Programme Area: Energy Storage and Distribution

Project: Storage and Flexibility Modelling Project

Title: Energy Storage Mapping Report

Abstract:

The report provides an assessment of the services that storage (heat, hydrogen, electricity and gas) could provide and an assessment of the related technologies.

Context:

This project will develop energy system modelling capability to increase understanding of the role of energy storage and system flexibility in the future energy system. The modelling capability will provide a whole systems view of the different services that could be provided and at which points in the energy system they are most appropriate. Management consultancy Baringa Partners are delivering this new project to develop the capability to improve understanding with regards the future role of energy storage and the provision of cross-vector system flexibility within the context of the overall UK energy system.

D1.1 Energy Storage Mapping Report

CLIENT: Energy Technologies Institute

DATE: 19/08/2016

Version History

Version	Date	Description	Prepared by	Approved by
V1_0	27/06/2016	Draft Final	LH, JG, AB	OR
V2_0	19/08/2016	Final incorporating ETI comments	JG, AB	OR
V3_0	15/08/2017	Minor edits for publication	LH	LH

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Table 1 List of Acronyms

Acronym	Description
AAHEDC	Assistance for Areas with High Electricity Distribution Costs (charges)
BEGA	Bilateral Embedded Generation Agreements
BM	Balancing Mechanism
BMU	Balancing Mechanism Unit
BSC	Balancing and Settlement Code
BSIS	Balancing Services Incentive Scheme
BSUoS	Balancing Services Use of System (charges)
CCGT	Combined Cycle Gas Turbine
CfD	Contract for Difference
CM	Capacity Market
CMSC	Capacity Market Supplier Charge
CUSC	Connection and Use of System Code
DA	Day Ahead
DG	Distributed Generation
DNO	Distribution Network Operator
DSR	Demand Side Response
DUoS	Distribution Use of System (charges)
ERPS	Enhanced Reactive Power Service
FCDM	Frequency Control by Demand Management
FFR	Firm Frequency Response
FR	Fast Reserve
ID	Intra-Day
LLF	Line Loss Factors
LOLE	Loss of Load Expectation
LRMC	Long Run Marginal Cost
MBSS	Monthly Balancing Services Summary
NGET	National Grid Electricity Transmission
NIV	Net Imbalance Volume
OCGT	Open Cycle Gas Turbine
ORPS	Obligatory Reactive Power Service
ORR	Operational Reserve Requirements
PPA	Power Purchase Agreement
PS	Pump Storage
RO	Renewables Obligation
ROCOF	Rate of Change of Frequency
SBP	System Buy Price
SOF	System Operability Framework
SRMC	Short Run Marginal Cost
SSP	System Sell Price
STOR	Short Term Operating Reserve
TNUoS	Transmission Network Use of System (charges)
TSO	Transmission System Operator

1 Introduction

1.1 Background

The primary objective of the *Storage & Flexibility Modelling Project* is to develop the capability to improve understanding of the future role of energy storage and the provision of system flexibility within the context of the overall energy system. This aims to provide a techno-economic evaluation of energy storage across multiple energy vectors (electricity, heat, gas and hydrogen) accounting for the different services that could be provided (frequency response or avoiding wind curtailment) and at which points in energy system (transmission, distribution, building level) they are most appropriate.

Stage 1 of the project is comprised of 3 deliverables:

- **D1.1 Energy storage mapping report** *(this report)* a first principles framework for mapping the system technical services and benefits that storage (heat, hydrogen, gas and electricity) and competing flexibility options could provide
- **D1.2 Assessment of the near term market potential for energy storage**, over the next 5-10 years given the current market structures, with a particular focus on electricity
- **D1.3 Approach for modelling long term role of energy storage** - which defines the modelling approach to analysing the longer term role for storage and other relevant flexibility options in GB from a system operator perspective

1.2 Purpose of this report

To support the development of an approach for a long-term storage modelling framework (in the separate D1.3) the purpose of this report is to define the flexible services that should be represented (both underlying technical requirements and wider system benefits) and the technologies (storage and the competing alternatives) that are capable of provide these services.

It is not intended to provide an exhaustive review of the current and likely future state of storage technologies, but to review the most promising and/or those exhibiting significantly different characteristics such that they could be categorised within a long-term modelling framework

Note that further detail on the scale and market structure that exists to deliver these services is described in the separate deliverable *D1.2 Assessment of the near term market potential for energy storage.*

1.3 Structure of this report

The structure of the report is as follows:

- Section 2 categorises the various flexibility services
- Section 3 describes the technologies (storage and alternatives) which can provide these services
- Section 4 describes how the technology options map in terms of being able to deliver the flexibility services

2 Flexibility Services

2.1 List of possible required services

In this section we outline the long list of potential services[1] that storage could provide, and describe these in terms of technical properties and a brief overview of ‘market’ size (further detail is provided in D1.2). Through a process of filtering we seek to define the set of potential services to include in the long term modelling framework focusing on those that are deemed to be most material.

Energy storage technologies can provide a wide range of services to an energy system, across multiple energy vectors. By “service” we refer to any use of storage that may reduce the total cost of securely meeting end user demand across an energy system. Most of these services can be characterised as “balancing” services – temporally storing energy to better match supply and demand. The challenge is that these services vary significantly over a number of dimensions:

- Energy vector (electricity, heat, gas, hydrogen)
- Network level affected (transmission, distribution, building or ‘behind-the-meter’)
- Timescales (from seconds to years

Baringa have conducted a detailed literature review to assess the potential services that storage could provide. The full list of services is outlined in Table 2, separated into those that are found across multiple energy vectors and those that are specific to single energy vectors. It can been seen that there are more services required for electricity when compared to the other energy vectors – this is due to the lack of native storage in the electricity network (gas, hydrogen and heat having a non-trivial level of “physical” storage in their pipes).

[1] Note that these refer to system-related services rather than underlying consumer services such as mobility, portability, responsiveness, quality, etc.

Table 2 List of possible required flexibility services

	Electricity	Heat	Gas	Hydrogen
General services	Seasonal storage			
	Network congestion relief			
	Network infrastructure investment deferral			
	Demand shifting and peak reduction[2]			
	Variable supply resource integration			
	Off-grid			
Vector specific services	Rate of Change of Frequency (RoCoF) control	Waste heat utilisation	Pressure regulation	Pressure regulation
	Frequency containment	Pressure regulation	Operating margins	
	Frequency replacement	Temperature regulation		
	Reserve replacement	Emergency backup		
	Voltage support			
	Black start			
	Fault level			

In Table 3 each service is described in more detail, with an indication of where in each energy vector network the service is required. Many different classifications of these services exist in the literature, but the following sections aim to categorise them in a manner that is as far as possible MECE (Mutually Exclusive and Collectively Exhaustive) to help frame the way they are considered for the modelling framework.

Table 3 Description of possible required flexibility services

Vector	Service	Location in network (Building, Distribution, Transmission)	Description	Notes
Multiple	Seasonal storage	B / D / T	The ability to store energy for days, weeks, or months to compensate for a longer-term supply disruption or seasonal variability on the supply and demand sides of the energy system (e.g. storing gas in the summer to use in the winter).	
Multiple	Network congestion relief	D / T	Technologies used to temporally and/or geographically shift energy supply or demand in order to relieve congestion points in the transmission and	

[2] Other studies often refer to this as arbitrage, but this is a commercial strategy facilitated by system differences that can arise from factors such as varying demand (within day or seasonally) that then lead to price differentials that can be exploited by flexible technologies such as storage.

Vector	Service	Location in network (Building, Distribution, Transmission)	Description	Notes
			distribution (T&D) grids in the near term - typically constrained by thermal limits (apparent power) or voltage, or e.g. pressure limits in gas/hydrogen pipelines	
Multiple	Network infrastructure investment deferral	D / T	Technologies used to temporally and/or geographically shift energy supply or demand in order to defer the need for new investment over the longer term - typically constrained by thermal limits (apparent power) or voltage, or e.g. pressure limits in gas/hydrogen pipelines	
Multiple	Demand shifting and peak reduction	B / D / T	Energy demand can be shifted in order to match it minimise peak demand and facilitate more efficient operation of the system by help to reduce supply-side costs. These shifts are facilitated by changing the time at which certain activities take place (e.g. the heating of water or space)	
Multiple	Off-grid	B	Off-grid energy consumers frequently rely on fossil or renewable resources (including variable renewables) to provide heat and electricity. To ensure reliable off-grid energy supplies and to support increasing levels of local resources use, energy storage can be used to fill gaps between variable supply resources and demand.	Not very applicable to GB energy system with respect to electricity. For heat there are ~3-4M off-gas grid homes.
Multiple	Variable supply resource integration	B / D / T	The use of energy storage to change and optimise the output from variable supply resources (e.g. wind, solar thermal or photovoltaic), mitigating rapid and seasonal output changes and bridging both temporal and geographic gaps between supply and demand in order to increase supply quality and value (e.g. avoiding spill).	
Electricity	RoCoF control	B / D / T (but managed by TSO)	Automatic injection and withdrawal of active power in response to deviations in frequency, especially fast deviations (i.e. high Rate of Change of Frequency, RoCoF). Response is very fast <0.5 sec.	This service approximately maps to Enhanced Frequency Response in GB
Electricity	Frequency containment	B / D / T (but managed by TSO)	Injection (occasionally withdrawal) of active power in response to instantaneous loss of generation or	"Frequency containment" is the term used by ENTSOE[3], and

[3] The ENTSOE classification of frequency containment (primary), frequency replacement (secondary), reserve replacement (tertiary) is a more comprehensive, but generic classification of electricity-related balancing

Vector	Service	Location in network (Building, Distribution, Transmission)	Description	Notes
			load, leading to high Rate of Change of Frequency (RoCoF). Response is fast - <10 secs	approximately maps to Primary and High Response in GB
Electricity	Frequency replacement	B / D / T (but managed by TSO)	Injection (occasionally withdrawal) of active power in response to instantaneous loss of generation or load, to move frequency back to operating point. Response is medium - <2mins	"Frequency replacement" is the term used by ENTSOE, and approximately maps to Secondary Response and Fast Reserve in GB
Electricity	Reserve replacement	B / D / T (but managed by TSO)	Longer term balancing of supply and demand by increase in active power. Response is slower, <15 mins - 4 hours	"Reserve replacement" is the term used by ENTSOE, and approximately maps to STOR (Short Term Operating Reserve) in GB[4]
Electricity	Voltage support	D / T	The injection or absorption of reactive power to maintain voltage levels in the transmission and distribution system under normal conditions is referred to as voltage support.	
Electricity	Black start	D / T (but managed by TSO)	In the rare situation when the power system collapses and all other ancillary mechanisms have failed, black start capabilities allow electricity supply resources to restart without pulling electricity from the grid.	
Electricity	Fault level	D / T	Control equipment is used to break the network when a short circuit fault occurs. This assumes the (short circuit) fault level will be within a certain range, related to the amount of synchronous generation and load on the system. At distribution level networks are becoming constrained by the amount of synchronous distributed generation (fault level too high) and at transmission level networks may become constrained by the lack of synchronous generation in summer (fault level too low). Literature review suggests issue is more severe at distribution level.	Storage does not contribute directly to fault level (as it is connected through power electronics). Role of storage in relieving fault level constraints is second order – by displacing synchronous generation at distribution level.
Heat	Flexible waste heat utilisation	B / D	Capturing of waste heat (e.g. CHP facilities, thermal power plants) and matching with thermal demand (e.g. for heating/cooling buildings, supplying industrial process heat) via buffer heat	

services to facilitate comparison across markets; as the nomenclature and disaggregation of specific products to provide these services may vary.

[4] Technically plant must be available within 240 minutes under STOR, but a strong preference in tendering process for plant with sub-20 minute dispatch times.

Vector	Service	Location in network (Building, Distribution, Transmission)	Description	Notes
			storage to maximise flexible operation of CHP plant	
Heat	Pressure regulation	D	The ability to inject or withdraw water to keep the pressure at the required level. Needed when there is an imbalance between supply and demand.	Literature review suggests this is not an explicitly managed, real-time operating constraint for district heat networks, and is dealt with through the initial design and broader energy balance when operating
Heat	Temperature regulation	D	The ability to maintain operation of the network within acceptable maximum temperature limits, given the ratings of individual pipe and other components.	Literature review suggests this is not an explicitly managed, real-time operating constraint for district heat networks, and is dealt with through the initial design and broader energy balance when operating
Heat	Emergency backup	D	Maintain supply in case of unplanned outage of supply on district heat network	
Gas	Operating margins	T	Gas production and storage capacity used as backup to manage the grid in periods of severe stress, and for regular balancing of the grid	
Gas	Pressure regulation	T	The ability to inject or withdraw gas to keep the gas pressure at the required level (linepack flexibility). Needed when there is an imbalance between supply and demand.	
Hydrogen	Operating margins	T	Hydrogen production and storage capacity used as backup to manage the grid in periods of severe stress, and for regular balancing of the grid	
Hydrogen	Pressure regulation	T	The ability to inject or withdraw hydrogen to keep the pressure at the required level (linepack flexibility). Needed when there is an imbalance between supply and demand. Note that hydrogen volumetric energy density is ~25% of the level of natural gas, so potential swings in demand may have a larger pressure effect on hydrogen vs gas	

Of the services listed above, a number can be removed from further consideration –

- Off-grid

- This is not very applicable to GB, where almost all electricity demand is grid connected
- **Do not include this service** as not applicable to GB

- Electricity fault level
  - Storage cannot provide this service directly, as power electronic connected assets do not affect fault level. The ability for storage to resolve this constraint is second order, through displacing synchronous distributed generation that contribute to constraint.
  - **Do not include this service** as ability of storage to provide this service is second order
- Heat network pressure regulation and temperature regulation
  - Literature review does not suggest this is an explicit constraint on district heat networks (in terms of being actively managed in real-time operation) – energy balancing encompasses this, within a system which has considered pressure limits at the design stage
  - **Do not include this service** as already covered by other services

2.2 Separating system benefits and requirements

It is clear from the tables above that there are a large number of potential areas where storage can provide flexibility services. Some of these services are interlinked, and are not true independent services. For example, *Demand shifting and peak reduction* and *Network infrastructure investment deferral*, where a reduction in peak demand over a constrained network may result in lower network investment costs. However, some of the services are truly independent, for example *Voltage support* on the electricity network.

We can categorise these overarching services into two types, "**System Technical Requirements**" and "**System Benefits**". The definitions of these two categories is described in Table 4.

Table 4 Definition of System Technical Requirements and Benefits

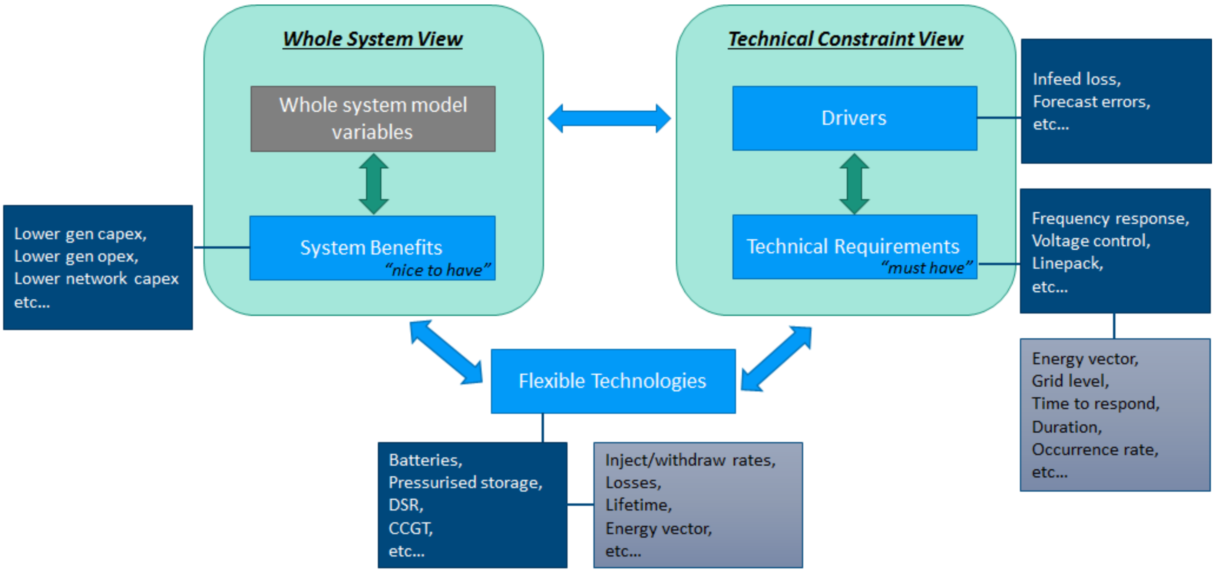
System Technical Requirements	System Benefits
Necessary constraints to operate the system safely and securely	Nice-to-have services for an efficiently utilised system, not necessary but may reduce costs if available
Network specific	Applicable across multiple energy vectors
Usually independent	Usually not independent from other Benefits
Usually technical	Usually economic
E.g. Pressure regulation on gas network	E.g. Variable supply resource integration

System technical requirements are necessary services ("must haves") to run an energy system safely within acceptable limits, whereas system benefits are effectively a "nice-to-have" resulting in more efficient and lower cost operation of the system in terms of capital costs (e.g. generation or network) or reduced operating costs by the potential for peak shaving, more efficient integration of renewables (e.g. avoided spill), etc.

From the perspective of the long-term modelling framework the system benefits can be captured by a well specified whole energy system model, such as ESME, provided it has 'sufficient' temporal and spatial granularity to reflect the costs of the building and operating the system from an overarching energy balance perspective. By contrast, the technical requirements provide additional constraints, which are often not represented in whole system models due to either lack of granularity or issues which move beyond a simple energy balance, such as pressure constraints or appropriate provision of reactive power to manage voltage levels.

Figure 1 illustrates this separation of system benefits and requirements from a modelling perspective.

Figure 1 Modelling characterisation of system benefits versus technical requirements



As an illustration, the need to decarbonise the energy system may require the introduction of intermittent renewables such as wind and solar PV, an example of the *whole system model variables* related to the decision to build such plant. This new intermittent generation will lead to additional *technical requirements*, as it is not possible to forecast the output with 100% accuracy. Hence the level of forecast error on increasing levels of wind/solar will act as a key *driver* for additional reserve replacement requirements, which could in principle be provided by storage. In addition, there may be further economic costs of integrating such intermittent generation that could be reduced by the introduction of storage (or other flexible technologies) – i.e. potential *system benefits*. Network constraints may, for example, lead to the spill of some proportion of the additional intermittent generation. Carefully positioned storage, be it at distribution level or even behind the meter building-level storage, would be one potential option to realise these system benefits. In summary, wider energy system choices may lead to an increased role for storage (and other flexibility options) as part of helping to reduce the overall costs of the energy system (system benefits) and/or deliver the technical requirements necessary to operate the energy system.

In Table 5 we categorise the list of services as either system benefits or requirements. It can be seen that there are many more benefits than requirements. As described above, system benefits can be modelled endogenously in a whole system type model, while system requirements are additional constraints that need to be explicitly modelled.

By categorising services in this way the number of services that must be defined in detail (i.e. the system requirements) is much reduced from the original list of services. It should be noted that the storage mapping described here is for the purposes of modelling the long term value of storage to an energy system, and so it is the system cost (rather than storage value streams) that is of interest. It is this focus on whole system costs that allows benefits to be included in the modelling framework without the need for storage mapping to these services.

Table 5 Services mapped to System Benefits and Requirements

	Electricity	Heat	Gas	Hydrogen
System Benefits	Seasonal storage			
	Network congestion relief			
	Network infrastructure investment deferral			
	Demand shifting and peak reduction			
	Variable supply resource integration			
	Flexible waste heat utilisation			
System Requirements	RoCoF control	Emergency backup	Pressure regulation	Pressure regulation
	Frequency containment		Operating margins	
	Frequency replacement			
	Reserve replacement			
	Voltage support			
	Black start			

2.3 Defining system benefits

System benefits are captured endogenously in an energy systems model of sufficient granularity and reflect a reduction in the overall costs of building and operating the energy system, separate to costs that *must* be incurred as part of the technical requirements to operate the system. In Table 6 the system benefits are detailed, with the location and time scale over which benefits may be realised.

It can be seen that for the benefits they are broadly recognised at timescales of hourly or greater, whereas most system requirements tend to be within this window and from the order of seconds to 10s of minutes[5]. As long as the modelling granularity is hourly, these benefits will be captured. The benefits are realised at different grid levels, and sufficient spatial granularity must be included to capture these benefits fully. This is particularly true for Network congestion relief and Network infrastructure investment deferral.

The system benefits are listed below, and all benefits result in some combination of savings to generation capex, generation opex, and/or network capex. These costs are traded off in most energy systems type models, which typically optimise to minimise total systems costs.

[5] Note that we are distinguishing between the underlying fundamentals of system benefits / requirements from the overarching market structure. Across Europe the time horizons between Gate Closure (of Intra-Day trading) and the start of settlement, and the period of settlement itself for balancing purposes can vary. These are currently 1-hour and ½ hour in GB, respectively. However, regardless of market structure there is a greater need for the System Operator to actively procure services ahead of time to provide 'certainty' around their ability to manage key technical requirements closer to real time, as opposed to relying on market mechanisms with more limited certainty around the availability of such balancing services. This is discussed further within deliverable D1.2.

Table 6 System Benefits

Vector	Application	Location in network (Building, Distribution, Transmission)	Timescale	Avoided generation capex	Avoided generation opex	Avoided network capex
Multiple	Seasonal storage	B / D / T	Months	✓	✓	
Multiple	Network congestion relief	D / T	hours	✓	✓	
Multiple	Network infrastructure investment deferral	D / T	hours-days			✓
Multiple	Demand shifting and peak reduction	B / D / T	hours-days	✓	✓	✓
Multiple	Variable supply resource integration	B / D / T	hours-days	✓	✓	
Heat	Flexible waste heat utilisation	B / D / T	hours-days	✓	✓	

2.4 Defining system technical requirements

The system requirements are technical constraints that need to be satisfied to operate energy networks safely and securely within acceptable limits. When defining the requirements there are two purposes:

1. Assess materiality of including the technical requirement in the long term storage modelling framework
2. Define technical characteristics to allow flexible technologies capable of providing each requirement to be "mapped"

Table 7 shows the parameters used to describe system requirements. The time to respond, response duration, and frequency of use are all used to map which technologies are capable of providing the requirement. The size of current requirement, potential future size, and drivers of the requirement are used to assess the materiality of the requirement for valuing the long term role of storage.

Table 7 Parameters for defining system requirements

Parameter	Description
Energy Vector	Which energy vector does this requirement apply to?
Grid Level	What grid level does this requirement apply to?
Time to respond	What is the maximum time providers of this service may respond in?
Response duration	How long does provision of this service last for each event?
Frequency of use	How often is this requirement used?
Size of current requirement	What is the size of this requirement in 2015/16?
Potential size of requirement in future	What might the size of the requirement be in the future?
Drivers of requirement	What are the fundamental drivers of the requirement?
Other notes	

The table above has been completed for each requirement, and is shown in detail in Appendix A. From the list of technical requirements, two stand out as being less material – Black Start for the electricity networks and Operating Margins for gas networks.

The current agreed cost to provide Black Start is ~£20m per year, compared with ~£100m per year for the other electricity network requirements. It should be noted that the regulator has launched an investigation over the proposed National Grid request to recover >£100m on black start contracts this year (compared to the originally agreed £20m), with some industry participants accusing them of agreeing to highly inflated terms to keep coal generators on the system, due to concerns about very low near term capacity margins[6]. However, this increased level of spend is not expected to persist beyond the relatively near-term, due to other policy measures such as the Capacity Market being used to drive increased capacity margins. Black start costs are therefore expected to be maintained at their historic level over the medium to longer term.

In addition, Black Start procurement is highly bespoke in terms of requirements (particularly spatially across the network), and storage is likely to provide only a very limited role by providing enough power to start up the synchronous generators that provide the bulk of Black Start capacity.

- Black Start
  - Requirement is only £20-30m per year, with highly bespoke technical and locational requirements, with only a small proportion of this likely to be accessible to storage
  - **Do not include this service** as materiality in valuing storage is low

The current cost to provide gas Operating Margins is ~£20m per year. This figure includes storage used to provide back-up capacity under a (rare) severe failure of the network, but also is used for regular pressure regulation, and so overlaps with the Pressure Regulation requirement.

- Operating Margin
  - Requirement is only £20m per year, and overlaps with Pressure Regulation requirement. Including both could result in double counting of requirements

[6] http://utilityweek.co.uk/news/national-grid-spent-113m-on-black-start-contracts-with-drax-and-sse/1250662#.V2OvkKKwm_E

- **Do not include this service** as materiality is low and is partially covered by Pressure Regulation requirement

A summary of the material requirements is shown in Table 8 below. These characteristics will be used to map storage technologies to requirements.

Table 8 Summary of System Requirement technical characteristics

Vector	Requirement	Time to Respond	Response Duration	Frequency of Use
Electricity	RoCoF control	<1 secs	up to 15mins	500-1000 per day
Electricity	Frequency containment	<10secs	~10-30seconds - but cumulative imbalance equivalent to 30mins	500-1000 per day
Electricity	Frequency replacement	<30secs	up to 30mins	20-40 times per day
Electricity	Reserve replacement	30mins-4hours	2hours-1day	1-30 times per day
Electricity	Voltage support	<1 sec	1s-1min	10-100 per day
Heat	Emergency backup	1 hour	Hours-days	1 per year
Gas	Pressure regulation	hours-days	~6hours	~1 per day
Hydrogen	Pressure regulation	hours-days	~6hours	~1 per day

2.5 Define mutual exclusivities

While some technologies may technically be able to provide multiple services, in practice some services cannot be provided at the same time due to the way technologies are utilised for each service. For example, a technology may have the response time and duration to be able to provide variable supply resource integration (i.e. charging up when high electricity generation from wind turbines) and Reserve Replacement. However, to provide Reserve Replacement to cover a rare event such as a plant tripping the technology needs to be positioned at around minimum stable generation (for thermal plant) or nearly full in the case of storage to be able to cover as much of a potential shortfall as possible. Simultaneously, this means that there is limited potential from these technologies to accommodate additional wind generation and avoid spilling this power as the battery is full already.

The separation into system benefits and technical requirements is useful in understanding which services can be provided concurrently with a single technology. The aim of the modelling framework is to consider both the benefits and requirements simultaneously to understand the potential trade-offs for different flexibility options, where there is a choice about the role they provide within the wider energy system. Benefits are realised through balancing energy supply and demand of the system efficiently. Benefits are not independent from one another: in some time periods a technology may be providing one benefit (e.g. *Demand shifting and peak reduction*) through injection of power to the system, and therefore simultaneously providing another benefit (*Network congestion relief* for example). In some periods, however, this injection of power for peak reduction may actually increase network congestion, providing a dis-benefit rather than benefit. It is clear that the benefits are not independent, and can be co-optimised using a supply / demand balancing energy system model.

System requirements are described through technical characteristics other than energy balance, and are often independent. At first glance it may appear possible to provide electricity *Frequency Containment* (injection of active power) at the same time as *Voltage Control* (injection of reactive power). In the following subsections we describe which requirements can be provided concurrently with other requirements and benefits, for each energy vector in turn.

2.5.1 Electricity

After filtering out those requirements that are not significant, there are five key technical requirements to consider:

- RoCoF control
- Frequency containment
- Frequency replacement
- Reserve replacement
- Voltage control

Each requirement can be mapped to one of the current products procured by the Transmission System Operator (TSO), National Grid. The contractual agreements for these current products provide guidelines for mutual exclusivities between these requirements that can be used for this analysis, because they effectively embed technical concerns about the inability of some services to be provided in parallel by the same technology. For example, voltage and reserve requirements could require opposing actions at the same time.

Current rules prevent capacity that is procured for any of these services from concurrently trading in the energy market. In general, capacity procured in one service may not provide any other service. This is to provide the TSO the security that back-up capacity for each service will be ready on demand when required. In the main this prevents technologies from providing any more than one service at a time, though in different periods across the day a technology could, in theory, provide different services.

The exceptions to this are RoCoF control, Frequency containment, and Frequency replacement. These all require the injection or withdrawal of active power, with different response times and slightly different response durations. The TSO currently allows generators (and storage units) to bid for bundles of these services – i.e. providing all three if the response time is fast enough and duration long enough.

Whilst reserve replacement is conceptually similar to this bundle of requirements (i.e. the injection or withdrawal of active power) due to the very long duration of operation this service is contracted separately, to ensure that plant providing this service are not unavailable when called on to provide the more frequent shorter duration services. For example, to provide coverage against the largest potential in-feed loss on the system which is a rare event as opposed to continually (albeit smaller volumes) for the other frequency-based requirements.

RoCoF control refers to very fast responding active power balancing, and maps to the new TSO product "Enhanced Frequency Response". The inclusion of this very fast acting response reduces the need for the slower Frequency containment. The TSO has indicated that the inclusion of faster RoCoF control will result in a total decrease in "frequency response" type products, as 1MW of RoCoF displaces >1MW of Frequency containment. The scaler from RoCoF capacity to Frequency containment capacity is not yet know, but is thought that ~1.5x. RoCoF capable capacity may be included in the Frequency containment requirement, but with a scaler on the capacity.

Table 9 shows a grid that summarises which electricity system requirements and services can be provided concurrently.

Table 9 Electricity flexibility service mutual exclusivities

	System Benefits	RoCoF control	Frequency containment	Frequency replacement	Reserve replacement	Voltage support
System Benefits	✓	✗	✗	✗	✗	✗
RoCoF control	✗	✓	✓	✓	✗	✗
Frequency containment	✗	✓	✓	✓	✗	✗
Frequency replacement	✗	✓	✓	✓	✗	✗
Reserve replacement	✗	✗	✗	✗	✓	✗
Voltage support	✗	✗	✗	✗	✗	✓

2.5.2 Heat

Heat systems have only one remaining requirement to consider in the form of Emergency backup. Emergency backup capacity must be provided to give N-1 supply contingency to each network. To be a true backup it cannot be used for normal use, and therefore cannot provide any system benefits under normal operation. Table 10 summarises this for heat networks.

Table 10 Heat flexibility service mutual exclusivities

	System Benefits	Emergency backup
System Benefits	✓	✗
Emergency backup	✗	✓

2.5.3 Gas

Gas systems have only one remaining requirement to consider in the form of pressure regulation. Pressure regulation can be described by the level of gas in the pipe network (i.e. "linepack"). This is kept within certain bounds at all time and means that pressure regulation can be described using energy balance only, without calculating pressure directly. Parameterising the Pressure regulation requirement through the energy balance, considering locational differences that may exist at different geographic nodes of the network, allows it to be considered with all other system benefits, which also are described in terms of energy balances.

The action of gas supply to inject or withdraw from the network (from e.g. storage, power-to-gas or imports) may help to relieve pressure regulation constraints, while also providing other system services (like peak load shifting for example). Meeting Pressure regulation requirements should be co-optimised with all system benefits in a whole energy system type model, and so we can consider it possible for technologies to provide this requirement concurrently with this services. Table 11 summarises this for gas networks.

Table 11 Gas flexibility service mutual exclusivities

	System Benefits	Pressure regulation
System Benefits	✓	✓
Pressure regulation	✓	✓

2.5.4 Hydrogen

Hydrogen networks will operate in a similar to gas networks, though with less embedded storage due to the lower density of hydrogen when compared with gas. As with gas, for hydrogen there is one requirement, Pressure regulation, and this can be provided with other services and co-optimised using a whole energy system model (this is summarised in Table 12).

Table 12 Hydrogen flexibility service mutual exclusivities

	System Benefits	Pressure regulation
System Benefits	✓	✓
Pressure regulation	✓	✓

3 Storage and competing technologies

3.1 Overview

To provide the system services a set of technologies is required. In this section we describe in turn:

- The set of technologies to be included, separated into
  - Storage technologies
  - Competing flexible technologies
- Definitions of the key properties of each technology focusing primarily on storage

There is a huge range of flexible technologies that can be included when modelling the value of storage. To include an exhaustive list would be time consuming, both in terms of data gathering and model complexity and run time, with diminishing returns in terms of the significance to the role of storage. We focus on technologies that appear more promising in the medium term or provide strong differentiation in their characteristics (technical or cost). In addition, the long term modelling framework is flexible such that more technologies can be added in future if required.

3.2 Storage technologies

Technologies are defined as energy storage technologies if they demonstrate two characteristics:

1. They can inject and hold energy for some period of time, before releasing it again (minus losses)
2. The form of energy discharged from the technology (heat, gas, etc) is the same as the form of energy used to charge the technology.
   - However, the stored energy may temporarily be in a different form, e.g. electrical flywheels convert electrical energy to mechanical kinetic energy to store, then convert back to electrical when discharging

It is important to distinguish between storage as a standalone technology, which can help to provide dispatch optionality to the wider system and is the focus of this analysis, versus storage which is just one part of a wider technology and it not considered explicitly here. Examples of the latter include:

- Small-scale solar thermal, seasonal heat storage and Concentrating Solar Power (CSP) where storage is integral to what is effectively a solar energy supply source for heat or electricity
- Industrial heat storage where the process itself (e.g. liquid bitumen in tanks) provides a heat store which can provide some flexibility as a competing Demand Side Response (DSR) option, but which would not be developed as a standalone heat storage technology in its own right

Storage technologies can vary significantly in terms of their method of operation. However, it is useful to describe technologies through a number of parameters which enable them to be mapped (see section 4) to the system services that each technology is capable of providing, and where in the network each technology is capable of being deployed. An energy system modelling framework can use these mappings to optimise the capacity investment and operation decisions, balancing supply and demand and meeting all system requirements using appropriate technologies and at minimum cost.

Table 13 shows the parameters used to define storage technologies and make investment decisions in an energy systems model. For some technologies it has not been possible to complete all fields. The information necessary to map technologies to system services has been collated, and the missing parameters can be collated at as part of the data gathering in Stage 2 before being used in an energy system model for storage valuation.

Table 13 Parameters for defining storage technologies

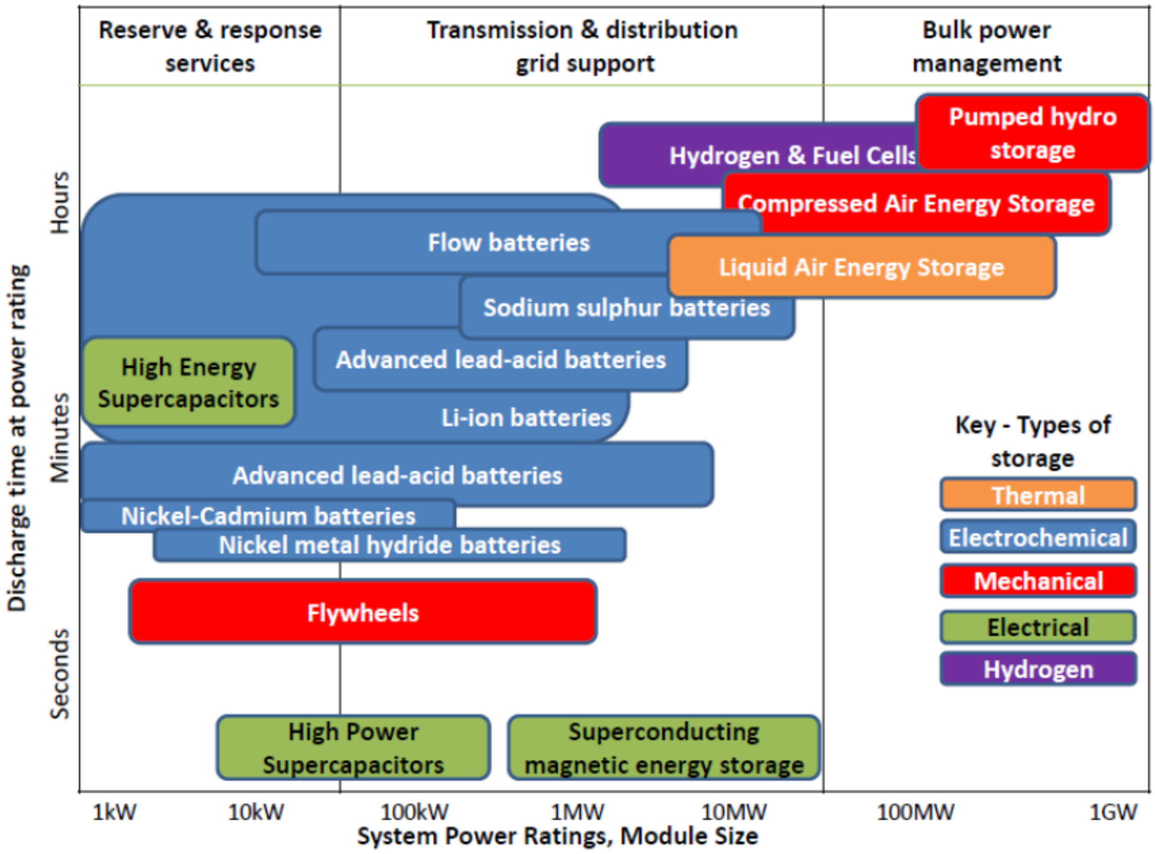
Parameter	Value
Type	What is the form of energy storage - mechanical, chemical, etc?
Input	What is the form of input energy from the storage?
Output	What is the form of output energy from the storage?
Maturity	How mature is the technology currently
Effective capacity (%)	Can the full storage capacity be used or is there a derating to avoid deep discharge?
Round trip efficiency (%)	How much energy is available after one charge/discharge cycle?
Temporal losses (%/day)	How much energy is lost when stored over time?
Response time	How quickly can the storage begin discharging/charging
Duration	How long typically can the storage discharge/charge
Inject/withdraw rate	What is the typical charge/discharge rate?
Energy density by mass	How much energy can be stored in in 1kg
Energy density by volume / area	How much energy can be stored in 1litre / sq m
Lifespan (full cycles)	How many full cycles before the capacity is degraded to ~80%?
Maximum build	Is there a maximum volume that may be built in the UK?
Maximum build per year	Is there a constraint on the volume that can be deployed per year?
Current CAPEX	Estimates of current CAPEX
Current OPEX	Estimates of current OPEX
Future CAPEX	Estimates of future CAPEX
Future OPEX	Estimates of future OPEX

Appendix B provides an overview of the parameters for the different storage technologies (n.b. the data at this stage is only intended to be indicative of the technology characteristics with more formal data gathering part of Stage 2). Where possible capital costs are defined as £/kW + £/kWh. This allows technologies to be sized and costed for different combinations of power output and energy storage volume, and therefore for different response duration. However, the economics of scaling different storage technologies to focus on provision of larger volumes of energy versus higher power outputs may vary considerably and these trade-offs will be explored via the long-term modelling framework.

The key parameters that are used to define system requirements are the time to respond and response duration. If technology costs can be described as above, the technology can be sized to any response duration, and so it is only the time to respond that is used to map technologies to requirements.

Figure 2 provides an illustration of the spread of different *electricity* storage technologies in terms of their likely range of power ratings and discharge times and an indication of the potential roles (subject to their economics) they might provide in the energy system.

Figure 2 Illustrative overview of electricity storage by discharge time/duration and power



Source: G Castagneto Gissey, J Radcliffe, PE Dodds (July 2016) RESTLESS project Briefing Paper: 'Regulatory Barriers to Energy Storage Deployment: The UK Perspective'[7]

Note: Hydrogen fuel cells are considered part of conversion technologies in the wider energy system in our framework as they are generally optimised to operate in one direction and are less efficient in a reversible configuration unless constructed with more expensive high-pressure electrolysers. However, in principle reversible fuel cells could be incorporated as a storage electricity storage option using the data parameters outlined in Table 13.

This is complemented by Table 14 which lists the set of storage technologies (for *both* electricity and other vectors) that have been referenced mostly widely as part of the literature reviewed for the different aspects of Stage 1, but which also includes response time as the other key determinant of the ability to provide different types of system services. For example, Li-ion batteries may typically provide response durations in the range of minutes to hours or longer (given combinations of capacity and power rating), but can respond at sub-second level to provide services such as ROCOF and frequency containment. This mapping of technology to provide different services is shown in section 4.1.

[7] http://www.restless.org.uk/project-results

The technologies selected span a range of technical characteristics. Whilst there are many other storage technologies not included here, where the technical characteristics are similar to those listed they can be included in the modelling framework at a later date, using the mapping methodology outlined in the following sections of this report. In the main, the more novel storage technologies (not included in the set below) have different costs and cost projections, but similar technical properties to many of the more common technologies.

Table 14 Summary of storage technology parameters

Output	Type	Technology	Response time	Duration
Electricity	Mechanical	Pumped hydro	secs-mins	scalable
Electricity	Mechanical	Compressed Air Energy Storage (CAES)	5-15mins	scalable
Electricity	Mechanical	Flywheels	seconds	scalable
Electricity	Electrochemical	Batteries - NaS	ms	scalable
Electricity	Electrochemical	Flow Batteries – (e.g. Vanadium Redox or zinc bromine)	ms	scalable
Electricity	Electrochemical	Batteries – Advanced Pb-Acid	ms	scalable
Electricity	Electrochemical	Batteries – Li-Ion	ms	scalable
Electricity	Electrochemical	Home battery storage – Li-ion	ms	~1 – 5 hours[8]
Electricity	Electrical	Super capacitors	ms	ms-1hour
Electricity	Electrical	Superconducting Magnetic Energy Storage (SMES)	ms	ms-5mins
Electricity	Thermal	Liquid Air	~1+ minute[9]	scalable
Heat	Sensible Heat Storage	Underground thermal energy storage (UTES) (water / earth / bedrock)	Hours	Days-months
Heat	Sensible Heat Storage	District heat network accumulator / buffer store	Sub-hour	hours-days
Heat	Sensible Heat Storage	Building scale hot water storage	Sub-hour	hours
Heat	Sensible Heat Storage	Building scale storage heaters (e.g. ceramic)	Sub-hour	hours
Heat	Latent Heat Storage	Building scale heat storage – various Phase Change Materials (PCM) materials being explored (e.g. Na-acetate Trihydrate, Paraffin, Erytritol)	Sub-hour	hours
Heat	Thermochemical energy storage	Building scale heat storage – various materials being explored – e.g. microporous materials (Aluminophosphate) , composite materials (Porous salt hydrates)	Sub-hour	scalable
Gas	Physical	Liquefied Natural Gas (LNG)	Hours	Scalable
Gas	Physical	Long Range Storage (LRS)	Within day but generally fixed rate withdrawal	Days-Months (but can have sizeable cushion gas requirement)
Gas	Physical	Short Range Storage (SRS)	Hours	Days – some scalability

[8] Given limits on space availability in buildings this may in practice limit the maximum volume of storage and hence the duration over which the storage can be used.
[9] If cryogenic feed pumps kept cold and turbine oil warm

Gas	Physical	Line-packing (primarily short term balancing)	Hours	Hours
Hydrogen	Physical	Geological storage	Within day but generally fixed rate withdrawal	Days-Months (but can have sizeable cushion gas requirement)
Hydrogen	Physical	Bulk storage – compressed, cold compressed (in between ambient compressed and <20K liquid storage), liquid	Hours	Hours-days – scalable
Hydrogen	Materials-based	Various options being explored (metal hydrides, high surface area adsorbents, chemical hydrogen storage materials)	Hours	Hours-days – scalable

3.3 Competing flexible technologies

The system services (technical requirements and benefits) that may be provided by storage technologies are currently provided primarily by non-storage flexible technologies. Storage will only have value to the system if it provides a net reduction in system costs when compared to these alternate technologies.

Similar to storage technologies, the competing flexible technologies can be described though a limited set of parameters, as shown in Table 15. At this stage only some parameters have been gathered, to allow storage mapping, and other parameters will be added later as required for the full energy storage valuation model.

Table 15 Parameters for defining competing flexible technologies

Parameter	Value
Type	What is the type of technology – generation, DSR, interconnector?
Input	What is the form of input energy to the technology?
Output	What is the form of output energy from the technology?
Maturity	How mature is the technology currently
Efficiency (%)	Ratio of useful output/input energy
Response time / ramp rate	How quickly can the technology start generating / absorbing energy
Lifespan	Typical working lifetime
Maximum build	Is there a maximum volume that may be built in the UK?
Maximum build per year	Is there a constraint on the volume that can be deployed per year?
Key drivers of costs	E.g. are this driven primarily by high fuel operating costs, but low CAPEX, etc

A summary of key competing flexible technologies is shown in Table 16. Further ***technical details for individual technologies are given in Appendix C*** (n.b. as per the storage technologies the data at this stage is only intended to be indicative of the technology characteristics with more formal data gathering part of Stage 2).

Table 16 Summary of competing flexible technology parameters

Output	Technology	Response time	Duration
Electricity	CCGT (potentially with CCS)	3 hours from cold, secs when spinning	Scalable
Electricity	OCGT	15 mins from cold, secs when spinning	Scalable
Electricity	Coal (Pulverised and IGCC, both potentially with CCS[10])	5-6 hours from cold, secs when spinning	Scalable
Electricity	New Nuclear	48 hours from cold, secs when spinning	Scalable
Electricity	Diesel engines	<10 mins from cold, secs when spinning	Scalable
Electricity	Gas engines	<10 mins from cold, secs when spinning	Scalable
Electricity	Biomass combustion (possibly with CCS[10])	Comparable to coal ~5-6 hours from cold, secs when spinning	Scalable
Electricity	CHP	3hours from cold, secs when spinning	Scalable
Electricity	Hydrogen Turbine	Comparable to OCGT ~15mins from cold, secs when spinning	Scalable
Electricity	Interconnectors	Seconds	Hours – dependent on system conditions in connected market
Electricity	DSR (home, commercial and industrial)	Hours if price signal, seconds if automated (smart homes)	Highly dependent on form of DSR, but generally scale of several hours
Heat	District heat backup boiler (gas / biomass)	Hours	Scalable
Heat	District heat waste heat recovery	Depends on characteristics of source (e.g. as per CHP above)	Scalable
Heat	Building scale direct heat production (gas / resistive electricity / biomass without storage)	Hours	Scalable
Gas	Gas interconnectors	Hours	Hours-days – dependent on system conditions in connected market
Gas	Gas DSR	Hours	~1 day up to a week[11]
Gas	Liquefied Natural Gas (LNG)	Hours	Scalable
Gas	Direct Synthetic Natural Gas production and injection[12] (electrolysis, gasification routes)	Hours	Scalable
Gas	Biomethane Grid Injection	Hours	Scalable
Hydrogen	Direct hydrogen production and injection[12]	Hours	Scalable

[10] Note that CCS variants are expected to have similar response times when spinning, however, for post-combustion capture plants the ability to ramp output up and down (i.e. effecting the volume of response available over short timescales) is slower compared to the non-CCS plant (for pre-combustion IGCC the ramp rates are similar to the non-CCS equivalent plant).

[11] Albeit with potentially varying degrees of DSR provided across the week (as outlined in National Grid's DSR methodology).

[12] Various routes – electrolysis, coal/biomass gasification

4 Technology Mapping

4.1 Technology to requirements map

Using the technical properties of each technology it is possible to map technologies to the system services they can provide. We shall perform this mapping for system benefits and requirements, for each energy vector in turn.

4.1.1 Electricity

The broader system benefits described in Table 6 can be optimised using an energy balance type model, with appropriate temporal granularity and including dynamic constraints for technologies (i.e. response time, ramp rates). With these properties included, it is not necessary to map technologies to system benefits, as the model will choose appropriate technologies to provide benefits where this lowers overall system costs. Table 6 shows that the temporal granularity must be hourly to allow the model to decisions for all system benefits correctly.

The system requirements are often at shorter timescales, and a mapping is needed to define which technologies can provide them. The response time and duration are used to map technologies to requirements. The mapping is show in Table 17.

The response *time* of a technology must be less than the response time of requirements that the technology may provide. Electricity storage technologies tend to be fairly fast responding, especially batteries, and so this is not a binding constraint for most technologies and most requirements. Many of the competing flexible technologies are thermal generation technologies, and these have comparatively slow start up times. These generation technologies can only respond quickly when already generating ("spinning"), and may turn up or down between their minimum stable and maximum output level to provide response.

The response *duration* of a technology must be greater than the response duration of requirements that the technology may provide. It is important to note that some of the requirements have duration that is longer than might be expected from their short time scales. This because while individual actions to respond to the requirement may be short, they often come in quick succession, leading to total effective response times that are far longer.

For electricity storage technologies the duration must be greater than twice the response duration. This is because responding to a requirement can involve charging or discharging, and it is not known which direction will be required. Storage technologies must aim to be in the midpoint of their usable range, ready for responding in either direction. Thus, to provide a requirement of say 30mins duration in either direction, the storage technology must have a usable range of 1hour. However, for most storage technologies we have been able to describe the cost of a technology in £/kW + £/kWh terms – from which it is possible to build and cost storage of any duration – so in most cases duration is not used as a constraint to the mappings. For some technologies, the cost of scaling to long durations may be prohibitive, but this is a decision that can be optimised by an energy systems model.

The competing flexible technologies selected at this stage can respond indefinitely and so are not constrained by response duration.

Table 17 Electricity technology -> requirements map

Technology	RoCoF control	Frequency containment	Frequency replacement	Reserve replacement	Voltage support
Storage Options					
Pumped hydro	✗	✗	✓(>30min)	✓(>2hr)	✓(>2min)
Compressed Air Energy Storage (CAES)	✗	✗	✗	✓(>2hr)	✗
Flywheels	✓(>15min)	✓(>30min)	✓(>30min)	✗	✓(>2min)
Batteries – NaS	✓(>15min)	✓(>30min)	✓(>30min)	✓(>2hr)	✓(>2min)
Flow Batteries	✓(>15min)	✓(>30min)	✓(>30min)	✓(>2hr)	✓(>2min)
Batteries - Advanced Pb-Acid	✓(>15min)	✓(>30min)	✓(>30min)	✓(>2hr)	✓(>2min)
Batteries - Li-Ion	✓(>15min)	✓(>30min)	✓(>30min)	✓(>2hr)	✓(>2min)
Home battery storage - Li-ion	✓(>15min)	✓(>30min)	✓(>30min)	✗	✓(>2min)
Super capacitors	✓(>15min)	✓(>30min)	✗	✗	✓(>2min)
Superconducting Magnetic Energy Storage (SMES)	✗	✗	✗	✗	✓(>2min)
Liquid air	✗	✗	✗	✓(>2hr)	✗
Other Flexibility Options					
CCGT	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
OCGT	✗	✓(spin)	✓(spin)	✓	✓(spin)
Coal	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
New Nuclear	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
Diesel engines	✗	✓(spin)	✓(spin)	✓	✓(spin)
Gas engines	✗	✓(spin)	✓(spin)	✓	✓(spin)
Biomass	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
CHP	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
Hydrogen Turbine	✗	✓(spin)	✓(spin)	✓(spin)	✓(spin)
Interconnectors	✗	✓	✓	✓	✓
DSR (home, commercial and industrial[13])	✗	✓	✓	✓	✓

4.1.2 Heat

As with electricity, system benefits do not need to be mapped as the decision to use the most appropriate technology can be captured in a model with enough granularity.

There is only one system requirement for heat, which is the provision of emergency backup supply. This requires a response time of 1hr and a duration of ~12 hours. All heat storage and competing flexible technologies have response times of faster than 1 hour and can be sized to have duration of greater than 12 hours, and so all technologies are capable of providing this requirement

[13] Where not driven indirectly by a heat or gas/hydrogen related storage device. For example, DSR of refrigeration appliances would be considered within home DSR, whereas hot water storage tanks are discrete heat storage devices.

4.1.3 Gas and hydrogen

As with electricity, system benefits do not need to be mapped as the decision to use the most appropriate technology can be captured in a model with enough granularity.

There is only one material system requirement for gas/hydrogen, which is pressure regulation of the transmission network. This requires a response time of a few hours and duration of ~6 hours. All gas/hydrogen storage and competing flexible technologies have response times of less than 1 hour and duration of greater than 6 hours, and so all technologies are capable of providing this requirement.

4.2 Technology to location map

There are three dimensions to where technologies can be situated:

1. Network hierarchy
    - Building
    - Distribution level
    - Transmission level
2. Population density
    - Rural
    - Sub-Urban
    - Urban
3. Geographical
    - Scotland
    - North of England
    - East Anglia
    - etc

It is assumed that all technologies can be situated in all geographical regions (Scotland, East Anglia etc) unless these are explicitly excluded (e.g. due to lack of suitable geological storage capability for gas/hydrogen). There be some maximum cap on possible deployment again due largely due to geology and the current ESME model has these constraints for some of the larger technologies. This information will need to be collated for all technologies where constraints exist.

Population density only affects technologies connected at distribution level – at transmission level the densities are low enough not to be a constraint. It is assumed that a single technology that connects at distribution level will be small enough to connect in areas of high, urban population density, and so population density is not a constraint in this sense. However – the total sum of technologies deployed in urban areas should be tracked by the model, as a very high deployment may not credible in terms of space requirements. At a minimum the results from an investment decision model should be checked ex-post for credibility, or a constraint added to the model to ensure reasonable rates of deployment in populous areas. Similarly, building level technologies, such as heat storage, are likely to be constrained practically by the availability of space within the building itself that would be devoted to storage.

Where technologies are situated in the network hierarchy is primarily a function on their footprint and typical size (MW). Table 18 and Table 19 show the network location mappings for storage and competing technologies respectively.

Table 18 Storage technology -> network location map

Output	Technology	Grid Level (Transmission, Distribution, Building)
Electricity	Pumped hydro	T
Electricity	Compressed Air Energy Storage (CAES)	T / D
Electricity	Flywheels	T / D
Electricity	Batteries – NaS	T / D
Electricity	Flow Batteries	T / D
Electricity	Batteries - Advanced Pb-Acid	T / D
Electricity	Batteries - Li-Ion	T / D
Electricity	Home battery storage - Li-ion	B
Electricity	Super capacitors	T / D
Electricity	Superconducting Magnetic Energy Storage (SMES)	T / D
Electricity	Liquid air	T / D
Heat	Underground thermal energy storage (UTES)	D
Heat	District heat network accumulator / buffer store	D
Heat	Building scale hot water storage (sensible)	B
Heat	Building scale storage heaters (e.g. ceramic) (sensible)	B
Heat	Building scale heat storage - Phase Change Materials	B
Heat	Building scale heat storage – Thermochemical Energy Storage	B
Gas	Liquid natural gas (LNG)	T
Gas	Long range storage (LRS)	T
Gas	Short range storage (SRS)	T
Gas	Line-packing	T / D
Hydrogen	Geological storage	T
Hydrogen	Bulk storage - compressed, cold compressed (in between ambient compressed and <20K liquid storage), liquid	T / D
Hydrogen	Various options being explored (metal hydrides, high surface area adsorbents, chemical hydrogen storage materials)	T / D

Table 19 Competing flexible technology -> network location map

Output	Technology	Grid Level (Transmission, Distribution, Building)
Electricity	CCGT (potentially with CCS)	T
Electricity	OCGT	T
Electricity	Coal (Pulverised and IGCC, both potentially with CCS)	T
Electricity	New Nuclear	T
Electricity	Diesel engines	T / D
Electricity	Gas engines	T / D
Electricity	Biomass	T / D
Electricity	CHP	T / D
Electricity	Hydrogen Turbine	T
Electricity	Interconnectors	T
Electricity	DSR (home, commercial and industrial)	B
Heat	District heat backup boiler (gas / biomass)	D
Heat	District heat waste heat recovery	T / D
Heat	Building scale direct heat production (gas / resistive electricity / biomass without storage)	B
Gas	Gas interconnectors	T
Gas	Gas DSR	B
Gas	Liquified Natural Gas (LNG)	T
Gas	Direct Synthetic Natural Gas production and injection[14] (electrolysis, gasification routes)	T / D
Gas	Biomethane Grid Injection	T / D
Hydrogen	Direct hydrogen production and injection[12]	T / D

[14] Various routes – electrolysis, coal/biomass gasification

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Appendix A System requirement details

A.1 Electricity

Table 20 Electricity RoCoF control

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	All levels (it is a power balance issue) but dealt with by TSO	
Time to respond	<1 secs	[1]
Response duration	~30 seconds but up to 15mins (up or down) through repeated action	[1]
Frequency of use	500-1000 per day	[2]
Size of current requirement	new product - NG aiming for up to 200MW	[1]
Potential size of requirement in future	Unclear – though likely to increase as system inertia reduces	
Drivers of requirement	Increase in largest infeed loss (Hinkley point), increase in the largest infeed demand (new interconnector), reduction in system inertia Rate of change of frequency is inversely proportional to system inertia	
Other notes	This requirement is bi-directional, and is approximately balanced in each direction (ie 200MW up and 200MW down). Increased RoCoF Control results in a reduction in Frequency Containment and Replacement, 1MW of RoCoF control > 1MW of Containment or Replacement.	

Table 21 Electricity Frequency Containment

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	All levels (it is a power balance issue) but dealt with by TSO	
Time to respond	<10secs	[3]
Response duration	~30seconds – but for storage technologies cumulative imbalance to 30mins through repeated action	[3] [2]
Frequency of use	500-1000 per day (+/- 0.5 Hz deviation)	[2]
Size of current requirement	~1200MW summer, ~1000MW winter Peak of 1800MW in Summer overnight £150mn per year	[3] [4]
Potential size of requirement in future	~3-4x higher in 2030	[5]
Drivers of requirement	Increase in largest infeed loss (Hinkley point), increase in the largest infeed demand (new interconnector), reduction in system inertia	
Other notes	This requirement is broadly bi-directional, and is approximately balanced in each direction (ie 1100MW up and 1100MW down), but this is dependent on the relative sizes of the largest generator vs interconnector and may become asymmetric in future.	

Table 22 Electricity Frequency Replacement

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	All levels (it is a power balance issue) but dealt with by TSO	
Time to respond	<30secs	[3]
Response duration	up to 30mins	[3]
Frequency of use	20-40 times per day	[5]
Size of current requirement	~1400MW summer, ~1300MW winter ~£140mn per year	[3] [7] (minus Frequency Containment figure above)
Potential size of requirement in future	Similar increase to Frequency containment - 3-4x increase by 2030	
Drivers of requirement	Increase in largest infeed loss (Hinkley point), reduction in system inertia	
Other notes		

Table 23 Electricity Reserve Replacement

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	All levels (it is a power balance issue) but dealt with by TSO	
Time to respond	30mins-4hours	[4]
Response duration	2hours-1day	[6]
Frequency of use	1-30 times per day	[5]
Size of current requirement	~3000-4000MW £95mn per year (£60mn in 2015 due to mild year)	[8] [4]
Potential size of requirement in future	Will increase due to increase in Reserve for Response, and increase in wind generation. Could decrease if wind forecast error improves.	
Drivers of requirement	Wind capacity and forecast error, Solar PV capacity, demand, largest infeed loss (over extend duration) , system inertia	
Other notes	This requirement is bi-directional, though Up reserve (ie increase of active power to balance a shortfall in supply) is slightly higher than Down reserve	

Table 24 Electricity Voltage Support

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	Transmission and Distribution - issue is mainly being created at distribution level but resolved at transmission level	
Time to respond	<1 sec	[6]
Response duration	1s-1min	[6]
Frequency of use	10-100 per day	[6]
Size of current requirement	33.6TVArh injection of reactive power, 6.2TVArh absorption on transmission system 1800MVar peak £75mn per year on transmission	[9] [5] [4]
Potential size of requirement in future	14000MVar peak in 2035	[5]
Drivers of requirement	Reduction in inductive load (ie motors), increase in capacitive load (ie EnergySaving lighting), increased use of capacitive cables, reduction in apparent power import to LDNs (or even export upwards)	
Other notes	Majority of reactive power compensation is conducted at transmission level	

Table 25 Electricity Black Start

Parameter	Value	Source
Energy vector	Electricity	
Grid Level	Transmission	
Time to respond	1hour	[6]
Response duration	1hour-4hours	[6]
Frequency of use	<1 per year	[6]
Size of current requirement	£20mn	[4]
Potential size of requirement in future	Similar to current size	
Drivers of requirement	Level of demand	
Other notes	Service providers must be available in case of black start - ie storage must be fully charged and not used for other services. Typical black start timeframe is 1. Batteries discharge, 2. Diesel backup generators fire up, 3. Large synchronous generators fire up.	

A.2 Gas and hydrogen

Table 26 Gas Pressure Regulation

Parameter	Value	Source
Energy vector	Gas	
Grid Level	Primarily Transmission	
Time to respond	hours	[11]
Response duration	~6hours	[11]
Frequency of use	~1 per day	[11]
Size of current requirement	Current linepack swings are ~20mcm per day. Range of linepack values for 2015-16 was 317-367mcm, this can be considered the safe operating margin. Currently ample storage to provide balancing in this range.	[12] [11]
Potential size of requirement in future	Likely to decrease due to decreasing gas demand	[10]
Drivers of requirement	Projected reduction in gas demand reducing balancing requirement. Increased intermittent power generation may make gas use from CCGTs more intermittent, increasing balancing requirements (though in many scenarios gas demand for power generation is decreasing long term)	[10]
Other notes	Linepack refers to volume of gas held in in the gas network. Swings of 20mcm per day are observed, with limits of 50mcm across the year. This is the result of NG taking balancing actions to correct for market imbalances, and ensure pressures remain at safe levels. Can use linepack limits as proxy for pressure limits.	

Table 27 Gas (and hydrogen) Operating Margins

Parameter	Value	Source
Energy vector	Gas (and similarly for hydrogen)	
Grid Level	Primarily Transmission	
Time to respond	hours	
Response duration	~6hours	
Frequency of use	~1 per year	
Size of current requirement	1160GWh in winter, 490GWh in summer £22mn	[14] [13]
Potential size of requirement in future	Likely to decrease with declining gas demand	[10]
Drivers of requirement	Projected reduction in gas demand reducing balancing requirement. Increased intermittent power generation may make gas use from CCGTs more intermittent, increasing balancing requirements (though in many scenarios gas demand for power generation is decreasing long term)	[10]
Other notes	Operating margins are used for both imbalances and for severe system failures. There is some overlap with pressure regulation in terms of imbalances.	

Table 28 Hydrogen Pressure Regulation

Parameter	Value	Source
Energy vector	Hydrogen	
Grid Level	Transmission (ie assume similar to gas NTS)	
Time to respond	hours (assume same as gas)	
Response duration	~6hours (assume same as gas)	
Frequency of use	~1 per day (assume same as gas)	
Size of current requirement	Assume pressure range similar to gas, ie acceptable range in network hydrogen volumes of ~+/- 7.5%.	
Potential size of requirement in future	Likely to be similar in % terms, but absolute levels will increase due to increasing hydrogen demand	
Drivers of requirement	Increasing H2 demand - Gas to H2 switching, H2 as storage for excess renewable electricity generation	
Other notes	As hydrogen energy density ~25% that of natural gas this implies a much tighter balancing range in terms of energy.	

A.3 Heat

Table 29 Heat Emergency Backup

Parameter	Value	Source
Energy vector	Heat	
Grid Level	Distribution	
Time to respond	1 hour	
Response duration	Hours-days	
Frequency of use	1 per year	
Size of current requirement	All heat networks need back-up heat supply in case of failure – ~N-1 contingency, often provided by gas / diesel boilers	
Potential size of requirement in future	N-1 requirement likely to remain	
Drivers of requirement	Absolute level in MW is driven by the level of heat network deployment	
Other notes		

Appendix B Storage technologies details

B.1 Electricity

Table 30 Pumped hydro details

Parameter	Value	Notes	Source
Type	Mechanical		
Input	Electricity		
Output	Electricity		
Maturity	Mature		
Effective capacity (%)	100%		[15]
Round trip efficiency (%)	81%		[15]
Temporal losses (%/day)	0%		[16]
Response time	10 secs-2 mins		[16]
Duration	8-16h		[15]
Inject/withdraw rate	100-5000MW		[16]
Energy density by mass	0.5-1.5Wh/kg		[16]
Energy density by volume / area			
Lifespan (full cycles)	50-100 years		[16]
Maximum build	Limited opportunities for new storage sites		
Maximum build per year			
Current CAPEX	559 £/kW + 96 £/kWh	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 5.1 £/kW/year VOM 0.23 £/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Mature technology - likely to remain fairly constant		
Future OPEX	Mature technology - likely to remain fairly constant		

Table 31 CAES details

Parameter	Value	Notes	Source
Type	Mechanical		
Input	Electricity		
Output	Electricity		
Maturity	Medium	Adiabatic overground generation is in R&D phase (immature)	
Effective capacity (%)	100%		[15]
Round trip efficiency (%)	70%	Assume underground CAES	[15]
Temporal losses (%/day)	0%		[16]
Response time	5-15mins		[16]
Duration	2-20hours		[15]
Inject/withdraw rate	100-300MW		[16]
Energy density by mass	30-60Wh/kg		[16]
Energy density by volume / area			
Lifespan (full cycles)	25-40 years		[16]
Maximum build	Ideally situated in salt caverns - above ground is far more expensive		
Maximum build per year			
Current CAPEX	617.5 £/kW +22.6 £/kWh	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 3.2 £/kW/year VOM 2.53 £/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Salt cavern situated CAES unlikely to reduce in cost. Above ground may see cost savings, though likely to remain expensive.		[17]
Future OPEX	Salt cavern situated CAES unlikely to reduce in cost. Above ground may see cost savings, though likely to remain expensive.		[17]

Table 32 Flywheel details

Parameter	Value	Notes	Source
Type	Mechanical		
Input	Electricity		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	100%		[15]
Round trip efficiency (%)	85%		[15]
Temporal losses (%/day)	20%-100% per day	If not used losses within day some flywheels could lose all stored potential energy	[16]
Response time	seconds		[16]
Duration	Typical 15s-15mins, but with some developments looking at duration of 1+ hour		[16] [54]
Inject/withdraw rate	0.002-20MW		[16]
Energy density by mass	5-130Wh/kg		[16]
Energy density by volume / area			
Lifespan (full cycles)	20 years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	668 £/kW +3982 £/kWh	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 4.47 £/kW/year VOM 0.23£/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Limited reductions expected		[18]
Future OPEX	Limited reductions expected		[18]

Table 33 NaS Battery details

Parameter	Value	Notes	Source
Type	Chemical		
Input	Electricity		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	80%		[15]
Round trip efficiency (%)	75%		[15
Temporal losses (%/day)	20% per day		[16]
Response time	~100 ms		[19]
Duration	hours		[16]
Inject/withdraw rate	0.5-50MW		[16]
Energy density by mass	150-240Wh/kg		[16]
Energy density by volume / area	0.313 kWh/sq m		[15]
Lifespan (full cycles)	2000-4500 cycles, 10-15 years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	431 £/kW +297 £/kWh usable capacity	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 4.39 £/kW/year VOM 0.4 £/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Limited cost reductions expected		[20]
Future OPEX	Limited cost reductions expected		[20]

Table 34 Flow battery storage details

Parameter	Value	Notes	Source
Type	Chemical	Various (e.g. Vanadium Redox or Zinc Bromine)	
Input	Electricity		
Output	Electricity		
Maturity	Immature		
Effective capacity (%)	100%		[15]
Round trip efficiency (%)	71%		[15]
Temporal losses (%/day)	0-10% per day		[16]
Response time	~100 ms		[19]
Duration	hours		[16]
Inject/withdraw rate	0.03-7MW		[16]
Energy density by mass	75		[16]
Energy density by volume / area	0.201 kWh/sq m		[15]
Lifespan (full cycles)	10000+ cycles, 5-20 years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	738 £/kW +546 £/kWh usable capacity	Vanadium Redox Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 6.18 £/kW/year VOM 0.96 £/MWh	Vanadium Redox Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Cost expected to half by 2020	Vanadium Redox	[20]
Future OPEX			

Table 35 Advanced Lead-acid storage details

Parameter	Value	Notes	Source
Type	Chemical		
Input	Electricity		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	57%		[15]
Round trip efficiency (%)	89%		[15]
Temporal losses (%/day)	0.1-0.3% per day		[16]
Response time	~100 ms		[19]
Duration	hours		[16]
Inject/withdraw rate	0.001-50MW		[16]
Energy density by mass	30-50Wh/kg		[16]
Energy density by volume / area	0.295 kWh/sq m		[15]
Lifespan (full cycles)	100-1000 cycles, 3-15 years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	907 £/kW +757 £/kWh usable capacity	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 27.3 £/kW/year VOM 1.16 £/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Limited cost reductions expected		[20]
Future OPEX			

Table 36 Li-ion Battery details

Parameter	Value	Notes	Source
Type	Chemical		
Input	Electricity		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	88%		[15]
Round trip efficiency (%)	89%		[15]
Temporal losses (%/day)	0.1-0.3% per day		[16]
Response time	~100 ms		[19]
Duration	hours		[16]
Inject/withdraw rate	0.001-0.1MW		[16]
Energy density by mass	75-250		[16]
Energy density by volume / area	0.308 kWh / sq m		[15]
Lifespan (full cycles)	1000-10000 cycles 5-15years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	929 £/kW + 799 £/kWh usable capacity	Real 2016 1.5 USD = 1 GBP	[15]
Current OPEX	FOM 13.34 £/kW/year VOM 2.15 £/MWh	Real 2016 1.5 USD = 1 GBP	[15]
Future CAPEX	Cell costs to half by 2020		[20]
Future OPEX			

Table 37 Home battery storage (Li-ion) details

Parameter	Value	Notes	Source
Type	Chemical		
Input	Electricity		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	90%		[21]
Round trip efficiency (%)	89%		[15]
Temporal losses (%/day)	0.1-0.3% per day		[16]
Response time	~100 ms		[19]
Duration	1.7 - 5 hours (max size, 6kWh)		[21]
Inject/withdraw rate	1.2MW		[21]
Energy density by mass	25-50 kWh/kg		[21]
Energy density by volume / area	7.58 - 22.8 kWh / sq m		[21]
Lifespan (full cycles)	1000-10000 cycles 5-15years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	1000 £/kW + 400 £/kWh usable capacity	Real 2016 1.5 USD = 1 GBP	[21], [22]
Current OPEX			
Future CAPEX	Costs to half by 2020		[22]
Future OPEX			

Table 38 Super capacitor details

Parameter	Value	Notes	Source
Type	Electrical		
Input	Electricity		
Output	Electricity		
Maturity	Immature		
Effective capacity (%)	100%		
Round trip efficiency (%)	85-98%		[16]
Temporal losses (%/day)	2-40% per day		[16]
Response time	ms		[16]
Duration	ms-1hour		[16]
Inject/withdraw rate	0.01-1MW		[16]
Energy density by mass	0.1-15Wh/kg		[16]
Energy density by volume / area			
Lifespan (full cycles)	20+ years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	80-400 £/kW or >10000 £/kWh	Real 2016 1.25 EUR = 1 GBP * assume this is storage cost only, no installation and connection costs	[19]
Current OPEX			
Future CAPEX	if deployment increases, reductions in cost expected		
Future OPEX	if deployment increases, reductions in cost expected		

Table 39 Superconductive magnetic energy storage details

Parameter	Value	Notes	Source
Type	Electrical		
Input	Electricity		
Output	Electricity		
Maturity	Immature		
Effective capacity (%)	100%		
Round trip efficiency (%)	95%		[16]
Temporal losses (%/day)	10-15% per day		[16]
Response time	ms		[16]
Duration	ms-5mins		[16]
Inject/withdraw rate	0.01-10MW		[16]
Energy density by mass	0.5-5 Wh/kg		[16]
Energy density by volume / area			
Lifespan (full cycles)	10000 cycles, 20 years		[16]
Maximum build			
Maximum build per year			
Current CAPEX	240 £/kW or >10000 £/kWh	Real 2016 1.25 EUR = 1 GBP * assume this is storage cost only, no installation and connection costs	[19]
Current OPEX			
Future CAPEX	if deployment increases, reductions in cost expected		
Future OPEX	if deployment increases, reductions in cost expected		

Table 40 Liquid air energy storage details

Parameter	Value	Notes	Source
Type	Electrical		
Input	Electricity		
Output	Electricity		
Maturity	Moderate	Individual components mature, integration for LAES more novel	55
Effective capacity (%)			
Round trip efficiency (%)	60-70% round trip		55
Temporal losses (%/day)	0.2% / day		55
Response time	~1+ minute	If cryogenic feed pumps kept cold and turbine oil warm	55
Duration	Hours	Power and capacity scalable through use of additional power turbines and storage tanks, potentially 500 MWh at 100 MW	55
Inject/withdraw rate	100kW-10s/100s MWs	300kW / 2.5 MWh pilot in 2011 in UK ,	55
Energy density by mass	0.1 – 0.1 kWh/kg		55
Energy density by volume / area			
Lifespan (full cycles)	~25 years	For all major individual components	55
Maximum build		Scalable	
Maximum build per year			
Current CAPEX	~£1800/kW	First of a kind and 'mature' cost estimates for 20MW/80MWh system. All in cost per kW including balance of plant.	55
Current OPEX			
Future CAPEX	~£1000/kW		
Future OPEX			

B.2 Gas and hydrogen

Table 41 Liquefied Natural Gas (LNG)

Parameter	Value	Notes	Source
Type	Gas		
Input	Gas		
Output	Gas		
Maturity	Mature		
Effective capacity (%)	'Heel' of ~5-10%		[28]
Round trip efficiency (%)		~1.5-2% of send-out gas used in regasification process	[30]
Temporal losses (%/day)			
Response time	Hours	Very high rates of deliverability	
Duration			
Inject/withdraw rate	~5 mcm/d		[28]
Energy density by mass	~32 mcm typical facility but scalable		[28]
Energy density by volume / area			
Lifespan (full cycles)	~20-25 years	Expected	
Maximum build	Scalable		
Maximum build per year			
Current CAPEX			
Current OPEX			
Future CAPEX			
Future OPEX			

Table 42 Long Range Storage (LRS)

Parameter	Value	Notes	Source
Type	Gas	Depleted field / aquifer	
Input	Gas		
Output	Gas		
Maturity	Mature		
Effective capacity (%)	Site specific but e.g. 50% cushion gas requirement		
Round trip efficiency (%)	Negligible loss rates outside of accident		
Temporal losses (%/day)			
Response time	hours	but relatively few cycles across the year (e.g. 1-2) due to seasonal arbitrage	
Duration	Capacity site specific but circa. 500 mcm		[28]
Inject/withdraw rate	Deliverability site specific but~5 mcm/d		[28]
Energy density by mass			
Energy density by volume / area			
Lifespan (full cycles)	40+ years		
Maximum build	Depends on geology	11 projects with planning permission with ~14 bcm capacity (mix of LRS/SRS)	[29]
Maximum build per year			
Current CAPEX	Highly site specific but ~€0.4-0.7 / cm of storage	Excludes cushion gas	[28]
Current OPEX	Highly site specific but ~€0.01-0.8 / cm of storage		[28]
Future CAPEX			
Future OPEX			

Table 43 Short Range Storage (SRS)

Parameter	Value	Notes	Source
Type	Gas	Salt cavity	
Input	Gas		
Output	Gas		
Maturity	Mature		
Effective capacity (%)	Site specific but e.g. 20% cushion gas requirement		[28]
Round trip efficiency (%)	Negligible loss rates outside of accident		
Temporal losses (%/day)			
Response time	hours		
Duration	Capacity site specific but circa. 500 mcm		[28]
Inject/withdraw rate	Deliverability site specific but ~20+ mcm/d		[28]
Energy density by mass			
Energy density by volume / area			
Lifespan (full cycles)	40+ years		
Maximum build	Depends on geology	11 projects with planning permission with ~14 bcm capacity (mix of LRS/SRS)	[29]
Maximum build per year			
Current CAPEX	Highly site specific but ~€0.8-1.2 / cm of storage	Excludes cushion gas	[28]
Current OPEX	Highly site specific but ~€0.01-0.025 / cm of storage		[28]
Future CAPEX			
Future OPEX			

Table 44 Line-packing

Parameter	Value	Notes	Source
Type	Gas	Pipeline	
Input	Gas		
Output	Gas		
Maturity	Mature		
Effective capacity (%)			
Round trip efficiency (%)	Typical losses in range of 1-2% (volume) on transmission network		
Temporal losses (%/day)			
Response time	Sub-hour		
Duration	Hours		
Inject/withdraw rate	Current linepack swings are ~20mcm per day. Range of linepack values for 2015-16 was 317-367mcm	Function of pipe network topology and injection / withdrawal across the network	[12]
Energy density by mass			
Energy density by volume / area			
Lifespan (full cycles)			
Maximum build			
Maximum build per year			
Current CAPEX			
Current OPEX			
Future CAPEX			
Future OPEX			

Table 45 Geological hydrogen storage

Parameter	Value	Notes	Source
Type	Hydrogen – Geological	Salt cavern	
Input	Hydrogen		
Output	Hydrogen		
Maturity	Mature		
Effective capacity (%)	50%-90% cushion gas	Higher requirement in gas of faster cycling rates	[31], [25]
Round trip efficiency (%)	2.5%	Compression from ~20-60 Barg to 270	[31], [25]
Temporal losses (%/day)			
Response time	hours		
Duration	Site specific but ~70k-300km3, with pressure range of ~45-270 bara		[31], [25]
Inject/withdraw rate			
Energy density by mass			
Energy density by volume / area			
Lifespan (full cycles)	40+ years		[25]
Maximum build	Depends on geology	~3 TWh limit by 2050 based on build rate in ESME	[25]
Maximum build per year			
Current CAPEX	£9.5/kWh		[31], [25]
Current OPEX	Negligible		[25]
Future CAPEX	Assume to be similar		[25]
Future OPEX			

Table 46 Bulk storage

Parameter	Value	Notes	Source
Type	Hydrogen – Bulk	Compressed, Cold, Liquid stored at ambient temperatures through to <20K	
Input	Hydrogen		
Output	Hydrogen		
Maturity	Mature		
Effective capacity (%)			
Round trip efficiency (%)	~30% energy required for liquefaction		
Temporal losses (%/day)	0.25% / day		[32]
Response time	Hours		
Duration	~366 kgH2 for typical compressed system ~1m kgH2 typical liquid system	Scalable	[32]
Inject/withdraw rate	Dependent on size of compressor		
Energy density by mass			
Energy density by volume / area	~30 kg/m³ for a 700 bar high ~70 kg/m3 for liquid	Depends on pressure (ranges from ~50bar through to 700/1000 bar)	[32]
Lifespan (full cycles)	20		[32]
Maximum build	Scalable		
Maximum build per year	Scalable		
Current CAPEX	~£1077/kgH2 compressed ~£26/kgH2		[32]
Current OPEX	~30% energy required for liquefaction		[32]
Future CAPEX	Likely to be similar		[32]
Future OPEX	Energy for liquefaction could be reduced by ~1/2		[32]

Table 47 Materials-based

Parameter	Value	Notes	Source
Type	Hydrogen materials based	Metal hydride (e.g. magnesium based) Liquid organic hydrogen carriers (toluene/methylcyclohexane-based, Dibenzyltoluene)	
Input			
Output			
Maturity	Immature	Very early R&D	
Effective capacity (%)			
Round trip efficiency (%)	~30% hydrogen energy required for withdrawal but comparable thermal energy released during charging ~25% required for dehydrogenation (withdrawal), but comparable thermal energy released during hydrogenation step		[32]
Temporal losses (%/day)			
Response time	hours		
Duration		Scalable	
Inject/withdraw rate	Assumed to be 'slow' for metal-hydride Potentially 'faster' for liquid with catalyst		[32]
Energy density by mass			
Energy density by volume / area	~60 kg per m³ liquid carrier		
Lifespan (full cycles)			
Maximum build			
Maximum build per year			
Current CAPEX	Unclear – very early stage R&D		
Current OPEX			
Future CAPEX	"Not foreseeable whether [either] will play a significant role in future hydrogen infrastructure"		[32]
Future OPEX			

B.3 Heat

Table 48 Underground thermal energy storage

Parameter	Value	Notes	Source
Type	Sensible Heat Storage	Various types – Tank (water), borehole (e.g. clay, sand, rock), aquifer (water), cavern/pit (rock, water)	
Input	Heat		
Output	Heat		
Maturity	Moderate	Primarily system integration challenges	[23]
Effective capacity (%)			
Round trip efficiency (%)			
Temporal losses (%/day)	Key function of store radius, insulation, delta to ambient temperature next to store. Can be <0.1%/hour for stores with large radius		[23]
Response time	Hours	UTES often linked to heat pumps to extract heat from store	
Duration	Months		
Inject/withdraw rate	Function of heat exchanger and size of supply source		
Energy density by mass			
Energy density by volume / area	1.16kWh/m3/K (water)		
Lifespan (full cycles)			
Maximum build	Site specific considerations, particularly when using existing geology One of largest in Germany is ~75,000m3		
Maximum build per year			
Current CAPEX	Highly site and technology specific, but strong decreasing costs at large sizes – e.g. pit store with 75k m3 of water at ~€30/m3 to 300m3 tank at ~€470/m3		[23]
Current OPEX			
Future CAPEX	Likely to be relatively limited decline as focus on systems integration		
Future OPEX			

Table 49 District heat network accumulator / buffer store

Parameter	Value	Notes	Source
Type	Sensible Heat Storage	Water tank	
Input	Heat		
Output	Heat		
Maturity	Mature		
Effective capacity (%)			
Round trip efficiency (%)			
Temporal losses (%/day)	Key function of store radius, insulation, delta to ambient temperature next to store. Can be <0.1%/hour for stores with large radius		[23]
Response time	Sub-hour		
Duration	Hours-days		
Inject/withdraw rate	Function of heat exchanger and size of supply source		
Energy density by mass			
Energy density by volume / area	1.16kWh/m3/K (water)		
Lifespan (full cycles)			
Maximum build	Function of heat network deployment		
Maximum build per year			
Current CAPEX	£36k-46k/MWh		[24]
Current OPEX	Negligible		
Future CAPEX	Mature unlikely to be further significant reductions		
Future OPEX	Negligible		

Table 50 Building scale hot water storage

Parameter	Value	Notes	Source
Type	Sensible Heat Storage	Water tank	
Input	Heat		
Output	Heat		
Maturity	Mature		
Effective capacity (%)			
Round trip efficiency (%)	50-90% over typical daily cycle (depending on insulation) but losses time dependent		
Temporal losses (%/day)	Key function of store radius, insulation, delta to ambient temperature next to store. Can be <1.0%/hour for well insulated store		[25]
Response time	Sub-hour		
Duration	Hours		
Inject/withdraw rate	Function of heat exchanger and size of supply source		
Energy density by mass			
Energy density by volume / area	1.16kWh/m3/K (water)		
Lifespan (full cycles)	~15 years average 1 cycle per day		[25]
Maximum build	Function of building size, e.g. typical 100-200l tank for smaller size domestic buildings		
Maximum build per year			
Current CAPEX	£4.3/kWh	Energy stored at ~60^{o}C	[25]
Current OPEX	Negligible		
Future CAPEX	Unlikely to be significant reductions as mature		
Future OPEX			

Table 51 Building scale storage heaters

Parameter	Value	Notes	Source
Type	Sensible Heat Storage	Ceramic	
Input	Heat		
Output	Heat		
Maturity	Mature		
Effective capacity (%)			
Round trip efficiency (%)			
Temporal losses (%/day)			
Response time	Sub-hour		
Duration	~7-hours		[26]
Inject/withdraw rate	Limited by power rating of circuit (~1kW to 3.4kW)		
Energy density by mass	~5kWh/kg		[26]
Energy density by volume / area			
Lifespan (full cycles)	10-15 years, winter only cycling		
Maximum build	Large domestic room storage units ~12-24 kWh		[26]
Maximum build per year			
Current CAPEX	~£250-£500 for small to large units		Various retail sites
Current OPEX	Negligible		
Future CAPEX	Unlikely to be significant reductions as mature		
Future OPEX			

Baringa

Table 52   Building scale heat storage – Phase Change Material

Parameter	Value	Notes	Source
Type	Sensible Heat Storage	Range of materials being investigated e.g. Na-acetate Trihydrate, Paraffin, Erytritol	
Input	Heat		
Output	Heat		
Maturity	Moderate	Challenges involved in commercialising PCM systems operating in the temperature range suitable for heat pumps, but commercial systems expected to become available in next few years	[27]
Effective capacity (%)			
Round trip efficiency (%)	50-90% over typical daily cycle (depending on insulation) but losses time dependent		[27]
Temporal losses (%/day)			
Response time	Sub-hour		
Duration	Hours		
Inject/withdraw rate	Function of heat exchanger and size of supply source		
Energy density by mass	50-150 kWh/t		
Energy density by volume / area			
Lifespan (full cycles)	~15 years average 1 cycle per day	Assumed comparable to sensible heat storage	
Maximum build	Similar to hot water storage tanks	Trade off saving space versus additional energy ~3 time energy density ~4 times likely cost	[24]
Maximum build per year			
Current CAPEX			[27]
Current OPEX			
Future CAPEX	€10-50/kWh		
Future OPEX	Negligible		

Table 53 Building scale heat storage – Thermochemical Energy Storage

Parameter	Value	Notes	Source
Type	Thermochemical energy storage	Range of materials being investigated including microporous materials (e.g. Aluminophosphate), composite materials (e.g. Porous salt hydrates)	
Input	Heat		
Output	Heat		
Maturity	Immature	High cost, complexity and key R&D challenges around materials and reactor design	[23]
Effective capacity (%)			
Round trip efficiency (%)	75-100% over typical cycle		[27]
Temporal losses (%/day)			
Response time	Sub-hour		
Duration	Hours		
Inject/withdraw rate	Function of heat exchanger and size of supply source	Charging reaction temperatures also vary significantly from ~90°C to 800+°C	[23]
Energy density by mass	120-250 kWh/t		[27]
Energy density by volume / area			
Lifespan (full cycles)			
Maximum build			
Maximum build per year			
Current CAPEX			
Current OPEX			
Future CAPEX	€8-100/kWh		
Future OPEX	Negligible		

Appendix C Competing flexible technologies details

C.1 Electricity

Table 54 CCGT (potentially with CCS)

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Natural gas		
Output	Electricity		
Maturity	Mature (non CCS)		
Efficiency (%)	53%	On a Higher Heating Value basis. Efficiency can increase if waste heat is used into a heat network. CCS variants ~5-10 percentage points less efficient	[34]
Response time	~3 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	400 MW		
Lifespan (years)	30 years		[34]
Maximum build			
Maximum build (GW/year)	~2 GW/year	GB-wide potential	[34]
Key drivers of costs	Price of natural gas & CO2, cost of CCS infrastructure		

Table 55 OCGT

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Natural gas		
Output	Electricity		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	38%	On a Higher Heating Value basis.	[34]
Response time	15 mins from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	100 MW		
Lifespan (years)	30 years		[34]
Maximum build			
Maximum build rate			
Key drivers of costs	Price of natural gas & CO2		

Table 56 Coal (potentially with CCS)

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Coal	Based on PC coal and IGCC coal with & without CCS	
Output	Electricity		
Maturity	Mature (non CCS)		
Effective capacity (%)	100%		
Efficiency (%)	40-50%	On a Higher Heating Value basis. Efficiency can increase if waste heat is used into a heat network. IGCC more efficient compared to PC coal. CCS variants ~10-15 percentage points less efficient	[34]
Response time	5-6 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	400 MW		
Lifespan (years)	40 years	Across pulverized coal and integrated gasification combined cycle coal	[34]
Maximum build			
Maximum build rate (GW/year)	~4 GW/year	Combines pulverized coal and integrated gasification combined cycle coal GB-wide potential	[34]
Key drivers of costs	Price of natural coal & CO2, cost of CCs infrastructure		

Table 57 New Nuclear

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Uranium		
Output	Electricity		
Maturity	Moderate	For new build EPR	
Effective capacity (%)	100%		
Efficiency (%)	33%	Efficiency can increase if waste heat is used into a heat network.	[35]
Response time	48 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	1,600 MW	For new build EPR	
Lifespan (years)	50 years		[34]
Maximum build (GW)	39.8 GW	GB-wide potential	[34]
Maximum build rate (MW/year)	500 MW/year	GB-wide potential	[34]
Key drivers of costs	Capex		

Table 58 Diesel engine

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Diesel		
Output	Electricity		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	20% to 45%	Depending on size	[35]
Response time	<10 mins from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	~4-15 MW	Small, modular design	[38]
Lifespan (years)	25 years		[51]
Maximum build			
Maximum build per year			
Key drivers of costs	Price of oil		

Table 59 Gas engine

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Gas		
Output	Electricity		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	~42-52%	Depending on size, high efficiency even under low part load	[51]
Response time	<10 mins from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	~4-30 MW	Small, modular design	[51]
Lifespan (years)	25 years		[51]
Maximum build			
Maximum build per year			
Key drivers of costs	Price of gas		

Table 60 Biomass (potentially with CCS)

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Wood chips		
Output	Electricity		
Maturity	Medium		
Effective capacity (%)	100%		
Efficiency (%)	33%	On a Gross Calorific Value basis. Efficiency can increase if waste heat is used into a heat network.	[34]
Response time	Comparable to coal ~5-6 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	400 MW		
Lifespan (years)	30 years	Across dedicated biomass generation and IGCC biomass with CCS	[34]
Maximum build			
Maximum build rate (GW/year)	2 GW/year + 2 GW/year with CCS		[34]
Key drivers of costs	Capex costs, costs of CCS infrastructure		

Table 61 CHP

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Natural gas, biomass, diesel		
Output	Electricity & heat		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	10% to 40%	Electrical efficiency depends on size and configuration of heat:power ratio	[35], [34]
Response time	3 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	10kW to 50MW		
Lifespan (years)	30 years	Comparable to diesel generators	[34]
Maximum build			
Maximum build rate (MW/year)	400 MW/year	This figure applies to biomass CHP only	[34]
Key drivers of costs	Cost of gas, biomass		

Table 62 Hydrogen turbine

Parameter	Value	Notes	Source
Type	Thermodynamic		
Input	Hydrogen gas		
Output	Electricity		
Maturity	Immature		
Effective capacity (%)	100%		
Efficiency (%)	50%	On a Higher Heating Value basis	[34]
Response time	~15mins from cold, secs when spinning	Comparable to OCGT	
Duration	Unlimited		
Typical capacity (MW)	100 MW	Comparable to OCGT	
Lifespan (years)	20 years		[34]
Maximum build			
Maximum build rate (GW/year)	2 GW/year		[34]
Key drivers of costs	Capex & price of hydrogen		

Table 63 Interconnector

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Electricity		
Output	Electricity		
Maturity	Mature		
Effective capacity (%)	97.4%	Based on UK-Netherlands interconnection	[37]
Efficiency (%)	98% to 99%	Based on IFA losses	[39]
Response time	Seconds		
Duration	Hours - dependent on system conditions in connected market		
Typical capacity (MW)	500 MW to 2,000 MW		
Lifespan (years)	50 years to 60 years	For HVDC	[40]
Maximum build (GW)	4 GW at present, ~8GW projects proposed	Possibility for significant further interconnection beyond this.	See D1.2 deliverable for list of projects
Maximum build per year			
Key drivers of costs	Electricity prices in connected markets		

Table 64 DSR (home, commercial and industrial)

Parameter	Value	Notes	Source
Type	Service		
Input	Electricity demand		
Output	Reduced or increased electricity demand		
Maturity	Moderate		
Effective capacity (%)	100%		
Efficiency (%)	100%		
Response time	Hours if manual dispatch, seconds if automated		
Duration	Highly dependent on form of DSR, but generally scale of several hours		
Typical capacity (MW)	~100 kW to ~10 MW		
Lifespan (years)	N/A		
Maximum build (GW)	9 GW (distributed generation), 10 GW (I&C), 7 GW (heat pumps), 1.2 GW (electric vehicles)	GB-wide potential by 2035. These figures are subject to a wide range of uncertainty.	[41]
Maximum build per year			
Key drivers of costs	Consumer's willingness to accept to compensation for temporary reduction in 'service'		

C.2 Gas and hydrogen

Table 65 Gas interconnectors

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Natural gas		
Output	Natural gas (at a different location)		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	0.2%	Gas shrinkage on NTS	[42], [43]
Response time	Hours		
Duration	Hours to days		
Typical capacity (GW)	~30 GW	Based on record gas imports to UK through the Interconnector pipeline	[44]
Lifespan (years)	20 years to 60 years	For gas transmission assets	[45]
Maximum build			
Maximum build per year			
Key drivers of costs	Price of gas in connected markets		

Table 66 Gas DSR

Parameter	Value	Notes	Source
Type	Service		
Input	Natural gas		
Output	Reduced gas demand	Primarily large industrial/commercial consumers or gas power generation with distillate back-up facilities	
Maturity	Moderate	Market mechanism to activate this is still under trial design with expected go-live in Q4 of 2016	[52]
Effective capacity (%)	100%		
Efficiency (%)			
Response time	Hours		
Duration	1 day up to 1 week	But with potentially varying degrees of DSR moving up to 1 week	
Typical capacity (mcm/day)	Near-term estimates of potential • ~25-30 Daily Metered large consumers • ~6-7 directly connect NTS industrials • ~~50-70 gas-fired power stations with distillate back-up		[53]
Lifespan (years)			
Maximum build			
Maximum build per year			
Key drivers of costs	Consumer's willingness to accept to compensation for temporary reduction in 'service'		

Table 67 Liquefied Natural Gas (LNG) terminal

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Liquefied Natural Gas		
Output	Natural gas		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	87%	Total efficiency of liquefaction, shipping & regasification based on Nigeria to UK LNG shipping	[46]
Response time	Hours to Days	Hours if LNG storage on-site, otherwise days	
Duration	Hours to Days	Depending of on-site storage availability	
Typical capacity (MW)	25 GW to 30 GW	Based on South Hook	[47]
Lifespan (years)	40 years		[48]
Maximum build			
Maximum build rate			
Key drivers of costs	Global price of LNG & shipping costs		

Table 68 Direct Synthetic Natural Gas production and injection

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Synthetic Natural Gas		
Output	Natural gas		
Maturity	Depending on technology	Electrolysis is the most mature, and gasification the less mature	
Effective capacity (%)	100%		
Efficiency (%)	60%	For biomass gasification with CCS	[34]
Response time	Hours		
Duration	Hours to Days		
Typical capacity (MW)	100kW to 10 MW		
Lifespan (years)	30 years		[34]
Maximum build			
Maximum build rate			
Key drivers of costs	Biomass costs, CCS infrastructure		

Table 69 Bio-methane Grid Injection

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Bio-methane		
Output	Natural gas		
Maturity	Moderate		
Effective capacity (%)	100%		
Efficiency (%)	10% to 30%	Based on Swedish demonstration plant	[49]
Response time	Hours		
Duration	Hours to Days		
Typical capacity (kW)	0.5kW to 10kW		[50]
Lifespan (years)	25 years		[50]
Maximum build			
Maximum build rate			
Key drivers of costs	Capex		

Table 70 Direct hydrogen production and injection

Parameter	Value	Notes	Source
Type	Infrastructure		
Input	Electricity, coal, gas, biomass	Several technologies can produce hydrogen: coal & biomass gasification, electrolysis & Stem Methane Reformers	
Output	Hydrogen		
Maturity	Depending on technology	Electrolysis is the most mature, and biomass gasification the less mature	
Effective capacity (%)	100%		
Efficiency (%)	45% to 70%	Depending on the technology: coal gasification being the most efficient and biomass gasification the least efficient	[34]
Response time	Minutes (electrolysis) to hours (other technologies)		
Duration	Unlimited		
Typical capacity (MW)			
Lifespan (years)	20 years to 40 years	Electrolysis has the shortest lifetime, whereas coal & biomass gasification have the longest ones.	[34]
Maximum build			
Maximum build rate			
Key drivers of costs	Capex, fuel costs		

C.3 Heat

Table 71 District heat backup boiler (gas / biomass)

Parameter	Value	Notes	Source
Type	Boiler		
Input	Natural gas, biomass		
Output	Electricity, heat		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	80% to 95%		[34]
Response time	3 hours from cold, secs when spinning		
Duration	Unlimited		
Typical capacity (MW)	10kW to 50MW	Similar to CHP	
Lifespan (years)	15 years	Comparable to diesel generators	[34]
Maximum build			
Maximum build rate	400 MW/year	This figure applies to biomass CHP only	[34]
Key drivers of costs	Cost of gas, biomass		

Table 72 District heat waste heat recovery

Parameter	Value	Notes	Source
Type	District heating		
Input	Waste heat		
Output	District heat		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	86%	Based on offtake of waste heat technology	[34]
Response time	Depends on characteristics of source (e.g. as per CHP above)		
Duration	Unlimited		
Typical capacity (MW)			
Lifespan (years)	30 years		[34]
Maximum build			
Maximum build rate			
Key drivers of costs	Capex		

Table 73 Building scale heaters (gas, electricity, biomass)

Parameter	Value	Notes	Source
Type	Boiler		
Input	Natural gas, electricity, biomass, oil		
Output	Heat		
Maturity	Mature		
Effective capacity (%)	100%		
Efficiency (%)	70% (biomass) to 350% (advanced air source heat pump)		[34]
Response time	Minutes to Hours	Depending on fuel and control system (automatic or manual)	
Duration	Minutes to hours	Assuming integrated with heat storage to provide flexibility without significantly comprising comfort	
Typical capacity (kW)	20kW to 70kW	For boilers providing hot water and heat	
Lifespan (years)	20 years for heat pumps, 15 years for other boilers		[34]
Maximum build			
Maximum build rate			
Key drivers of costs	Fuel cost		