Imperial College London

# Energy Storage for Balancing Intermittent Renewables: Outlook for a Range of Technologies up to 2030, Informed by Expert Elicitation and Historical Data

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## Motivation

- **Affordable, scalable, energy storage technologies** are highly desirable for balancing electricity supply and demand, allowing higher penetration of intermittent renewables, and the exploitation of price arbitrage for inflexible electrical power generation.
- However, there is a **lack of reliable information** on the state of the art and likely evolution of different storage technologies, making it **challenging to plan** for, and to model, their role in a future energy system.
- We seek to identify the **most promising technologies** in terms of **cost** and **environmental impact** for balancing intermittent renewables on a grid and an off-grid scale.
- For each of these technologies, we seek to identify the possible **drivers** of **future cost reduction** and **technical improvement**, to understand the relative roles of **R&D funding** and **scaling up** of production in driving these improvements, and finally to obtain **cost and performance predictions** under a range of funding and deployment scenarios.

**Literature Review**
Establish background on technologies

→

**Technology Selection**
Survey among UK Energy Storage Research Network to identify most promising technologies

→

**Expert elicitation**
Elicit predictions concerning future development from technology experts.

→

**Energy System Modelling**
Use elicited parameters as inputs to energy systems models

## What are the available technologies?

- A wide range of technologies exist, which differ widely in their **costs, maturity, scalability, lifetime, response time, efficiency, site specificity,** and **embedded energy.**

| Technology | Pumped Hydropower | Compressed Air | Pumped Heat | Flywheels/ Supercapacitor | Electrolyser/ fuel cell | Li-ion Battery | Lead Acid Battery | Redox Flow Battery |
|---|---|---|---|---|---|---|---|---|
| Capital $/kWh | 10 – 100s | 10 – 100s | 10 – 100s | 100 - 1000s | 1000s | 100s | 10 – 100s | 100s |
| Cost ¢/kWh/cycle | <1 – 10 | <1 – 10 | <1 – 10 | 10s – 100s | 100s – 1000s | 10s – 100s | 10s – 100s | 10s |
| Response time | Seconds – Minutes | Minutes | Seconds | Milliseconds – Minute | Minutes | Milliseconds | Milliseconds | Milliseconds |
| Maturity | Mature | Deployed | Demo under construction | Deployed/ demo | Demo | Deployed | Mature | Deployed |
| Round trip efficiency (%) | 70 - 85 | 50 - 75 | ~72 | 85 – 98 | <40 (mature) Upto 66 (developing) | 80-90 | 65 - 85 | 65 - 85 |
| Daily Self Discharge | < 0.5% | < 10% | ~0.5 – 1% | High (100%, 5-20%) | ~0% | ~0% | ~0.2% | ~0% |
| ESOI* | 210 | 240 | ? | ? | ? | 10 | 2 | 3 |
| Most suitable applications | Peak shifting/ grid support | Peak shifting/ grid support | Peak shifting/ grid support | Grid Support | Off-grid/seasonal/transport | Off-grid/ transport | Off-grid | Off-grid |

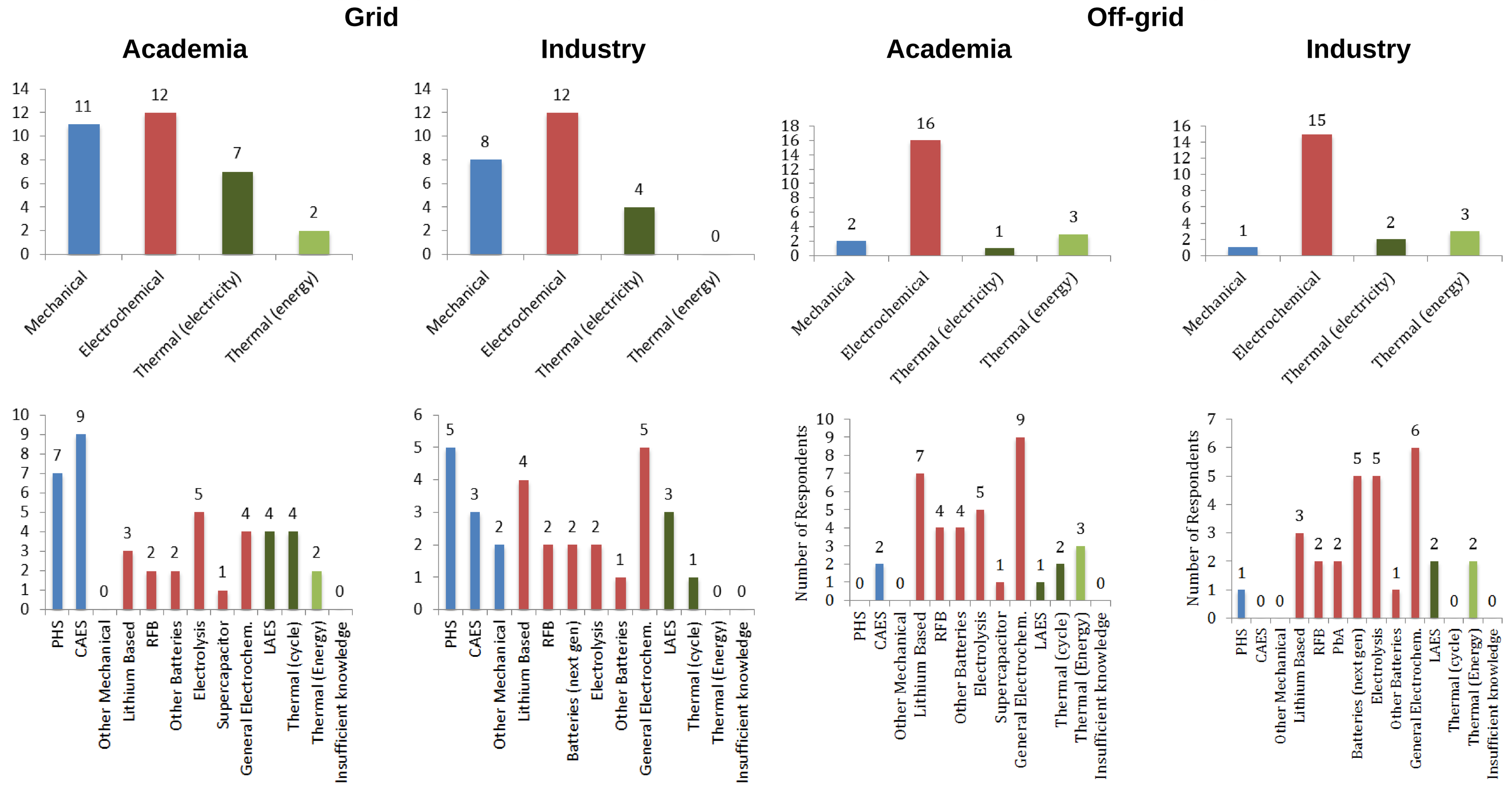
* ESOI refers to the total amount of energy stored over the lifetime of a storage technology unit, divided by the amount of energy used in producing that unit. **Sources:** Banhart 2013, IEA 2014, Luo 2015, Oberhaufer 2012

- The **quality of data** on **cost and technical parameters** varies widely between technologies. Availability of data tends to be higher for **more mature** technologies produced in **large numbers of units** (eg. Li-ion batteries).

## Which technologies are most promising?

- By conducting a **survey** among **academic and industrial experts** from the UK Energy Storage Research Network, we identify technologies which could be low in **cost** and **environmental impact** in 2030, but whose development pathway is uncertain**. Key questions asked were**

On a (grid/off-grid) scale, which three electricity storage technologies could be the **least expensive by 2030** for **balancing intermittent renewables?** *(top) Number of respondents mentioning any technology in category, (bottom) total number of mentions of individual technology*




- On a **grid scale**, responses from Academia and Industry indicate that **mechanical** (in particular PHS and CAES), **thermal storage** (in particular LAES and PHES), and **electrochemical** technologies could all be cost effective.
- On an **off-grid** scale, responses indicate that **electrochemical** technologies are likely to be most cost effective, but with **no clear consensus on the form which** that electrochemical storage would take.

On a (grid/off-grid) scale, which electricity storage technologies could have the **lowest environmental impact** by 2030 for balancing intermittent renewables on a grid scale?

**Grid** → **Mechanical**, **Electrochemical**, **Thermal**

**Off-Grid** → **Electrochemical**, **Mechanical**

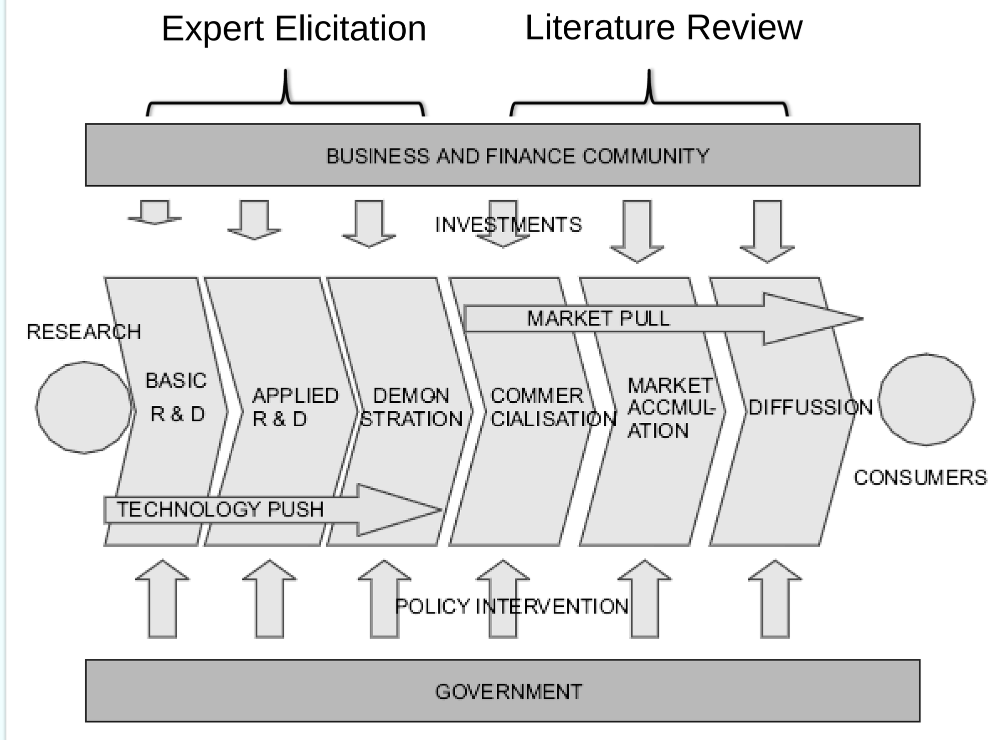
- Respondents specified a broad range of areas of **expertise**, including **energy systems, policy/economics**, and electrochemical and thermal technologies.
- We identify **five technologies** which could be low in cost and environmental impact in 2030, but whose development pathway is uncertain: **lithium-ion** and **redox-flow batteries**, **electrolysers**, **compressed air energy storage**, and **thermal electrical energy storage**.

Other criteria identified as important by Respondents:


## What drives down technology costs?

Technology costs are widely held to fall as a result of **technical innovations** and **scaling up of production,** driven by **research, development, demonstration, and deployment funding, and favourable policy.**

**Expert elicitation** represents a formal procedure to elicit technical judgements from experts in the form of subjective probability distributions that go **beyond well-established knowledge**. This can be a valuable addition to other forms of evidence in support of public policy decision making in areas of uncertainty.(Morgan 2014).




**Technology Innovation Pathways (after Grubb 2004)** Schematic demonstrating the impact of policy and funding on technology development and costs.

**US DoE Expert Elicitation Guidelines** (US NRC 1996)

- ***Empirical data** are **not reasonably obtainable**, or the analyses are not practical to perform*
- *More than one **conceptual model** can explain, and be consistent with, the available data*
- ***Uncertainties** are large and significant*
- ***Technical judgments** are required to assess whether bounding assumptions or calculations are appropriately conservative.*

Use of formal **expert elicitation** should be considered whenever one or more of these conditions exist

We use the expert elicitation technique to better understand the role of innovations from R&D, and literature review to understand the role of commercialisation and scaling.

## Next Steps and Call for Experts

- We are currently in the process of devising and conducting expert elicitations on **lithium-ion** and **redox-flow batteries**, **electrolysers**, **compressed air energy storage**, and **thermal electrical energy storage**, and would be keen to hear from **technical** and **economic** experts on these technologies.
- Following the elicitation of probabilistic ranges for relevant parameters, and making use of **historical data** on development of similar technologies, we intend to develop scenarios for how these technologies are expected to develop in the period up to 2030, making use of global integrated assessment models, and a finer scale off grid solar plus PV model.

## Acronyms

**CAES** = compressed air energy storage, **ESOI** = Energy Stored on Investment, **LAES** = liquid air energy storage, **NaS** = sodium sulphur, **PbA** = lead acid, **PHES** = pumped heat energy storage, **PHS** = pumped hydroelectric storage, **RFB** = redox flow battery, **SMES** = Super Magnetic Energy Storage, **ZnBr** = zinc bromide

## References


**Banhart 2013** Barnhart, C. J., & Benson, S. M. Energy & Environmental Science, 6(4), 1083. **US NRC 1996** US Nuclear Regulatory Commission. Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program. **Grubb 2004** Keio Econ Stud 41:103-32 **IEA 2014** International Energy Agency, Energy Technology Perspectives. **Luo 2015** Luo, X., Wang, J., Dooner, M., & Clarke, J. Applied Energy, 137, 511–536. **Morgan 2014** PNAS, 111(20), 7176–7184. **Oberhaufer 2012** Oberhaufer A., Meisen, P., "Energy Storage Technologies & Their Role in Renewable Integration", Global Energy Network Institute (GENI) 2012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