to take advantage of storage alongside network reinforcement, flexible generation and demand response.

Policy support need not be technology specific, but the analysis in this thesis suggests that it should set clear aims for technology targets (cost, duration, efficiency, lifetime, reliability), deployment targets (location within GB, voltage level on the network), and operational requirements (holding of strategic reserves, minimising CO₂) and that it will need careful, sophisticated analysis to select appropriate, effective policy instruments.

8.7 Further research

This study set out to remain high-level in several areas. Neither technology, nor electricity markets have been addressed in much detail. Several areas for further work can therefore be identified.

Market design

Large parts of this study assume idealised market conditions. Illustrative examples of potentially unintended consequences as a result of market interventions suggest that market design for storage could be a challenging task. A better understanding of market (rather than business) models and their ability to stimulate the ‘right’ investment and operating decisions deserves further attention and may help in the design of appropriate policy and market instruments. Such studies should consider the competing interests of different stakeholders and assess if some stakeholders might be unduly penalised under particular market frameworks. Furthermore, the presence of market power

in combination with storage capacity may lead to undesirable operating patterns for storage. An agent based approach simulating storage operators with different degrees of market power might identify operating strategies which would not be in the best system interest, and support policy makers in avoiding them.

Real options analysis

The value of storage differs substantially depending on scenarios and assumptions. To illustrate and explore the value of strategic and pre-emptive investment in storage, a real-option based approach might be one potentially fruitful way of inquiry, to inform the value of storage as part of a future-proof portfolio of technologies. The case of pumped hydro storage in the UK (Section 4.3) has shown that storage investment can in some instances prove valuable, even if the envisaged future does not materialise. Within the CCS scenario in Section 5.3.6 storage still may have a role to play, albeit in a reduced capacity. Pre-emptive investment in storage may therefore bear a high risk for individual investors, but provide a valuable hedge for overall system costs to society. An option based approach that assigns probabilities to different futures could quantify this hedging value.

Technology mapping

This thesis provides a broad range of target costs for different storage configurations. A follow up study comparing these cost targets with values of expected cost developments for the wide range of storage technologies presently being developed, could yield valuable insight into commercial opportunities and areas in need of technological innovation. This exercise should contrast present technology capabilities with long term cost reduction potential, based on the potential scale of deployment suggested by this thesis.

Re-run existing scenarios

Section 2.2 argues that some of the least cost allocation models, which underly current scenarios for future plant mix of the UK, are inadequate in representing storage. For scenarios in which deployment of storage is likely to play a significant role, a reevaluation of the pathway and its cost optimal allocation of assets might lead to new insights. For instance, the presence of storage may enable more ambitious deployment of renewables. Or it could shift the relative attractiveness of conventional forms of generation and lead to a different plant mix. A re-run of such least cost pathways with explicit inclusion of storage capacity as estimated in this thesis is therefore recommended.

Assess the potential contribution of the demand side towards storage

A major shortcoming of this and other studies on storage services is the lack of understanding of their value to the demand side. Most current models postulate that the electricity provision to consumers will remain unchanged, following the ‘predict and

provide' paradigm. Illustrative results for generic demand response assumptions in Section 5.5.2 have shown how sensitive storage might be to demand side flexibility. If the overlap of these technically very different, but functionally equivalent system services was attempted within a single framework, trade offs and synergies between physical electricity storage and demand response could be assessed better. Some demand response measures (especially those requiring little agency from the consumer) can be represented in similar ways to the technology agnostic approach applied in this thesis. Direct consumer response, however, is not yet sufficiently well understood to attempt a cost based comparison with physical storage. Controlled experiments to ascertain consumer price elasticity of demand and willingness to forgo energy services are required to inform their relationship with the future role of electricity storage.

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Dissemination of research

Following publications have resulted from this dissertation and are in part included and cited within this thesis.

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Grünewald, P., 2010b. *The role of storage in a low carbon energy system*. Seminar presentations. ICEPT Energy Policy Discussion Seminar, 8th June 2010, CEP Imperial College. London.

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Techno-economic Model

The techno-economic model applied in Chapter 5 is data-rich. This section describes the sources of data and how they were processed. Section A.1.2 and following sections discuss the sensitivity of the model outputs to changes in input data. Section A.2 presents the process and results of the model validation.

A.1 Input data

A.1.1 Raw wind data

The scenarios explored in this study include cases with high levels of wind penetration. DECC's Grassroots scenario, for instance, considers a total of 69 GW of installed wind capacity for the year 2030. Particular attention is therefore directed to the profiling of such a future resource.

Two fundamental techniques are available to deal with the variability of the UK wind resource. The first is to decompose wind statistically into a range of probability profiles (see Coker (2011)), the second is to work with extensive historic time series. For reasons of demand correlation the latter is chosen in this study.

Recorded weather data for 12658 weather stations throughout the UK are available as part of the Met Office MIDAS database for Land Service Station recordings dating back to 1853. These data are accessible on request from the British Atmospheric Data Centre (BADC) (Šúri et al., 2007; UK Meteorological Office, 2006).

The BADC claim the accuracy of the wind speed data to be within 1 knot or 10% and that this accuracy is met 'in most instances by the current synoptic network'. The exposure of the wind instrument is 'open terrain at a height of 10m above the ground', where open terrain is defined as 'an area where the distance between the anemometer and any obstruction is at least 10 times the height of that obstruction.' (BADC, 2012, §5.5)

The type, temporal resolution and continuity of the recordings differs between stations, and a pre-selections based on the following criteria narrows the choice of stations considerably:

- continuous hourly recordings in the period 2003-2009
- suitable location (no urban areas)
- preference for stations that also record solar irradiation (for use in PV simulation)

The selection does not consider whether planning consent is likely to be granted in this region or if the site is otherwise favourable for development. The choice of weather stations is instead intended to give a broad representation of the wind profile for a wide range of GB regions. The distribution of the weather stations shortlisted for this study is shown in Figure 5.6 on page 125.

Wind speeds are converted into power output through the following steps. Firstly, speeds are converted from knots into meter per second ($1\text{knot} = 0.514\text{m/s}$). Since the winds speeds are said to be recorded in “open terrain”, the values are scaled up from 10 m above ground to correspond to a typical hub height of 50 m, as

$$u_{50} = u_{10} \left(\frac{50\text{ m}}{10\text{ m}} \right)^p \quad (\text{A.1})$$

where u_x is the wind speed at height x (Best et al., 2008). The value for p depends on surface roughness and is assumed to be 0.1429 (Best et al., 2008). This method has recently been scrutinised by Ademovic (2011), who identified variability in the relationship between surface wind speeds and hub height speeds. During hot summer days, vertical air flows rising from the warmer ground lead to reduced diurnal variability. Since atmospheric conditions are not represented in the model, this cause of error cannot be eliminated and has to be accepted as a possible source of error.

Wind speeds are converted using power curves for commercially available wind turbines. As Figure A.1 shows, the profile follows a common pattern. Power output cuts in above 4 m/s and scales to the power of three with wind speeds up to 12-15 m/s. Above this wind speed output flatlines and cuts out at around 25 m/s. This common pattern is normalised to be scalable with the installed wind resource for given scenarios. The power generated at location i at time t can thus be written as

$$P_w(i, t) = P_{site(i)} \times u_{50}(i, t) \times P_u(u) \quad (\text{A.2})$$

where P_{site} is the installed wind capacity in location i and $P_u(u)$ is the normalised power generated at wind speed u . Thus, larger turbines of 6 GW or more can be represented, while no assumptions are made for their possible future improvement in terms operation at lower or higher wind speeds.

Raw data have be examined for their integrity. With large amounts of data this process can be aided by statistical analysis and visual inspection of data plots. Checks include consistency of minima, maxima and mean values with reference data. Outliers, missing values or non-numeric entries are identified by simple algorithms. Furthermore the data are scanned for missing periods and inconsistencies in the sequence of readings.¹

¹In some instances weather stations recorded two values while transitioning from one measurement device to another.

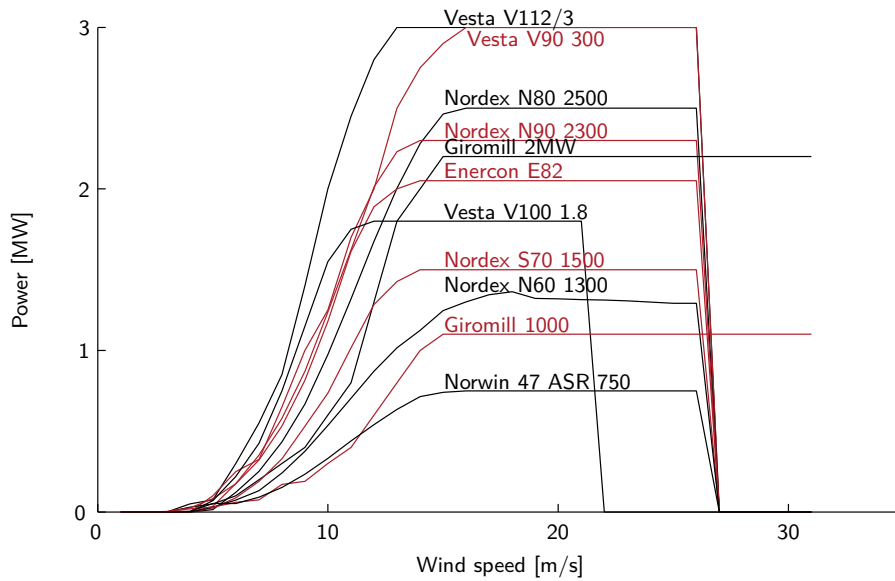


Figure A.1: Power curves based on manufacturer information for selected models. Source: Dan Drew

Since minor inconsistencies are common in these data, a simple 1D linear interpolation is performed to ensure equidistant readout timing and the occasional linear interpolation of a missing reading. Two-dimensional maps of the data, such as shown in Figure A.2 proved a useful tool in visually analysing raw input data for flaws and inconsistencies.

Furthermore the wind profiles are compared with values in literature and against common trends in the UK wind resource distribution. Coastal areas are expected to yield higher resources than inland locations, and northerly sites would be expected to broadly produce greater output than southerly ones. This coarse screening revealed for instance one weather station in Scotland producing lower than expected readings and on closer inspection in Google Earth proved to be located in a Glen.

To generate the wind resource available to future GB networks a judgement has to be made on where these are located and the share of the total capacity in each location. Since planning and transmission constraints are not included in this study, the allocation is simulated based on resource optimisation. This is to say that optimal distribution has to balance the best wind resource with sufficient diversification. The best wind resource, i.e. the highest mean wind speed, tends to be located in Scotland. Locating all of the wind generation here is, however, sub-optimal. Land availability poses one constraint and wake effects (wind slowing behind densely spaced wind turbines) lower the efficiency of wind energy recovered if sited too densely. Furthermore, the above mentioned transmission reinforcement requirements, to deliver the energy to high load regions in the South, make a more diversified allocation of sites desirable Sinden (2007).

The simulation takes account of the value of diversification through the improved

matching of a diverse wind resource with existing demand profiles. The resulting distribution may not be optimal from a network or even a commercial perspective (under the current market framework), yet it ensures that wind is deployed in such a way as to most effectively meet demand and thus displace conventional generation. From a storage perspective this approach is important, because it creates a ‘worst case’. Any less well diversified wind profile would lead to a greater mismatch between resource and demand, and thus more curtailment, favouring more storage.

The algorithm to select this ‘optimally diversified resource’ is one of incremental improvement. First, the entire wind resource is placed in only one location. The simulation establishes for each site in turn the amount of net energy generated. Net energy is defined here as all wind energy generated less any curtailed energy:

$$E_{net}(i) = \int_t P_w(t)\delta t - \int_t P_w(t) - D(t) + G(t)\delta t \forall D(t) < (P_{wind}(t) + G(t)) \quad (\text{A.3})$$

where D and G is the demand and generation at time t respectively. If the combined generation of wind and other plants exceeds demand, curtailment takes place and reduces the net energy produced.

Table A.1: Iterative process to allocate the distribution of the installed wind capacity

j	Location (i)				
	1	2	3	...	k
1			1		
2	$1/j$		$1/j$		
3	$1/j$		$2/j$		
$\vdots$					
n	x_1/n		x_3/n		x_k/n

The site with the highest net energy production is selected in each iteration and added to the combination. In the next iteration the present combination is simulated with addition of any other site (including itself) to improve on E_{net} . The iterations are illustrated in Table A.1. With increasing numbers of iterations the relative contribution of sites diminishes and the distribution becomes more refined. Up to 80 iterations are performed per run. However, after about 12 iterations, no significant changes to the distribution are observed. From the resulting distribution array x_i the wind resource at each site i can be written as

$$P_{site(i)} = \frac{x_i}{n} \times P_{W,GB} \quad (\text{A.4})$$

where $P_{W,GB}$ is the total installed wind capacity on the GB network. The GB wind resource is therefore the sum of all sites

$$P_{w,GB}(t) = \sum_i P_{site(i)} \times u_{50}(i, t) \times P_u(u) \quad (\text{A.5})$$

Different scenarios with different levels of installed wind capacity are simulated. For small levels of wind the solver selects exclusively from Scottish sites, due to the higher capacity factor. For wind penetration above 30 GW a consistent picture begins to emerge. The location of weather stations shortlisted for this process and the allocation of the GB wind resource is shown in Figure 5.6. Notably, only four sites are selected by the solver to provide an optimally diversified wind resource. The location of these sites does, however span the geographic extent of the UK mainland.

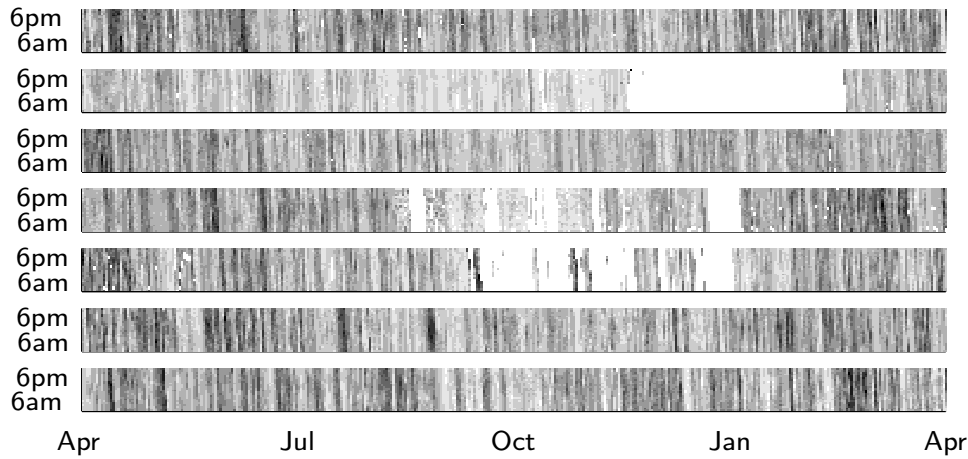


Figure A.2: Wind data, prior to clean-up. Visual representation supports the identification of inconsistencies in the raw input data. False readings are removed manually and records with missing data are excluded from the data set.

The mean capacity factor of 33%, achieved with this method, has been found to be broadly consistent with other studies (Zervos and Kjaer, 2008).

Offshore wind data is less accessible in the public domain. A set of data for 46 offshore sites has been made available for this study by Hawkins (2012); Hawkins et al. (2011). The data is presented in the same format as the onshore data, as hourly fractions of rated capacity output. Neither set of data captures unscheduled downtime or maintenance periods for wind turbines. These data are used to test the sensitivity of the model outputs to different input data in Section A.1.3.

The load factor measured at these offshore locations tends to be higher than for the onshore sites. Individual locations can exceed 50%. These sites tend to be further offshore and therefore more costly to connect (Cockerill, 2005). Regardless of cost im-

plications, the effect of the higher load factors on the value of storage is simulated in Section A.1.3 to establish the importance of the appropriate estimation of wind allocation. The offshore sites are selected by load factor alone. Table A.2 gives an overview of the load factors for an even spread across all offshore sites, and for a selection of the upper half and upper quartile of load factors.

Table A.2: *Load factor for a set of 46 offshore sites and subsets with a selection of the highest load factors.*

Offshore sites	Load factor
46	39.1%
23	44.5%
12	47.8%

A.1.2 Price uplift sensitivity

The parameters for uplift function in Section 5.1.2 are based on observed price formation behaviour in existing wholesale markets. The calibration against such values is used to extrapolate the price uplift in future scenarios. It is, however, not necessarily the case that future price formation follows the same trends as present bidding. This section explores the sensitivity of storage to changes in price formation.

Price formation is a complex process and depends on many factors besides the physical infrastructure. These can include market power, the regulatory system and to some extent the judgement of participants.²

This section therefore test the sensitivity of results to assumptions about future price uplift. At its most extreme, a future ‘market’ could be assumed to be dominated by a single actor (say within a re-nationalised system) with an obligation to supply. This actor has the luxury to spread all costs across all units of energy provided and could charge the levlised cost (plus a regulated markup) regardless of the state of the system. The flat price duration curve of this extreme example disguises all benefits of storage to external parties. Any savings from storage would apply ‘internally’ to the single actor.

The more competition exists, the less actors are able to redistribute internal costs. The other extreme is therefore a system in which every kW of capacity is traded on its own merit. For this reference case, plant are assumed to operate in a strict merit order, such that their load factor can be deducted directly from the net load duration profile (demand-wind). For every load level the number of hours for which the net load is higher than the present load yields the load factor for the marginal generator at this load level ($LF(P)$) as shown in Figure A.3.

²system operators who experienced a series of black-outs may change their willingness to accept high offer prices and traders might adjust accordingly

Figure A.4 presents an attempt to estimate lower bounds for price formation and contrasts these with the uplift function as used in this study.

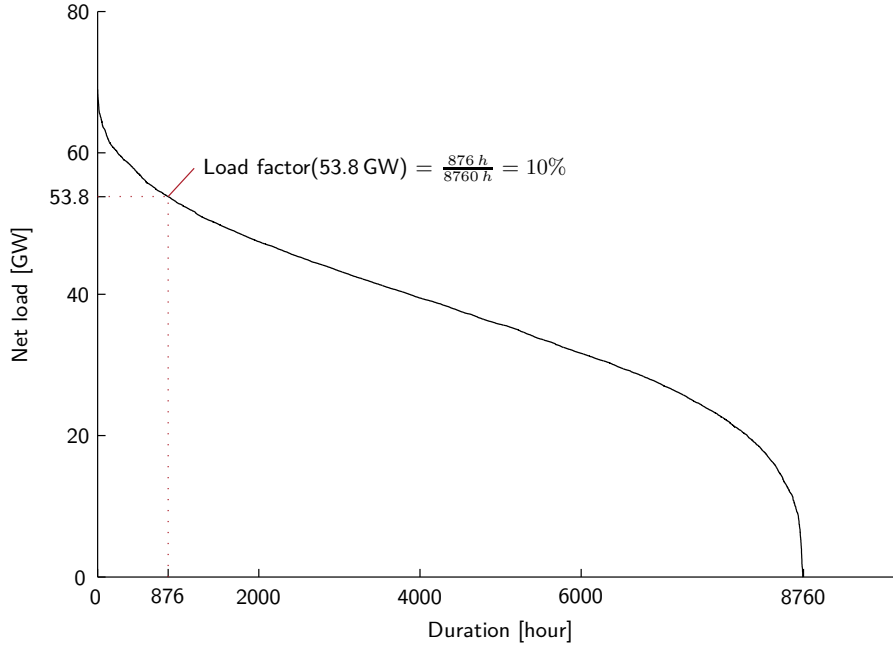


Figure A.3: The load factor for each marginal generation capacity is established from the net-load duration curve.

The annualised capital cost for this marginal generator must be regained within the hours that this generator operates, since no capacity mechanism or other form of cost spreading exist in this case. For base load plant this value is relatively low and marginal costs dominate price setting. Peaking capacity, which has low load factors, has to charge predominantly for their capital costs and marginal costs can become negligible. The minimum offer price is thus established in approximation as

$$\Pi(P) \approx \frac{CapEx}{8760 \times a \times LF(P)}. \quad (\text{A.6})$$

The cost distribution with one hour spread in Figure A.4 shows that in most instances this approach leads to lower prices than the uplift function. This is to be expected, because the uplift function includes profit for peaking capacity (as a reward for the operating in a higher risk market), whereas the cost distribution curve would lead to all capacities to break even. Yet, for some of the highest prices the load factor based prices can exceed the uplift function, because of the strict adherence to a single and consistent merit order. This curve constitutes the other extreme to the flat price duration discussed above. In this ‘most competitive’ case, price volatility is more extreme than observed

with the uplift in present markets, where actors have the ability to pool their resources to some extent and thereby mitigate some of their risk exposure.

In practice, price uplift can be expected to be somewhere between the price flat-line of the non-competitive market and the extreme uplift with hour-by-hour cost allocation. The extent to which the price uplift is ‘tamed’ can be attributed to the extent to which capacity is bundled. Figure A.4 shows how the bundling of capacity across larger time periods ‘tames’ the cost curve and the shape begins to flatten. With capacity bundled to groups of 40 hours the shape of the cost curve begins to resemble the shape of the empirically derived uplift function, except that it is offset due to the absence of profit. Higher levels of bundling lead to flatter curves, approaching the non-competitive case of flat cost profiles.

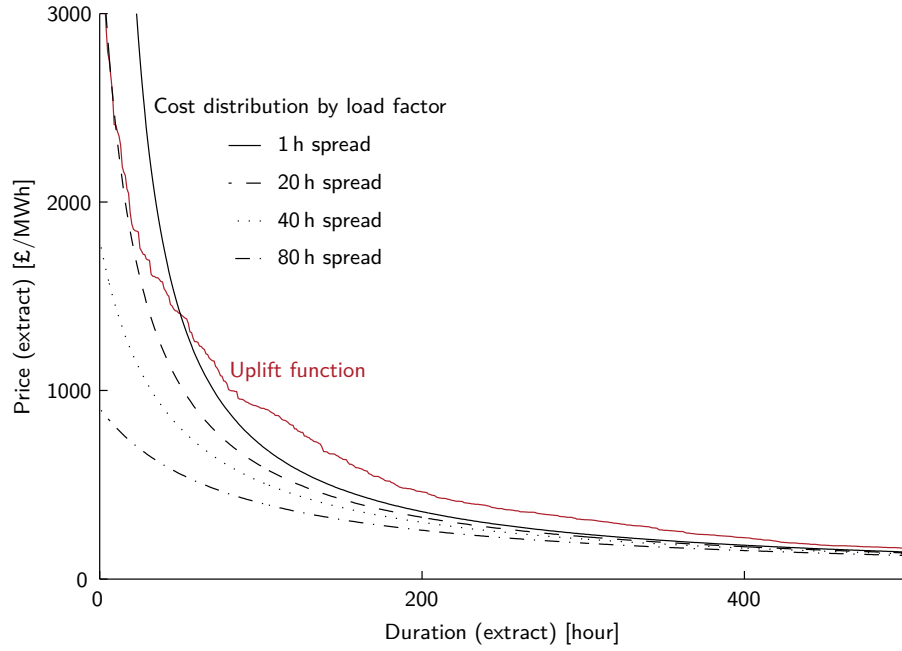


Figure A.4: Price duration with 40 GW wind, contrasting an uplift function and the minimal cost function based on load factors in a strict merit order system.

To test the sensitivity of the gross value of storage to changes in the makeup of future price formation, five cases are compared with 1, 20, 40, 80 and 160 hours of bundling respectively. The middle value of 40 hours is treated as the reference case, because it resembles the empirical uplift function most closely. Relative changes (s) to this reference value (v_r) are calculated as

$$s(i) = 2 \times \frac{v_i - v_r}{v_i + v_r} \quad (\text{A.7})$$

where i is the case to be compared with the reference case. The results are shown in Figure A.5. Different scales and durations of storage react differently to changes in the steepness of the cost function. The less bundled, steeper curve, results in higher arbitrage opportunities and increases the value of storage. However, halving the bundling period from 40 to 20 h only yields modest increases in value of up to 9%. Longer bundling periods, which result in a flatter price curve associated with less competitive markets can be detrimental to the value of storage, as one would expect. A larger share of the value of storage is internal to the actors performing the bundling. Doubling the cost spread from 40 hours to 80 hours can reduce the value of storage for the cases considered in Figure A.5 by between 12% and 32%.

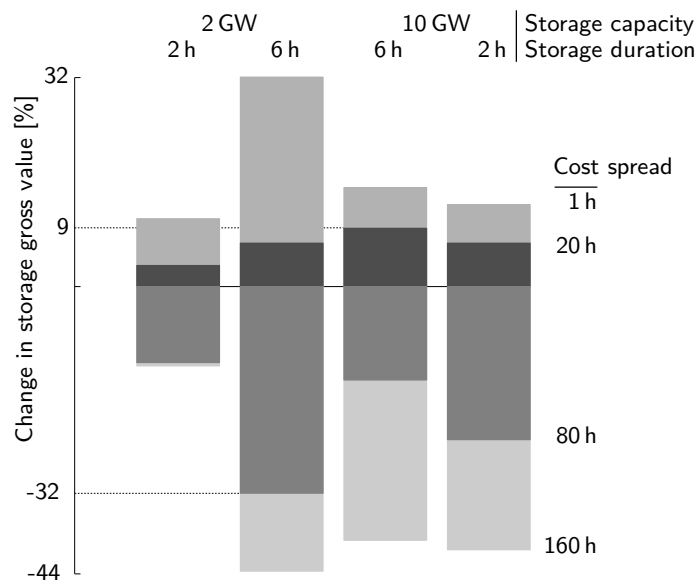


Figure A.5: Sensitivity of storage to price setting assumptions. Change in the gross value of storage for selected cost spreads and storage configurations. Values shown for 40 GW wind scenario.

The more extreme cases of 1 hour and 160 hour spread show that results are strongly affected, but that the uncertainties are not disproportionately greater than other uncertainties associated with this study.

In conclusion, the uplift function approach adopted in this study constitutes an empirical approximation of price setting behaviour. The shape of this curve is subject to market context and may change in future, *iter alia* as a result of changes in competitiveness of future markets. Stronger competition (here represented as a de-bundling

of capacity) could bring out higher commercial values of storage. A less competitive market, on the other hand, may lead to lower market values.

A.1.3 Wind profile sensitivity

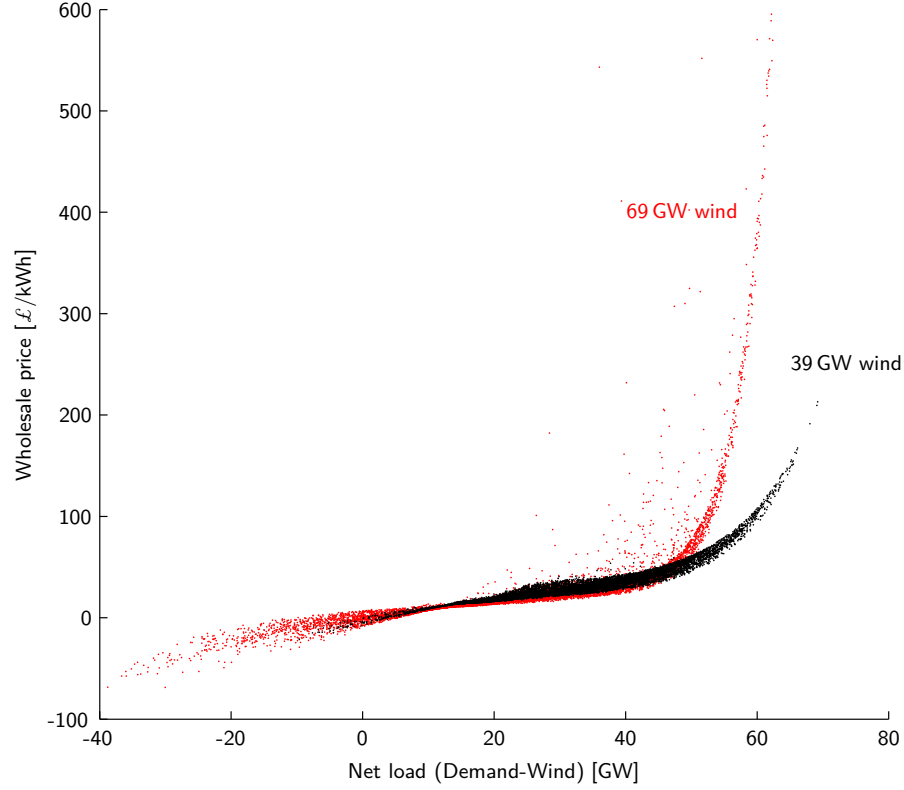


Figure A.6: Wholesale prices for given net loads. Examples based on DECC Grassroots scenario with 39 GW and 69 GW of wind respectively ($\kappa = 20$ and 2). Prices in the 69 GW case exceed beyond the 600 £/kWh displayed. Peak prices can reach in excess of 3000 £/kWh

The simulations of this study are based on the wind data discussed in Section A.1.1. These data, which are extrapolated from onshore wind speed measurements, can be compared to the independent set of offshore data developed by Hawkins (2012), shown in Figure A.8.

Figure A.9 show an example case for a 2030 scenario. The distribution is simulated over a 6 year period based on historic data starting on 1 Apr 2003. The mean value of storage is, as one would expect, lower for offshore sites due to their more consistent output. Across the whole set of offshore wind sites for which data is available, the reduction is around 10%. If off-shore sites are selected for maximum load factors, then

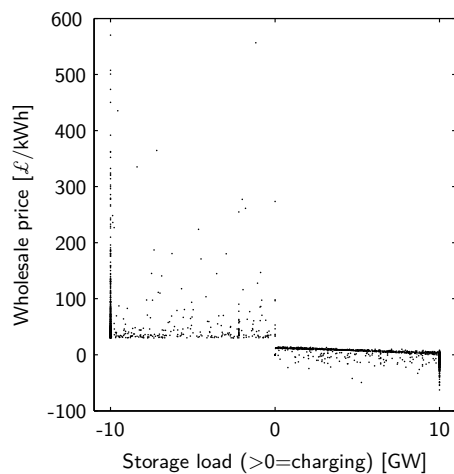


Figure A.7: Wholesale prices seen by a storage operator at different states of charging and discharging. (Prices extend beyond the range shown)

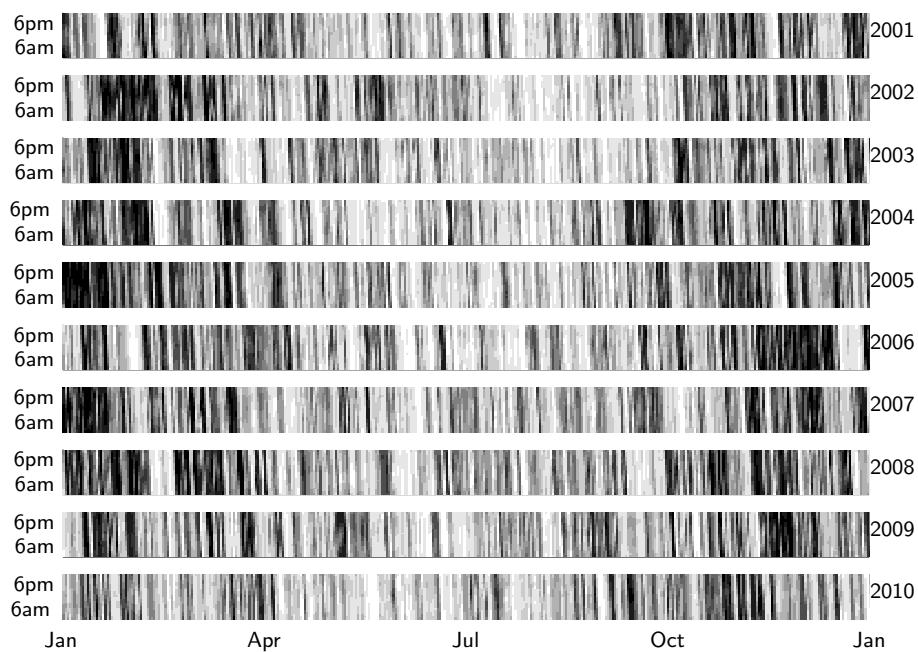


Figure A.8: Wind output for an averaged set of 46 sites around the UK coast over 10 years with hourly resolution. Black denotes output at rated capacity. Data based on Hawkins et al. (2011)

the discrepancy becomes bigger. Limiting sites to the top quartile of load factors can reduce the mean value by nearly a third.

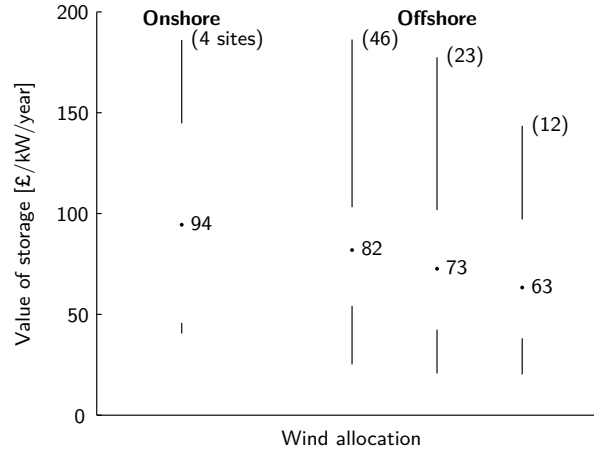


Figure A.9: Offshore wind provides less value for storage. Distribution across 46 offshore sites reduces the mean value by around 10% compared to onshore wind profiles for the four selected regions. When concentrating all offshore installations to the 12 locations with the highest load factor (12), the value could reduce further. (Case: Grassroots 2030, 10GW/6h storage with 75% efficiency.)

Solar data

Solar irradiance data were recorded as the duration of direct irradiation within each hour. Intermittent irradiation on a partially cloudy day can be misread as continuous sunshine, overestimating irradiance by up to 20%. on the other hand, diffuse sunlight that is not recorded, may still lead to PV output. Data were consequently scaled to meet the expected UK average irradiation of about 1100 Wh m⁻². (Šúri et al., 2007; UK Meteorological Office, 2006)

The use of historical data ensures that any correlation between weather patterns and energy consumption is adequately reflected, and their chronology is preserved. The data, covering 6 successive years, allows to interrogate issues arising from stochastic variations between years. This will be done in Section 5.6. First, the relationship between demand and wind resource, which motivated the use of historical data, is explored in the following section.

Correlation of wind resource and demand profiles

Some work has been carried out to develop time series stochastically, based on historical data (Hawkins et al., 2011; Chuter, 2006). This approach is helpful in expanding the

data available and to explore the probability of events with greater accuracy. However, when using more than one set of data, as is the case in this study (namely wind speeds and electricity demand), the independent representation as time series can omit causal links between them. It can be assumed with some confidence that electricity demand is not going to affect the wind speed.³ The opposite effect is however quite reasonable. Windy conditions could change behaviour, such that people are more likely to stay indoors, or that the wind chill increases the need for heating. The latter may become more pronounced if heating becomes more electrified in the future.

Figure A.10 shows a slight positive correlation. The data in this graph are drawn from the BADC and the National Grid. Each data point represents a 1 hour period, with the colour representing the years 2003–2008.

Some commentators argue that during peak demand hours the probability of high wind is lower (see Oswald et al. (2008), but also Gross (2008)). This trend can be observed, when using a higher order polynomial fit. Figure A.10 shows a drop in average load factor for the hours of peak demand, suggesting that during these hours other factors come into play. A possible explanation is the presence of anti-cyclones during the UK winter months, leading to low wind spells combined with low temperatures and thus high energy demand. Further, UK peak demand is strongly linked to time of year and time of day (typically around 5pm on a winters day). These moments are less influenced by the above factors. The correlation is therefore weaker and some regression to the mean takes place. The data does contradict Oswald in so far as the average load factor during times of high demand (≥ 50 GW) is still above the mean.

A.1.4 Demand data

The two dimensional visual representation of demand profiles, which is used to inspect the data for inconsistencies, is shown in Figure A.12. Each pixel represents a one hour reading, scaled such that peak demand is white and minimum demand black.

A.2 Model validation and parameter sensitivity

As explained in Section 3.1.3 on page 59, since at present the conditions for commercial viability of storage are not given in the UK, the model seeks to provide insight in an exploratory manner, by investigating future scenarios for their impact on storage.

Validating the model's predictions for storage values based on 'real world' measurements is therefore not possible. Nevertheless, some snapshots can provide indicative values for comparison. The first are the expected conditions, during the planning phase of Dinorwig's pumped hydro installation. These should yield values broadly in line with cost projections at the time and can be compared to the value estimates by the CEGB at the time. The second point in time used as a snap shot for verification is the present

³One could argue that a very large penetration of wind turbines would slow down the wind across the country, and more so if the load is high.

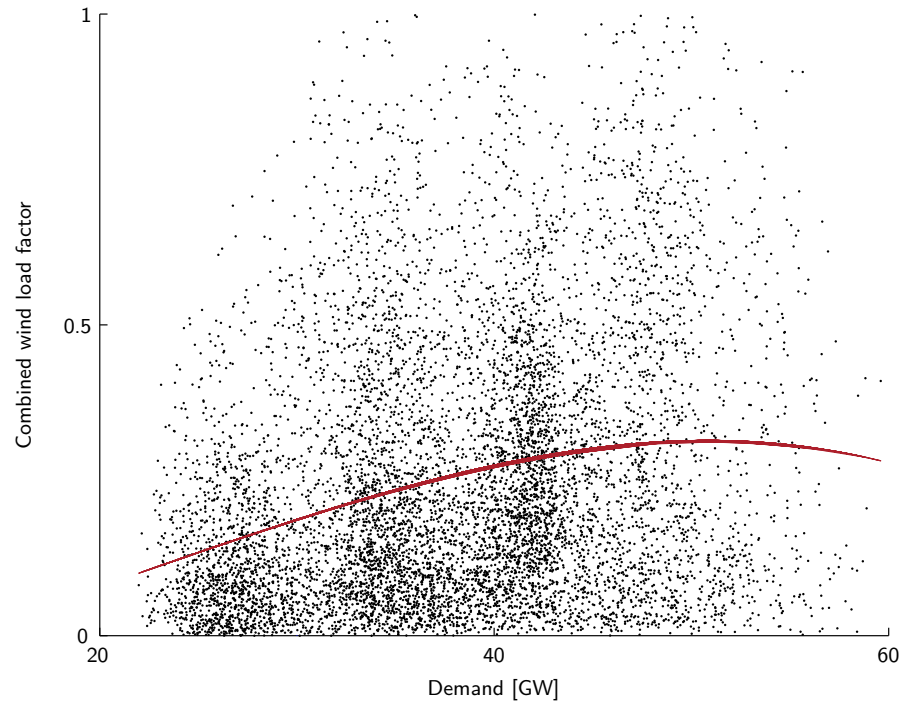


Figure A.10: *Correlation between wind resource and electricity demand. Overall wind and demand are loosely positively correlated. During high wind periods some mean regression takes place. Fit is 3rd order polynomial.*

system, which, if observed investment behaviour is taken as a guide, should produce values for storage that are below present technology costs.

Snapshots alone do not provide a strong validation of the model. Section A.2.2 therefore tests the outputs in a more structured way. All key input data are subjected to changes and the predicted outcomes are compared with model results. Any unusual model responses are identified and discussed.

A.2.1 Model alignment with ‘real world’ values

Chapter 4 introduced historic cases of storage uptake. The use of batteries in DC networks relied on extreme load profiles. The profile shown in Figure 4.1 on page 86 is itself not validated, and should be treated as an illustrative example. In the absence of other data, this profile is included in the model with the aim to test if the model valuation of storage is consistent with the favourable investment landscape at the time. Based on such load profiles the value of storage is approximately 20% higher than even the high wind scenario for 2030. This finding is largely independent of the exact generation mix, which is due to the extreme nature of the profile, making storage viable regardless of

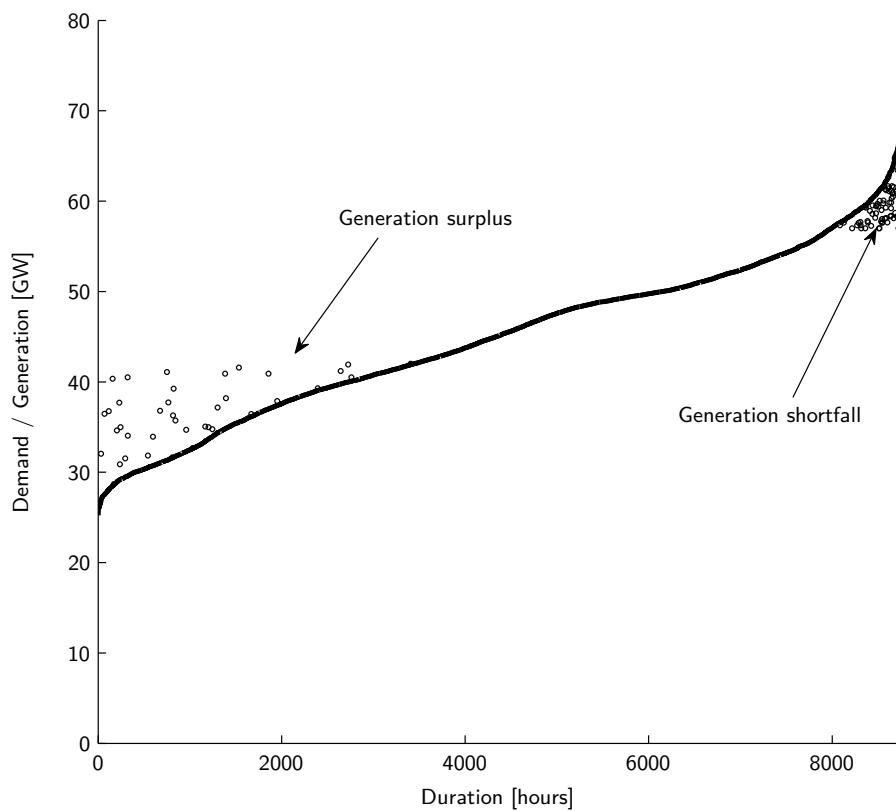


Figure A.11: *Illustrative example of generation shortfall and surplus against the load duration curve for 2009. The simulation assumes 69 GW wind, 15 GW of base load and 42 GW peaking plant. With these constraints, loads can exceed the combined resource available during peak loads and conversely, the combination of base load generation and wind can exceed demand towards the lower end of the load duration curve. Ramping and availability are not simulated here.*

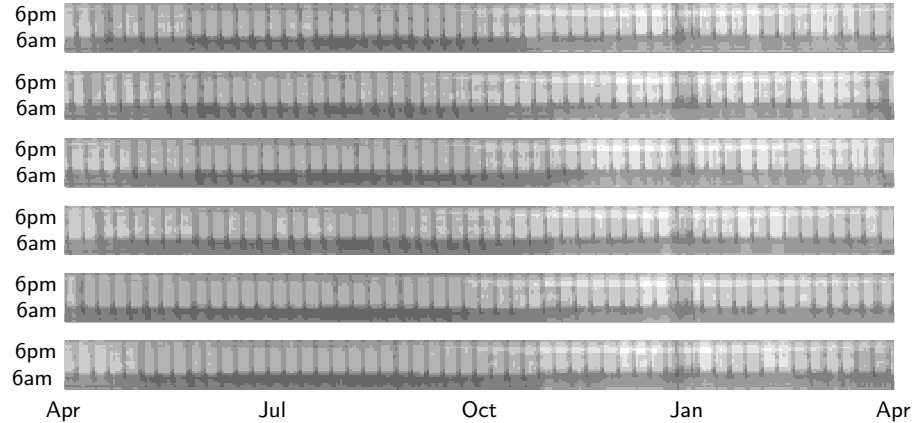


Figure A.12: Demand profiles for the UK based on National Grid (2010) data from April 2003–09. (Dark=low demand, light=high demand)

the technology mix (the DC generators would in the terms of this model be classified as ‘flexible’).

In terms of validation, the ‘consistent’ outcome of model and historic circumstances should not be seen as more than a test that the model operates with extreme load profiles.

The following tests draw on system conditions, for which a generation mix could be estimated. The parameter values used in the simulation are shown in Table A.3.

The first of these cases is the Dinorwig pumped hydro facility, discussed in Section 4.3 on page 91. The commercial case rested on anticipated high shares of nuclear power stations, and covering for faults in particular. These are specific to nuclear power at the time. Sudden drops in output due to unscheduled plant faults have reduced significantly for nuclear power stations over past decades, and their contribution to the value of storage is thought to be minor (Boon, 2010). This component of the value expectation is therefore not covered by the model as written. Approximately 55% of the remaining value, however, are due to system balancing functions in the widest sense and should be recognised by the model.

The high share of nuclear is represented by a capacity mix that constitutes 35 GW of base load (i.e. nuclear) with 20 GW of mid merit plant and 18 GW of peaking plant. This combination results in a value for the Dinorwig configuration (2 GW $\times$ 5 hours with 75% efficiency) of around £34.1/kW/year. If the unaccounted 45% for covering faults is included the total value might reach around £62/kW/year. Costed over a 20 year life at an IRR of 6% the capital value for the facility comes out at around £713/kW, which is above the cost estimated for Dinorwig in Section 4.3 on page 91 of around £560/kW.

The second test case is the present energy system, which arguably does not send sufficient investment signals for storage. Based on figures from MacLeay et al. (2010), the UK generation mix comprises approximately 6 GW of wind, 25 GW of plant operating

under base load conditions, with 30 GW of mid merit and 26.3 GW classified as peaking capacity. The simulation of a hypothetical addition of 2 GW of storage capacity yields around £1.85/kW/year in value, confirming that the present system is not in ‘need’ of additional storage capacity.

Table A.3: *Generation mix in validation cases. Based on MacLeay et al. (2010) and authors assumptions.*

Parameter	1970s	2010s	2030s
Wind [GW]	0	6	69
Baseload [GW]	35	25	15
Mid-merit [GW]	20	30	30
Peaking [GW]	27.6	26.3	34.6
Storage [GW]	2	2	2
Value [£/kW/year]	34.1	1.9	82.8

A.2.2 Model validation by parameter

The above approach of testing the model against ‘real world’ cases is limited to a small number of cases, which is not sufficient to give confidence in the ‘inner workings’ of the model. In the following, the model is therefore tested against ‘expected results’. The key input parameters are varied and the expected response is anticipated. Should the model output not correspond to the expected output, the causes can be scrutinised for their adequate representation of the intended market dynamics.

The analysis sets out from a ‘base case’ scenario, which is detailed in Table A.4. Changing these parameters leads to changes in the value of storage. Two extremes and two moderate changes are tested for each parameter. The extremes (setting a parameter value to 0 or to a very large number) test the robustness of the code, whereas small changes (on the order of 10% from the original value) expose sensitivity and logical direction of results. As shown in Table A.5, not all instances result in the anticipated direction of response. The causes for these ‘counterintuitive’ results is discussed below.

Increasing demand would intuitively suggest that the value for storage should increase. If the entire system was scaled up, then this is indeed what should happen. However, the model starts from a coherent scenario narrative in which the base load, mid-merit and peaking capacity are balanced to suit the demand profile. When the demand is artificially scaled up or down, only the peaking capacity is adjusted to maintain security of supply.

In the case where demand is scaled up and more peaking capacity operates, this peaking capacity now serves part of the demand profile which previously was the preserve of mid-merit plants. The load factor for peaking capacity is therefore higher and the

price duration curve becomes flatter. Thus, more demand—when modelled in this way—leads to a lower value for storage and vice versa. This response is correct and no changes to the model code are undertaken as a result.

Setting the price profile to a square function is an idealised case for storage. During the low state, storage charges, and when the function switches to high, storage changes to discharge. Although this is in some ways the most trivial of operating decision processes, this function revealed a weakness in the solver. The discontinuity at a single price point (the upper state of the price function) is challenging for this solver, when searching for optima. For upper values below £46/MWh, the solver does not converge. Provided the solution space does not contain discontinuities of this kind the solver is expected to operate as intended. However, the limitations of the solver are acknowledged here.

The binary states of the square function means that so long as spare storage capacity is available, storage is either charging or discharging at the maximum rate possible. It never runs in part load or idles. In other words, the load factor is at its theoretical maximum. The period of the square function does therefore not affect the value of storage, so long as it is shorter than the time to fully charge or discharge the storage capacity, i.e. the storage duration.

Table A.4: *Base case parameters as used in the parameter validation. Values based on MacDonald (2010); DECC (2011a) and MacLeay et al. (2010)*

Parameter	Value
Year of historic data	2006
Wind data	BADC (Onshore)
Demand data	National Grid
Storage capacity	10 GW
Storage duration	6 h
Storage efficiency	75 %
Wind capacity	69 GW
Base load capacity	15 GW
Base load short run cost	8 £/kWh
Mid merit capacity	30 GW
Mid merit short run cost	20 £/kWh
Peaking capacity	25 GW
Peaking short run cost	30 £/kWh
Fuel cost	48 £/kWh _{el}
Peaking capital cost	718 £/kW
Peaking operating costs	15 £/kW/year
Peaking mean profit target	100 £/kW/year
Capacity margin	20 %
α	4
κ	variable

Table A.5: *Model validation by parameter. Starting from the base case scenario in Table A.4, parameters are subjected to changes and the predicted outcome is compared with measured results.*

Parameter	Value	Prediction	Measured	Comment
Wind	0	0	0	✓
	-10%	↓	-17%	✓
	+10%	↑	+10%	✓
	+100%	↑↑	+63%	✓
Demand	-100%	0	-89%	Residual value due to ROCs. When ROC=0 value of storage = 0
	-10%	↓	+6.5%	Peaking plant is sized based on peak demand, therefore less peaking plant in this scenario, but all other plant remain the same. Larger role for storage in balancing.
	+10%	↑	-34.6%	More peaking capacity operating (since this is the only added capacity), therefore flatter price curve.
	+100%	0	-99.1%	See above
Price duration curve				
	0	0	0	✓
	flat at mean	0	0	✓
	-10%	↓	-1.4%	✓
	+10%	↑	+0.3%	✓
	Square wave ¹	↑↑	+30%	✓ Note, below £46/MWh, solver does not converge on square wave function.
Base load and mid merit plant				
	0 ²	↓↓	-96.4%	✓ Peaking capacity picks up the shortfall. Higher load factor leads to flatter price duration curve.
	-10%	↓	-13.7%	✓
	+10%	↑	+4.4%	✓
	+100%	↑↑	↑↑	✓ Peaking capacity becomes zero. Price function cannot be calibrated, because storage becomes price setter for balancing.

¹min=0, max=£50/MWh, period≤storage duration

²0.5 GW base load plant required for price function to converge

Stakeholder engagement

B.1 Stakeholder workshop

This section provides some additional information about the stakeholder workshop to complement Chapters 6 and 7. The workshop was held with thirty participants from 17–18th May 2012 at Imperial College London. The list of participants is given in Table B.1. Figure B.1 shows the distribution of some of the diagrams shown in Section 6.4.1. Section B.2 contains the content of a five page brief, which participants were sent one week before the event. The iPad application used to gather participants preferences is explained in Section B.2.1.

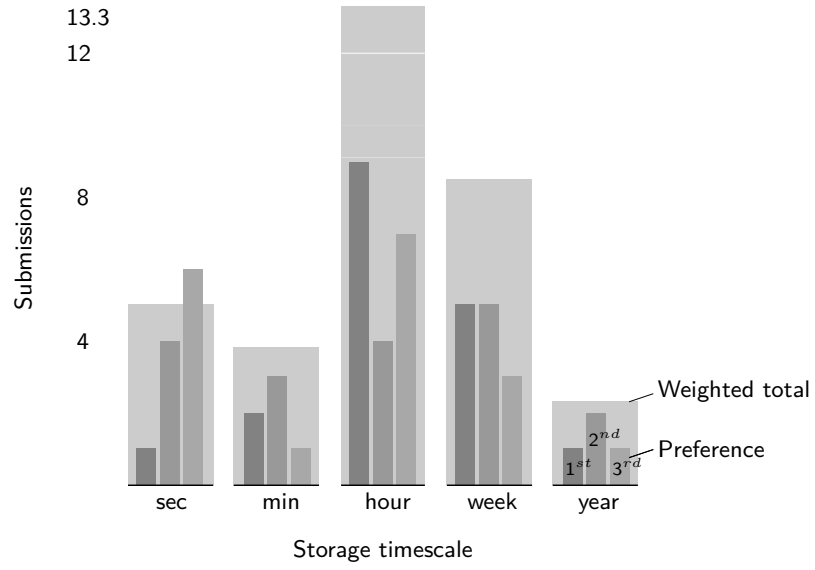


Figure B.1: Histogram of stakeholder storage duration preferences. The dominant storage duration ranges between hour and week. First, second and third preferences are aggregated by weight ($1\times$, $0.5\times$ and $0.33\times$ respectively)

Table B.1: *Workshop participants*

First name	Last name	Organisation
Rob	Arnold	DECC
Andy	Boston	E.On
Karima	Boukir	EDF Energy
Nigel	Brandon	Imperial College London
Hannah	Chalmers	University of Edinburgh
Tim	Cockerill	ICEPT, Imperial College London
Phil	Coker	University of Reading
Marcello	Contestabile	Imperial College London
Graham	Cooley	ITM Power
James	Cox	Poyry
Philip	Eames	Loughborough University
Gareth	Evans	Ofgem
Phil	Gruenewald	Imperial College London
Peter	Hall	Strathclyde University
Jeff	Hardy	UKERC
Alex	Hart	Ceres Power
David	Hodgson	UKTI
Philip	Johnson	National Grid
Emma	Kendrick	Sharp Laboratories Europe
Simon	Lord	First Hydro Company
Ron	Loveland	Wales government
Pierluigi	Mancarella	Imperial College / University of Manchester
Malcolm	McCulloch	Oxford University
Will	Mcdowall	UCL
Emma	Owen	DECC
Peter	Pearson	Cardiff University
Toby	Peters	Highview
Anthony	Price	Swanbarton Limited
Jonathan	Radcliffe	Energy Research Partnership
Samatha	Riches	EPSRC
Aidan	Rhodes	UKERC
Alistair	Steele	SSE plc
Goran	Strbac	Imperial College London
Robert	Sansom	Electrical and Electronic Engineering, Imperial
Jim	Skea	UKERC
Garry	Staunton	Staunton Associates
James	Sun	Carbon Trust

B.2 Brief for workshop participants

The following five page document was emailed to workshop participants one week before the event. It was intended to frame the objective of the event and introduce questions to be addressed. Envisaged outputs and suggested reading are provided at the end of the document.

The Future of Energy Storage: A workshop for stakeholders

17-18 May 2011, Imperial College London

Objective

This workshop sets out to understand the different preferences and barriers to deployment perceived by stakeholders in storage. Areas of common interest as well as possible conflicts of interest will be identified. This will help to inform the development of a regulatory framework that reflects the stakeholder interests, and thus better realises the potential benefits of storage in the UK.

Recent workshops and projects on storage concluded that the UK lacks a strategic vision and a roadmap for storage and that market mechanisms and barriers to deployment are not sufficiently well understood.¹

This workshop seeks to address these gaps by engaging with a wide range of stakeholders from across the energy value chain.

Why stakeholder views matter

Traditional categories of ‘generation’, ‘delivery’ and ‘demand’ may not be suitable to represent storage. A better approach to valuing storage requires a more holistic approach, which aggregates benefits for stakeholders across the energy system. This calls for a detailed understanding of how benefits are perceived by stakeholders. Only then can a regulatory framework be developed that rewards providers of such services appropriately.

¹The Royal Academy of Engineering and the Chinese Academy of Sciences, Storage workshop, London, Jan 2011 and Energy Research Partnership’s (ERP) Energy Storage Project, London, 2011

However, the benefits are not consistent amongst stakeholders. Competing options (be they storage or alternatives) need to be identified and carefully balanced.

Types of storage services

To avoid a discussion of the possible merit of specific technologies, this workshop will concentrate on the *types of services* or *functions* storage can provide. We intend to simplify the discussion by concentrating on two dimensions in particular: 1) time scales over which energy is held in storage and 2) location of storage on the system.

Time scales

Time scales for storage span several orders of magnitude. At one extreme storage can improve power quality with fast response during sudden demand pick-ups or drops. For such services energy is only held for short periods. At the other extreme storage can deal with long term effects, such as seasonal variation in demand. Examples of types of storage services for different time scales is given in Figure B.2.

Under purely commercial considerations, shorter storage durations tend to be favoured, as they provide a higher energy turn over. Longer storage duration may however bring about wider benefits, such as system resilience, that are currently not necessarily priced into the market.

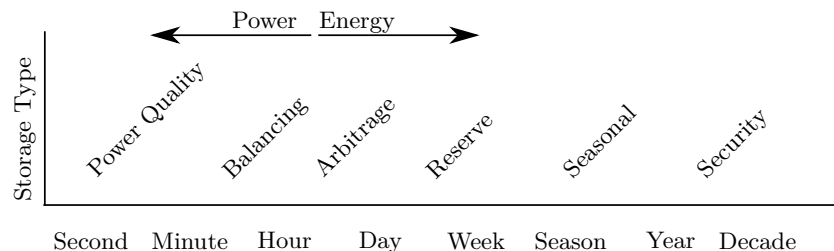


Figure B.2: *Types of storage applications and timescales over which energy is stored for. For short duration storage power is the overriding cost factor, whereas longer storage periods call for solutions with low energy related cost.*

Question:

- a) In your opinion, which timescales of storage are most critical to a future energy system?
- b) Under what circumstances do certain timescales become more or less important?

Scale and location

Future networks are expected to become more distributed. They will comprise a greater participation from the demand side as well as distributed generation.

Storage is faced with similar choices: current pumped hydro storage systems are remote from demand centres and feed into the transmission system. Large scale systems benefit from economies of scale, and extreme solutions have been suggested, such as tidal lagoons.

At the other extreme distributed storage may support smarter distribution networks. Figure B.3 gives a conceptual overview of scales for storage.

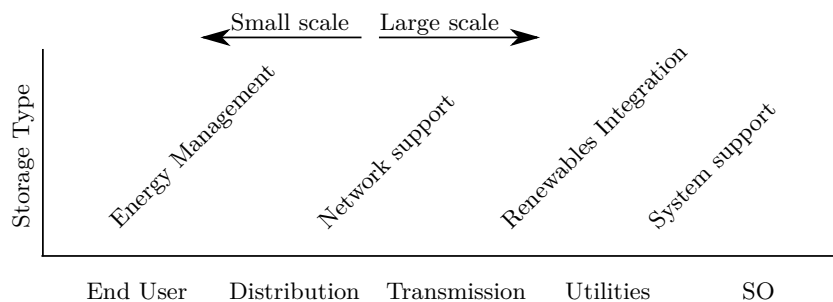


Figure B.3: *Locations for different types of storage on the energy system. Large scale solutions suit the high voltage end of the energy system, whereas smaller systems can be located closer to demand. Each location brings about a different set of benefits. (SO = System Operator)*

Question:

- How do you rate the relative importance of providing storage services at different locations?
- What is the scope for storage at a given location to provide benefits upstream or downstream?
- How does scale or location affect the responsiveness?

Storage Benefits

For the purposes of this workshop “benefits” encompass all private and social benefits, that arise from the presence of storage. Some of these may be indirect, abstract or difficult to monetise, but all efforts should be made not to exclude any benefits from the discussion. Commonly cited benefits of storage are listed in the Tables B.2 and B.3.

In the light of the surrounding uncertainties and unknowns, this workshop will not assign specific values to storage services. It is however intended to establish a qualitative

Table B.2: *Potential revenue streams for storage applications*

Benefit / service
Regulation (<1 hour)
Transmission and distribution investment deferral
Network charges avoided
Power quality
Energy arbitrage
Generation capacity credit
Supply reliability

Table B.3: *Less direct services with potential to be perceived as a benefit*

Benefit / service
Supporting integration of renewables
Reducing long term reliance on fossil fuel plants
Overall system efficiency
Enhancing impact of demand side management
Reduced price volatility
Energy independence / islanding
Resilience
Security of supply
CO ₂ emission reduction

review of their relative value to stakeholders.

Question:

- a) Do you agree with the list of benefits presented here?
- b) Which costs/downsides should be considered?
-  b) From your perspective, how would you rate the relative merit of these benefits?
- c) Under which conditions, do you expect these benefits to become more or less important?

Outputs

The findings of this workshop will be compiled into a report and circulated amongst participants, other stakeholders and policy makers in particular. They are further intended to be published in a peer reviewed journal and as working and discussion papers. We will seek active engagement with participants beyond this workshop to support and inform the development of a roadmap for storage in the UK. Follow up events are expected to

build on the output of this workshop.

Suggested reading

- Handbook of Energy Storage for Transmission or Distribution Applications, Eckroad (2002)
 - Energy storage in the UK electrical network: Estimation of the scale and review of technology options, Wilson et al. (2010)
 - Benefit/Cost Framework for Evaluating Modular Energy Storage, Schoenung (2008)
 - Value of bulk energy storage for managing wind power fluctuations, Black and Strbac (2007)
 - Utility-Scale Storage of Renewable Energy, Schaber et al. (2004)
 - Impact Of Intermittency: How Wind Variability Could Change The Shape Of The British And Irish Electricity Markets, Cox (2009)
 - Electricity Energy Storage Technology Options, EPRI (2010)
 - Energy storage technologies in the UK, ERP (2011)
-

Table B.4: *Workshop agenda*

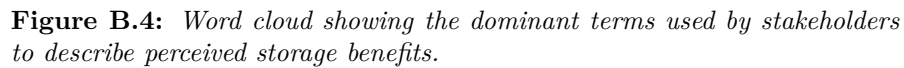
Day 1	
12:30	Registration and light lunch (Drawing Room)
13:15	Welcome and Workshop Context (Council Room) Peter Pearson
13:30	Table Introductions and Mapping Exercise Personal introductions, shared expectations Mapping of the types of storage perceived as needed
14:15	Scene Setting Presentations Chair: Peter Pearson (Cardiff University) Pathways to 2050, Jim Skea (UKERC) Impact of Intermittency, James Cox (Pöyry) Challenges for the energy system, Andy Boston, (E-ON) Storage overview, Peter Hall (Strathclyde University)
15:15	Refreshment Break
15:45	Round Table Chair: Peter Pearson, Cardiff University Open discussion to identify controversial areas, majority opinions and common ground. Interventions by Toby Peters (Highview), Philip Eames (Loughborough), Robert Sansom (Imperial) and Steward Reid (SSE).
17:00	Summary and Emerging Themes for Day 2 Peter Hall 10-15 minute summary of the discussion with a brief outlook on what needs doing next
17:30	Adjourn - Steering committee and Facilitators: brief internal review of the day. Facilitators and Tim C: group the benefits into broad themes, to be used the next day.
19:00	Dinner (The Garden Room, 58 Prince's Gate)

Table B.5: *Workshop agenda day 2*

Day 2	
09:00	Refreshments on arrival (Council Room)
09:20	Welcome and agenda for day Chair: Tim Cockerill – Reminder about the main points from day 1. Slides with the agenda with a short intro to the purpose of the sessions.
09:30	Working group introduction Phil G: Present the benefit clusters on the boards. Discuss grouping / identify missing ones. Explain the group session Discuss the following questions 1. Who does this benefit add value to? 2. How can this benefit be valued (monetised?)? 3. What ‘type’ of storage can best deliver this benefit? 4. What are the unknowns/uncertainties about this benefit? 5. Under which conditions does this benefit arise? Take a vote: how many would want to discuss each group Groups are given the stack of cards. Facilitators: 2 Groups to be lead to the boardroom, 1-2 groups stay. The Boardroom needs less furniture shifting and should be used for the larger group.
09:45	Working Groups Storage benefits Facilitator - brings the questions - arrange the rooms (Drawing room, just shift a few chairs for a circle) - assign one person to report back in plenary reflection - if necessary - nudges the group to address the questions. Facilitators / Meeting Place: take notes to support the person reporting back, and for the record.
11:00	Refreshment Break Facilitators / Meeting Place: arrange drawing room + plenary table.
11:30	Plenary Reflection Chair: Tim Cockerill Tim C – let each group representative give a 5 minute summary of their discussion. Followed by questions from all.
12:15	Speaker Intervention: Goran Strbac Tim C – make transition from ‘benefits’ to challenges, introduce Goran take questions after talk.

Table B.6: *Workshop agenda day 2 afternoon*

Day 2 afternoon	
13:00	Lunch Facilitators / Meeting Place: Shift chairs in the Drawing and Boardroom. Arrange two tables for about 10 people in either corner. On the tables, Lay out large sheet of paper with the Theme and Questions boldly written on it. Provide large pens
13:45	Knowledge café introductionPhil G: Introduce the Themes/Questions with slide Drawing room Challenges
14:00	Knowledge café Challenges, Planning under uncertainty, Support schemes, PolicyFacilitators / Meeting Place: 2 people per table. Encourage discussion and (since the attendees change) create links with earlier contributions. Take notes and encourage note taking on the table cloth.
15:00	Refreshment Break Meeting Place: Drawing room chairs back to seminar+penary layout Facilitators: Compare notes
15:30	Reflection and Mapping II Tim C – let facilitators summarise and moderate comments / questions Facilitators: Give a brief summary of the discussion at their table.
16:00	Workshop Summary Nigel Brandon Nigel: Summary of the key discussions, interesting points raised, next steps (China workshop, report of findings) encourage further collaboration
16:15	Adjourn and invitation to drinks reception Phil G: Bring up the before and after mapping graph
17:00	Close



Workshop participants submit their preference for location and timescales for storage via an iPad app. The interface is specifically designed to allow flexible and spontaneous interaction, while maintaining anonymity of each submission. The iPad is passed around the round table and each participants enters onto the same a blank graph, thereby avoiding bias and clustering towards early submissions.

The second screen starts with a blank cartesian diagram and axis labels for location and timescales. With three touches of the screen the first, second and third preference are selected and marked with different sizes on the screen, as shown in Figure B.6. An ‘undo’ button allows to retract and repeat unintended submissions. After the third touch the three points can be confirmed and the application returns to screen one for the next participant.

With four touches of the screen and one confirmation touch, data for location, timescales, stakeholder group and preference sequence are submitted. All data points are stored for the analysis shown in Section 6.4.1.

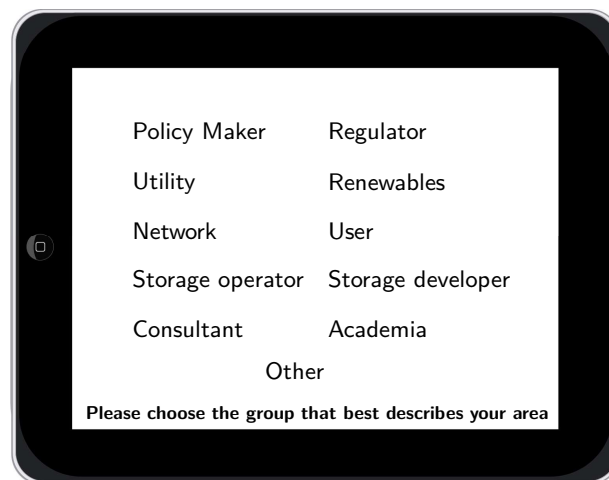


Figure B.5: First screen of storage preference app. Self selection of category by touch.

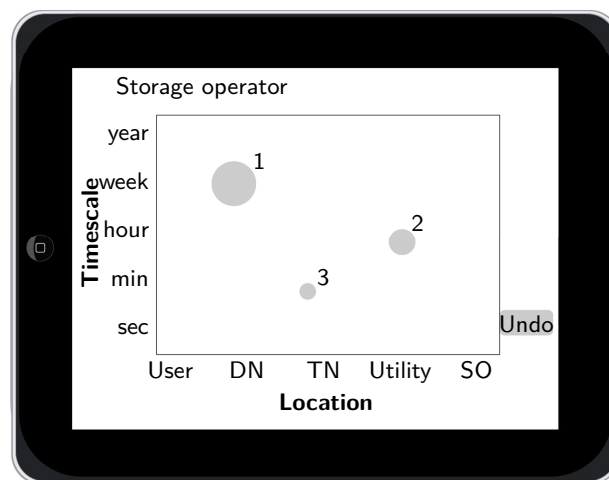


Figure B.6: Illustrative example of the second screen after preference selection. With three touches, first, second and third preference are expressed for both axes. Choices can be confirmed or dismissed.

B.2.2 Knowledge café

The following questions are laid out on the four tables (A–D). Each table has a cloth and participants are actively encouraged by their hosts to write on the cloth. Participants joining a table at a later stage can pick up on such comments or the table host repeats earlier discussions for them.

A. Challenges (Host: Hannah Chalmers)

1. What are the main challenges facing storage deployment?
2. How do barriers to deployment differ between “types” of storage?

B. Planning Under Uncertainty (Host: Phil Coker)

1. What information is needed to make informed decisions about the future of storage?
2. On what timeframes should such decisions be taken?

C. Support Schemes (Host: Aidan Rhodes)

1. What type of support is needed to bring storage to market?
2. How should storage be evaluated with respect to alternative solutions?

D. Policy (Host: Phil Grünewald)

1. How do current policies affect storage?
2. What type of regulatory framework is needed to realise the potential benefits of storage?
3. Are differing approaches needed for different “types” of storage?

B.2.3 Workshop steering committee

Table B.7: *Workshop steering committee*

Name	Organisation
Nigel Brandon	Imperial College London
Tim Cockerill	Imperial College London
James Cox	Pöyry
Phil Grünewald	Imperial College London
Peter Hall	Strathclyde University
Jeff Hardy	UK Energy Research Centre
David Hodgson	UKTI
Jonathan Radcliffe	Energy Research Partnership
Robert Sansom	Imperial College London
Jennifer Otoadese	UKERC Meeting Place

B.3 Semi-structured interviews

Table B.8: *Steps of the interview process. Questions are reformulated to suit candidates and interview flow.*

Theme	Topic / Example Questions	Purpose
Introduction	Explain the background of research, purpose of interview, use of data. Stress that interview seeks perceptions rather than facts.	Provide context and put interviewee at ease.
Background	Can you tell me about your organisation? Could you provide me with some background to your activities in this area?	Engage interviewee on a subject within their comfort zone.
Benefits	Can you see a role for electricity storage in future systems? How would the presence of more storage on the system affect your situation? What role can you see for yourselves in relation to electricity storage in future systems?	Identify level of engagement
Operation	From your point of view, how would you like to see storage operated? Do you believe that storage operation requires regulation? Are current markets suited to stimulate the right kind of storage? How do you envisage to contract storage services? Do you foresee competing interests in the operation of storage?	Depending on candidate this theme can lead to open discussion
Investment	Who, in your opinion is best placed to invest in storage? X suggests that you may be well placed to invest—do you agree?	Explore relationships with other stakeholders. Challenge without confronting.
Barriers	What do you perceive to be possible barriers to storage deployment? How do you judge the role of regulation in this area?	Invite discussion
Open discussion	Questions emerging from discussion	Repeat and agree key notes. Chance for general comments and informal conversation.
Closing remarks	Repeat purpose and use of interview and explain next steps.	Ensure consent.