ENERGY STORAGE IN THE UK AND BRAZIL

Challenges, Capability and Opportunities

Contents

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EXECUTIVE SUMMARY

Increasing the flexibility of energy systems as they undergo transformation driven by the trilemma of environmental policy, resilience, and economic growth, is an issue for both the UK and Brazil. In Brazil, increasing environmental concerns, electricity prices, and rising energy consumption influence the energy system and the technology mix within it. Meanwhile, a rapid deployment of variable renewable electricity generation, pressure to keep costs down for domestic and business consumers, and the political imperative of keeping the lights on, are drivers of the transformation in the UK.

Despite the clear differences between the countries, 'energy storage' (as a family of technologies) has the potential to help meet the challenges in both markets. The role of energy storage can cover wholesale energy services, renewables integration, transmission and distribution network support, commercial and industrial purposes, and domestic applications; whilst the technologies range from providing sub-second power to seasonal heat demand. By matching system needs to technology options we can guide priorities for innovation and policy. As examples:

- Large-scale electrical energy storage (>100 MWh) such as pumped hydro, compressed air, and liquid air, can integrate large-scale offshore renewables in the UK, and reduce transmission and generation infrastructure investment in Brazil.
- Electrochemical batteries and liquid air energy storage can integrate district-scale renewables in the UK, and enable providing sustainable electricity from variable renewables to remote communities in Brazil.
- Batteries and other electrical energy storage such as supercapacitors and fly-wheels, can be used for power system quality management such as voltage and frequency regulation.
- Many technologies can provide reserve power, according to the desired response time.
- For both countries, thermal energy storage could have an important role to play when connected with district heat networks or domestic and commercial heat pumps (in the UK), or with solar heating systems to provide hot water (in Brazil). Given that the future cooling demand can increase rapidly for space cooling, cold storage connected with solar cooling systems and integrated with cold waste could be deployed in the UK and Brazil.

However, many of the energy storage technologies are still being developed, with costs reducing and performance improving. At the same time, the markets through which value can be captured are not designed to reward energy storage, and regulatory and policy barriers exist that could delay large scale deployment.

This report presents opportunities for collaborative activities between the UK and Brazil in electrical and thermal energy storage innovation, which can reduce the risk and investment and maximise the value of energy storage technologies are reviewed in this report. In general, the UK has strong research and demonstration capabilities, whilst in Brazil there is an expanding energy sector with a need to strengthen the infrastructure and desire to consider the role of new technologies.

Although electrochemical batteries such as lithium-ion batteries, supercapacitors, lead-acid batteries are major research topics in both countries, the UK's research group has, also, published journal articles related to advanced energy storage and thermal energy storage including phase-change material and molten-salt storage.

For the research-level collaboration, the UK's universities have expertise in electrochemical energy storage (lithium-ion batteries, metal-air batteries, sodium-based batteries, supercapacitors, and flow batteries), thermal energy storage systems (PCM, and cryogenic energy storage) and energy system modelling and analysis. Research groups and universities in Brazil could benefit from the collaborative research activities.

- Electrochemical battery research for EVs and grid-scale applications
- Thermal energy storage, including the development of phase-change materials and thermodynamic processes.
- Energy system modelling and analysis to evaluate the role and value of energy storage across scales.

The major benefits of the collaborative demonstration projects are reducing costs and risks of a country, and increasing market opportunities by leveraging limited research capability and resources.

- Providing valuable lessons to Brazil for demonstration and deployment of energy storage from the UK's experiences
- New demonstration opportunities, including in off-grid or remote locations, where technologies being developed in the UK could be tested.

For the deployment of energy storage, policy makers and industry stakeholders in the UK and Brazil can collaborate to share the experiences that will improve the policy-making process.

- Dialogue between policy-makers and industry stakeholders in UK and Brazil on these experiences will improve the policy-making process.
- Manufacturing of energy storage systems requires some natural resources which are abundant in Brazil, and scarce in the UK.
- Energy storage manufacturers (UK) and energy providers (UK and Brazil) can collaborate to capture the maximum value of deployed energy storage in Brazil and the UK.
- A large deployment of energy storage technologies in the UK and Brazil will require end-of-use studies including re-use or recycling of energy storage technologies which are currently actively being studied in the UK.

Given that the UK is a leading country in energy storage innovation, and Brazil has a large energy market and resources, both countries can get benefits from the collaboration. Energy storage research communities in Brazil can learn advanced scientific findings from joint research projects. Energy storage developers and manufacturers in the UK will get economic benefits including cost reduction and securing rare earth. The collaboration between the UK and Brazil will be beneficial for both countries, and provide opportunities across the innovation process to open large global markets.

1 INTRODUCTION

Energy systems across the globe are being radically transformed by diverse drivers. Although the current conditions and future goals are country specific, these transformations stress the challenge of meeting simultaneous policy goals of environmental sustainability, supply security, and economic prosperity, known as the ‘energy trilemma’.

In Brazil, economic, environmental and social policy drivers are influencing the energy system and the technology mix within it. The factors include rising electricity prices (World Energy Council, 2015a), increasing environmental concerns, and supplying power to remote rural areas (Silva et al., 2010). Meanwhile, the UK is experiencing a rapid deployment of variable renewable electricity generation, reduced ‘firm’ generation capacity, and though electrical demand has been dropping, the expectation is for it to increase through the 2020s as heat and transport are electrified.

Energy storage has the potential to support the energy system in meeting these challenges, and so it is being selected by many countries and international organisations as a focus area for innovation.

Although Brazil built the world’s first reversible pumped-hydroelectric storage (5.3MW, then upgraded to 20MW (DOE, 2015)), no further commercial energy storage projects have been deployed in the country (DOE, 2015). Recently, however, the energy regulator ANEEL, has signalled an intent to support investigations into its potential (Spatuzza, 2016) . In 2013, the UK selected energy storage as one of the ‘Eight Great Technologies’ that support its science strengths and business capability, with the Government highlighting “the potential for delivering massive benefits – in terms of savings on UK energy spend, environmental benefits, economic growth and in enabling UK business to exploit these technologies internationally” (David Willetts, 2013). Following this, research funding has risen, with a number of publicly-funded demonstration activities put in place. Policy and regulatory bodies in the UK and EU are now looking seriously at how the widespread deployment of energy storage could be enabled, and what the consequences would be.

Elsewhere, in the United States, California has mandated energy storage capacity (1,325 MW) of three investor-owned utilities by 2020. France has also picked energy storage as one of the seven strategic goals from its Innovation 2030 Commission. Other nations such as Japan, Germany, Italy and South Korea are implementing policy and market mechanisms to support developing and deploying energy storage technologies.

It is becoming clear that for developing and deploying advanced energy technologies, international collaboration is essential not only to improve the technological performance and lower the cost, but also to identify the potential markets which are economically viable (Jennings et al., 2015). This report explores how the UK and Brazil could work together, to learn from experience, establish joint projects where there are complementary skills, and test new ideas or technologies.

This report is

- Section 2 describes the energy systems in the UK and Brazil, both from a historical perspective and considering how they may change under future scenarios;
- Section 3 assesses the current and potential applications for energy storage within these energy systems;
- Section 4 analyses the energy storage technology options that match against the applications; and

- Section 5 considers the opportunities for collaboration between the UK and Brazil, based on the preceding context.

Finally in Section 6, the conclusions are summarised with some proposed ‘Next steps’.

ACKNOWLEDGMENTS

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The work was informed by a workshop organised by ANEEL, the Brazilian electricity regulator, on 31 March 2016[1], and an energy storage mission to the UK by Brazilian energy sector stakeholders in February 2016, organised by the British Embassy in Brasilia.

We also wish to thank the UK Engineering and Physical Sciences Research Council (EPSRC) for financial support via grant EP/L019469/1 for the Energy SUPERSTORE Hub, which champions energy storage research within the UK and internationally.

[1] See http://www.aneel.gov.br/workshop-armazenamento.

2 ENERGY SYSTEMS IN THE UK AND BRAZIL

Brazil and the UK have significantly different geographical characteristics including land area (8,353,140 km^2 vs. 241,930 km^2 respectively), population density (24 people/km^2 vs. 267 people/km^2), and land-use (e.g. share of forest area is 59.3% vs. 12.9%) (Worldbank, 2016). Historical energy consumption trends and energy mixes are also different, but both countries are facing significant changes to future energy supply and consumption.

The key driver of energy transformation for the UK over the next 5 – 10 years is the deployment of renewables to reduce greenhouse-gas emissions from the electricity sector. However, the cost of energy supply to the consumer and the security of supply are increasingly important political considerations. For Brazil, there are other issues: securing electricity supply may increase environmental stresses on Amazon regions; climate change already causes more frequent drought that is reducing the capacity factor of hydroelectric power plants; and remote rural areas should have access to cheap and clean electricity (Almeida Prado Jr. et al., 2016).

Given the complexity of energy-related issues, accurately predicting future energy pathways is difficult (Pearson and Watson, 2012). However, we can use scenarios and models to explore a range of possible outcomes. We have studied four energy mixes for the UK and Brazil to evaluate the potential role of energy storage, though these are not 'desired' or 'predicted' pathways.

2.1 THE UNITED KINGDOM

2.1.1 CURRENT STATUS

The UK ranked 4th overall in the World Energy Council's energy trilemma index[2] (2015a), scoring highly for energy security, which has been improved due to a diversified electricity generation mix and higher than average dependence on domestically produced energy sources (World Energy Council, 2015b). However, relatively higher electricity price compared with other nations lowered energy equity. The per capita carbon emissions are 7tCO_2/year, more than the global average of 5.3 tCO_2/year; though the economy's emissions intensity is slightly lower at 0.21 kgCO_2/GDP, compared to a global average of 0.27 kgCO_2/GDP.

During the last four decades, three supply changes are notable (Figure 1). Firstly, the total primary energy supply has reduced, particularly since 2000. Secondly, although the total electricity generation was increasing until 2005, it started to reduce from 2007. And finally, whilst gas supply increased significantly after 1990 to replace coal generation, it has also declined recently. Since 2000 electricity generation from wind power has increased by 27.5 TWh (from 1 TWh in 2000) and PV by 2 TWh (from 1 GWh in 2000) in 2013. Electricity generated by biogas and municipal waste has been doubled during the same period.

[2] A measurement of energy security, energy equity and environmental sustainability (World Energy Council, 2015a) see https://www.worldenergy.org/data/trilemma-index/.

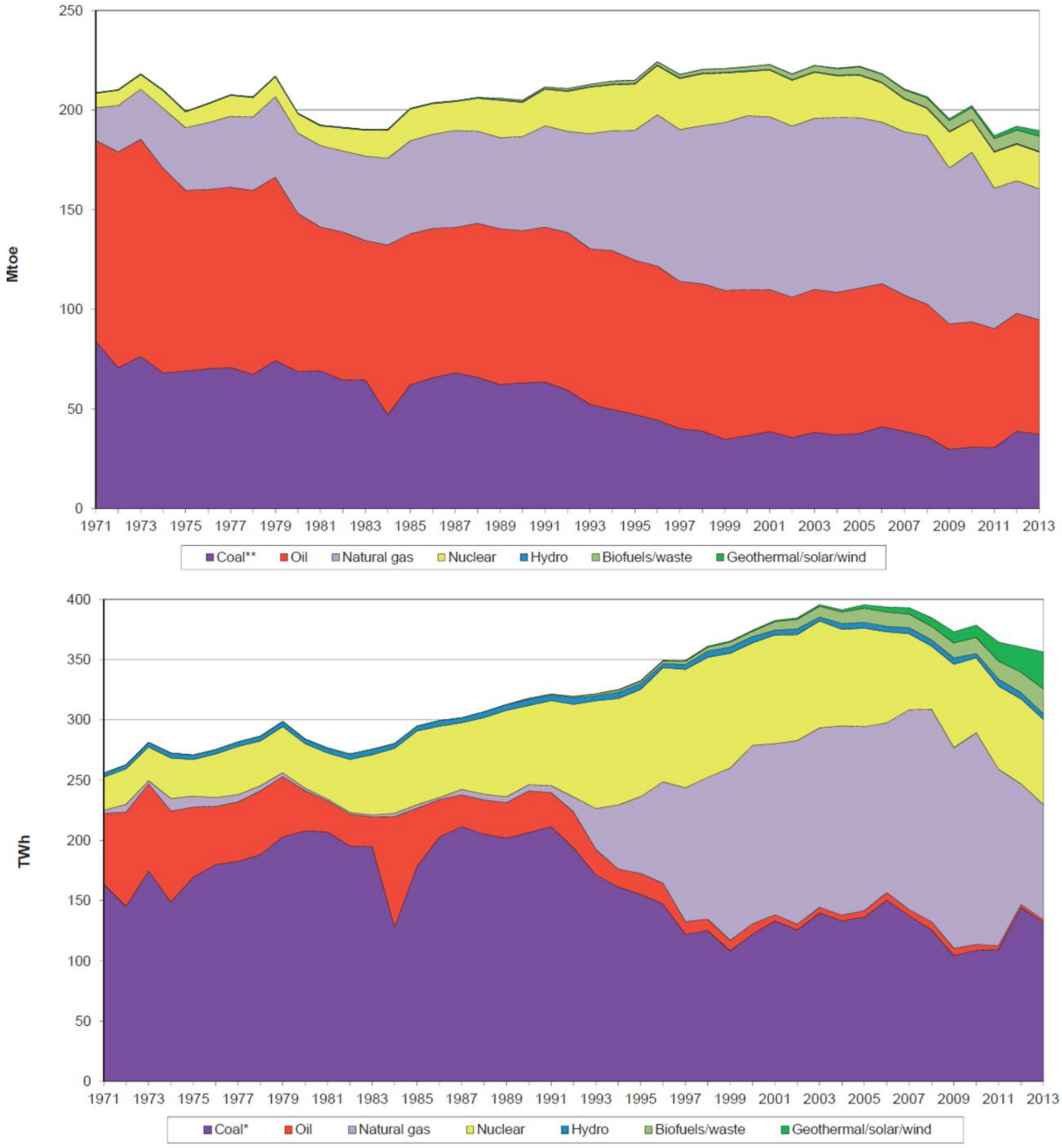

FIGURE 1 TOTAL PRIMARY ENERGY SUPPLY AND ELECTRICITY CONSUMPTION CHANGES IN THE UK FROM 1971 TO 2013 (IEA, 2016)

On the demand side, close to a half (48%, ~680 TWh) of the final energy consumption is for supplying heat, particularly space heating, during winter (Figure 2) (Chaudry et al., 2015). More than 80% of the heat demand is provided by gas-fired boilers connected to the national gas network. The transport sector share of the final energy consumption is 39%. Other consumption is from lighting and appliances (7%), cooling, and ventilation (1%), and computers and refrigerators (both less than 1%). Industrial electricity demand decreased slightly from 114 TWh to 98 TWh, while commercial demand increased from 90 TWh to 98 TWh since 2000. Residential demand has not been changed significantly (between 112 TWh and 113 TWh).

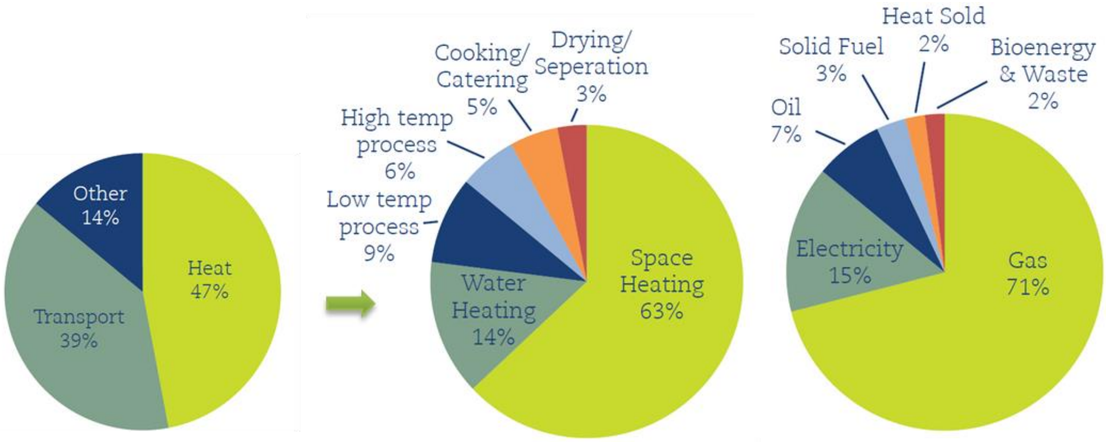

FIGURE 2 FINAL ENERGY CONSUMPTION BY END USE (LEFT), HEAT ENERGY CONSUMPTION BY PURPOSE, (CENTRE), AND BREAKDOWN BY FUEL OF TOTAL HEAT CONSUMPTION IN THE UK (RIGHT) (EAMES ET AL., 2014)

2.1.2 FUTURE PATHWAYS

The government has a nationally legislated target to reduce greenhouse-gas emissions by 80% by 2050 compared to 1990 levels; and from the EU for renewables to meet 15% of total energy demand by 2020, which translates into approximately 30% of electricity from renewable sources. The UK is facing a number of supply challenges, with coal-fired plants due to close by the mid-2020s and ageing nuclear power stations, whilst the proportion of electricity from variable renewable sources will continue to rise.

National Grid, the System Operator for electricity and gas grids in the UK, issues an annual report 'Future Energy Scenarios (FES): UK gas and electricity transmission' (National Grid, 2015). The latest report includes four scenarios including Gone Green (GG), Slow Progression (SP), No Progression (NP) and Consumer Power (CP). Although there are a number of other energy system scenarios for the UK, FES covers a sufficient range of possibilities.

Figure 3 presents the assumptions of Future Energy Scenarios by National Grid (National Grid, 2015). Gone Green expects moderated economic growth and strong environmentally friendly policies and renewable energy targets while technological growth and social acceptance are high. No Progression is the opposite pathway of Gone Green that included only limited technological growth, social acceptance, and environmentally friendly policies. Although the ambition toward greener future is high for Slow Progression, technological improvement is slower than Gone Green, and social choices for 'going green' are limited due to the limited economic possibility. Consumer Power does not have strong environmental policies or social engagement. However, consumerism and quality of life lead the behavioural changes and desire for environmentally friendly lifestyle.

FIGURE 3 POLITICAL, ECONOMIC, TECHNOLOGICAL, SOCIAL AND ENVIRONMENTAL ASPECTS ACCOUNTED IN NATIONAL GRID'S FUTURE ENERGY SCENARIOS (NATIONAL GRID, 2015)

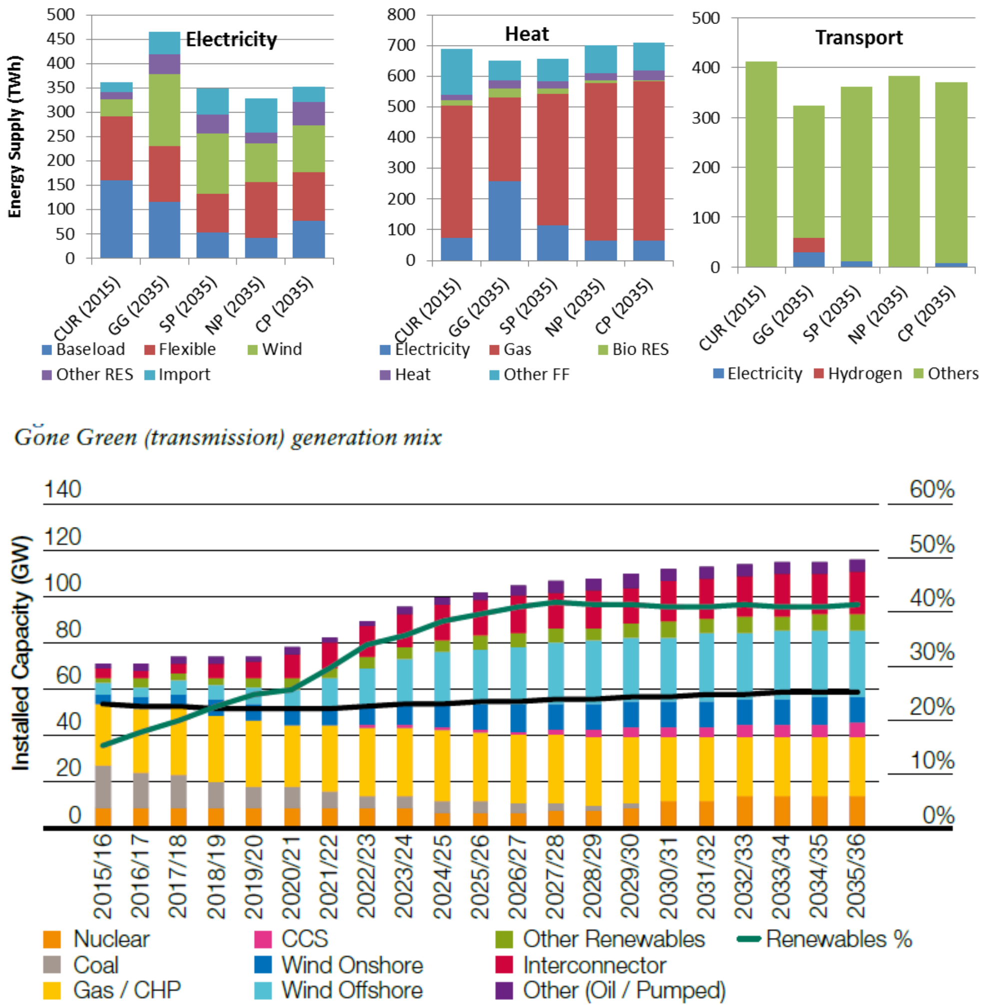

FIGURE 4 ENERGY MIXES OF THE UK IN 2035 (RESORTED BASED ON NATIONAL GRID'S FUTURE ENERGY SCENARIOS)

Figure 4 presents the energy consumption of electricity, heat and transport sectors which resort based on National Grid's Future Energy Scenarios. Electricity demand of Gone Green is the highest among the scenarios, due to the electrified heat and transport sectors. All the electricity scenarios predicted the reduced baseload generation and increased wind generation that will cause more flexibility issues to the grid. Heat pumps (both air and ground sourced) will be the major appliances of electrified heat supply. Although the supply share of electric and hydrogen vehicles is not significantly high, the consumption share is higher due to the high fuel efficiency of electric and hydrogen vehicles.

To support the delivery of its objectives, while minimising the cost to the consumer and maintaining the security of supply the UK government has implemented Electricity Market Reform (EMR) (Ofgem, 2014). The first round of the Capacity Market auctions for securing supply was completed in 2014 for selecting additional capacity to be in place by 2018. Contracts for Difference designed to incentivise new low-carbon generation technologies started in 2014. The UK government has also introduced a number of energy policies for reducing greenhouse-gas emissions from heat, including the Renewable Heat Incentive, the Green Deal, and other energy efficiency, microgeneration and bioenergy strategies. The success of these interventions has been variable (Chaudry et al., 2015; Eyre and Baruah, 2014) with the Green Deal now being replaced, though details are not yet known.

2.2 Brazil

2.2.1 Current status

Compared with the UK, Brazil recorded a lower trilemma index ranking (37th) by World Energy Council (2015a). Although environmental sustainability of the energy sector in Brazil is relatively higher (17th) than other indicators due to the high share of renewables including hydropower and bioenergy and their low greenhouse-gas emissions (1.54 tCO_2/toe), energy security and energy equity are at mid or low tables (ranked 48th and 78th in 2015, respectively).

During the last four decades, the total primary energy supply and electricity generation of Brazil has increased dramatically (Figure 5). The total primary energy supply increased from less than 75 Mtoe to almost 300 Mtoe, and the electricity generation increased from 50 TWh to 550 TWh during the period. Although the increased of oil and gas supplies is noticeable, 75% of the electricity consumption is provided by non-fossil fuel sources: 41% of the total primary energy is supplied from renewable sources, including bioenergy and hydropower, and non-fossil fuels such as nuclear power.

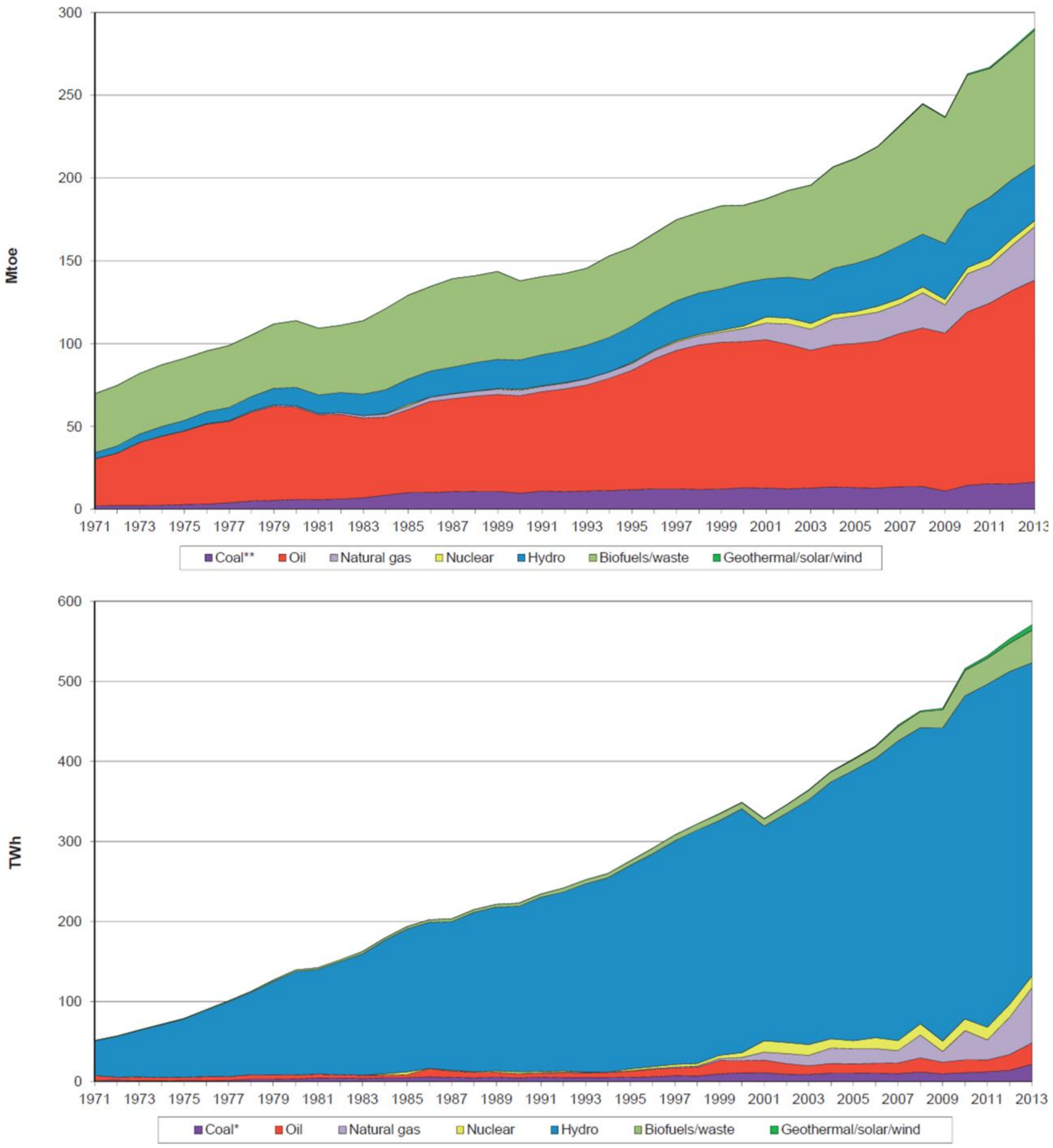

FIGURE 5 TOTAL PRIMARY ENERGY SUPPLY AND ELECTRICITY CONSUMPTION CHANGES IN BRAZIL FROM 1971 TO 2013 (IEA, 2016)

The transport sector consumes 36.5% of the total final energy consumption (228 Mtoe), and the industrial sector requires 36.1%. Other sectors including residential, commercial and public, and agricultural sectors consume only 20.5% of the total final energy. In Brazil, 74% of households use electric shower systems for heating water - about a quarter (24%, 32 TWh) of the residential electricity consumption. Air conditioning consumes about 20% of the residential energy demand (27 TWh), and a half of the commercial demand (66 TWh) (Melo et al., 2014; Sgarbi et al., 2014). The ten-year energy expansion plan of Brazil includes the renewable energy targets (Cabré et al., 2015). The plan aims to increase the renewable share of the total primary energy supply from 42.1% in 2014 to 42.5% in 2023. The renewable penetration of electricity generation will increase to 86.1% including 20 GW of wind power (8.1%).

The future large-scale hydropower production can be limited due to severe drought (Van Loon et al., 2016), environmental concerns (Almeida Prado Jr. et al., 2016; Faria et al., 2015) and other social and economic impacts (Fearnside, 2014; Kahn et al., 2014). In Brazil, about 300,000 communities (1.7% of National Interconnection System coverage) do not have access to traditional electricity grids and rely on diesel generators due to the lack of economic benefits of utility companies (Silva et al., 2010). Despite the significant potential of sustainable energy, current governmental policies are not sufficient for maximizing the use of sustainable sources except hydroelectric power (Luomi, 2014).

Expansion of Transfers between Subsystems (MWavg)

Stretch	MW promed	Year	Stretch	MW promed	Year
TP->SE/CO	2,120	2015	Imp. SUL	2,000	2020
AC/RO->SE/CO	150	2015	Exp. SUL	2,000	2020
Imp.->SE/CO	1,051	2016	Exp. NE	6,000	2020
Exp. NE	3,000	2016	Imp. NE	5,100	2020
Imp.->SE/CO via N/N	5,350	2016	Exp. SE via N/NE	3,730	2020
AC/RO->SE/CO	874	2016	Imp. SE via N/NE	6,000	2020
Imp. SUL	836	2017	AC/RO->SE/CO	700	2020
AC/RO->SE/CO	682	2017	Exp. SE via N/NE	4,600	2020
Imp. SE via N/NE	1,970	2018	Imp. SE via N/NE	8,120	2020
Imp. SUL	957	2018	T.PIRES/TP-⊠SE/CO	2,000	2020
Exp. SUL	874	2018	Imp. SE via N/NE	12,631	2022
T.PIRES/TP-⊠SE/CO	1,480	2018	T.PIRES/TP-⊠SE/CO	2,000	2022
AC/RO->SE/CO	129	2018	Imp. Sul	1,700	2023
Imp. SUL	983	2019	Exp. SUL	1,700	2023
Exp. SUL	1,269	2019	T.PIRES/TP-⊠SE/CO	2,000	2023
Exp. SE via N/NE	5,720	2019	T.PIRES/TP-⊠SE/CO	2,200	2024
Imp. SE via N/NE	7,501	2019			

Note: IMP: Imperatriz; AC: Acre; RO: Rondônia; MAN: Manaus; AP: Amapá; BM: Belo Monte; TP: Tapajós; Imp.: Imports; Exp.: Exports.

FIGURE 6 EXPANSION OF ELECTRICITY TRANSMISSION LINES BETWEEN REGIONS IN BRAZIL BETWEEN 2015 AND 2024 (MINISTRY OF MINES AND ENERGY, 2015)

In Brazil, South East and Midwest regions consume around 60% of the total electricity generation currently, and the structure is expected to remain until 2024 (Ministry of Mines and Energy, 2015). However, the majority of additional hydroelectric power projects are located in northern regions The discrepancy between the generation location and demand area requires a large expansion of transmission capacity from 125.7 thousand km in 2014 to 201.4 thousand km in 2024 (Figure 6).

2.2.2 FUTURE PATHWAYS

The Ministry of Mines and Energy of Brazil has published the electricity plan called 'Electricity in the 2024 Brazilian Energy Plan (PDE 2024)' in 2015 (Ministry of Mines and Energy, 2015). Together with the plan, three more scenarios (Current Policies, New Policies, and 450 Policies) produced by IEA are included (IEA, 2013). Current Policies includes the national energy efficiency plan introduced in 2011 to reduce electricity consumption by 10 % (106 TWh) compared with a reference scenario. New Policies also includes 36% GHG reduction targets by 2020, and a stronger energy efficiency plan. 450 Scenario assumes to reduce GHG emissions by 39% by 2020 and introduce carbon pricing by 2020.

According to the Brazilian government, the total primary energy production in Brazil will be doubled by 2024 compared with 2014, and the domestic supply will increase 33% (Gov 2025 in Figure 7). The total electricity consumption will grow from 531 TWh in 2014 to 791 TWh in 2024. The transmission and generation capacities will increase significantly while the isolated electricity network will be reduced. Currently, 41 GW of power plant capacities including 19 GW of large-scale power plants are contracted or being constructed, and additional 33 GW of capacity should be constructed between 2020 and 2024. The Brazilian government announced ProGD – Electrical Distributed Generation Program in December 2015 to provide 24.5 GW (48 TWh) of photovoltaic for 2.7 million customers.

Bioethanol and oil will be the main source of transport sector of Brazil. Bioethanol will provide 26% of the total transport fuel consumption for New Policies, 24% of Current Policies, and 50% of 450 Policies. Neither bioethanol nor oil is related to energy storage. None of the given scenarios describe heat-demand pathways explicitly.

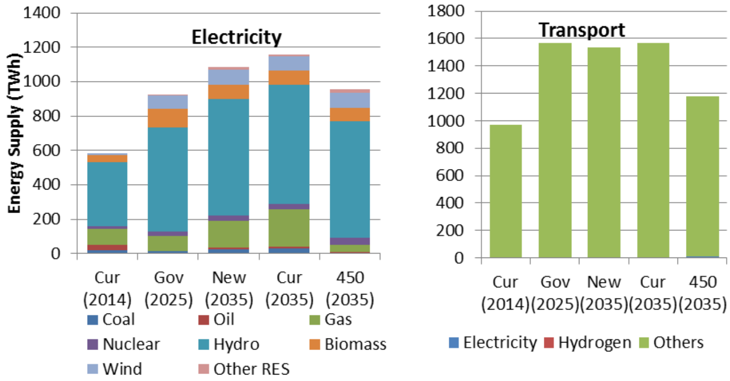

FIGURE 7 ENERGY MIXES IN 2025 (GOV) AND 2035 (OTHERS) BY THE BRAZILIAN GOVERNMENT (MINISTRY OF MINES AND ENERGY, 2015) AND IEA (IEA, 2013)

3 APPLICATIONS FOR ENERGY STORAGE

A number of studies have been published that estimate the future potential and the role of energy storage based on either technological characteristics or economic analysis (Carbon Trust, 2016; Deloitte, 2015; Sandia National Laboratories, 2013; Spataru et al., 2015). Based on the literature review, a number of energy services that energy storage can provide can be identified (Table 1) (Centre for Low Carbon Future, 2014). Energy storage can provide wholesale (bulk) energy services for centralised energy systems. Renewable energy systems can be integrated into the electricity grid smoothly by either large or small-scale energy storage. The investment in generation, transmission and distribution infrastructure can be delayed or reduced. Energy storage, also, can support the power quality and reliability of the electricity grid.

	Storage application	Description
Generation and system level	Wholesale energy services	Large centralised energy storage systems providing ancillary services and energy management
	Renewables Integration	Large centralised/decentralised energy storage systems allowing for time-shifting of renewable generation to match demand
Transmission Network	Storage for transmission & distribution network support	Storage systems that provide support or defer the need for transmission/distribution upgrades. Can be either stationary or portable
Distribution Network	Distributed energy storage	Energy storage embedded in the distribution network providing reliability to customers, easing transmission constraints and providing energy management on a smaller scale
	Power quality for commercial and industrial uses	Providing high-quality power for specialised applications and processes
	Backup and reliability for commercial and industrial uses	Backup power for specialised applications and processes
End users	Domestic energy storage	Small-scale energy storage systems providing backup, reliability, and time-shifting.

TABLE 1 ENERGY SERVICES AND APPLICATIONS THAT CAN BE PROVIDED BY ENERGY STORAGE (CENTRE FOR LOW CARBON FUTURE, 2014)

3.1 THE UNITED KINGDOM

A group from Imperial College London has published reports on estimating the value of energy storage by different market and operation conditions in the UK (Carbon Trust, 2016; Strbac et al., 2015). Their analysis has found that the economic value of energy storage could be around £2.4 billion annually by 2030. Some market and policy regulatory decisions are required to maximise the value of energy storage including aligning incentives and removing barriers, monetising system benefits, reducing policy uncertainties, demonstrating cost and performance of energy storage, and defining the performance and operating standards of energy storage.

3.1.1 ELECTRICAL STORAGE

Due to the high penetration of variable renewables and increasing electrification of demand, National Grid's 'Gone Green' scenario provides more opportunities for energy storage compared with the other scenarios. Under other scenarios bulk energy storage will not be significantly more important than the current system.

However, all scenarios show that providing energy services for dealing with the flexibility of a future electricity network (ancillary services and renewable integration services) will be more important than at present. Increasing bulk energy storage (pumped hydro storage and CAES) in the UK is limited due to geographical constraints. The additional realisable potential of pumped hydro storage has been estimated to be up to 106 GWh when 10km is allowed between upper and lower reservoirs, or up to 4.3 GWh for 5km separation (Gimeno-Gutiérrez and Lacal-Arántegui, 2015), compared to the existing 28GWh. Currently, there are two key markets for ancillary services in the UK which are Short-Term Operating Response (STOR, 1.7 ~ GW daily) and Firm Frequency Response (FFR, ~ 3.5 GW daily) (Curtis, 2015; Lau et al., 2015). Both STOR and FFR are expected to increase to deal with increasing intermittent sources in the UK (Taylor et al., 2012).

Analysis has found that energy storage with 10% of wind power capacity can provide an economic solution to integrating wind power into the grid, while maintaining a certain level of output frequency (Johnston et al., 2015). If scaled-up across all wind power plants in the UK, this would represent 5 GW of additional energy storage. Although other responsive generation options such as diesel generators can also provide frequency regulation services, energy storage can shift the load output of intermittent renewables based on market prices.

3.1.2 Thermal storage[3]

Although there are some pilot and demonstration projects for various thermal energy storage, hot-water tanks are the major thermal energy storage widely applied in the UK (Palmer and Cooper, 2013). 13.96 million hot-water tanks are deployed for domestic use in 27.42 million dwellings. The total number of hot-water tanks has been decreasing due to the rise of combi-boilers. 1,781 GWh of heat consumption is supplied from active solar heating systems, and 652 GWh is supplied from heat pumps.

In the UK, of all heat supply for industrial consumption, 48 TWh/yr is rejected with 11 TWh/yr that could be technically recovered, and 5 TWh/y could be economically viable (Elementenergy, 2014). Thermal energy storage would reduce peak heat demand during winter (through seasonal storage), and shift heat load during peak hours to off-peak hours (through diurnal storage). However, seasonal thermal energy storage is unlikely to be deployed widely in the UK, because of the large space requirements needed close to demand.

The electricity demand for heating in 2035 could reach between 65 TWh/y (in No Progression) and 258 TWh/y in 2035 (in Gone Green). Such an increase in winter demand, led by low carbon heating systems including heat pumps, could provide an opportunity for the deployment of small-scale thermal energy storage. Shifting peak electricity demand away from peak heating demand with thermal energy storage can reduce the need for generation capacity, and reduce pressure on the power grid at national and local networks.

3.2 Brazil

3.2.1 Electrical storage

The Brazilian government plans to build additional 11 hydroelectric plants (12 GW) on the top of six plants (19 GW) under construction. These may have environmental and social impacts (Kahn et al., 2014; Winemiller et al., 2016), including with Brazil's new commitment from COP 21 targeting to restore 3.28 million hectares of degraded lands (Padovezi, 2015).

[3] In this section, only thermal energy storage for thermal output is discussed.

Due to the large expansion of generation capacity in Brazil, energy storage can be used to defer reinforcement, or reduce the stress, on the national grid. New electricity storage technologies could reduce the need for additional hydropower capacity and when connected with clean, renewable energy sources could also provide sustainable energy for remote rural areas, replacing diesel consumption (Arabkoohsar et al., 2015) .

Retrofitting conventional hydroelectric plants to pumped hydro storage for mitigating seasonal and daily variation could have a number of benefits such as increasing energy efficiency, shifting electricity production from wet to dry seasons, mitigating the impact of severe drought, reducing backup capacity (biomass and gas), and integrating renewable energy sources (Hunt et al., 2014; IEA, 2013).

About 5 - 10 GW over 8 hours of bulk energy storage, which is about a half level between the peak and lowest electricity load, could be employed to shift daily electricity peak or seasonal electricity generation. Energy storage can reduce the need for peaking fossil-fuel based power plants. Reduced capacity of large-scale hydroelectric power plants will directly affect the required additional transmission capacity in Brazil.

The ancillary service requirement depends on the share of intermittent sources and system load (Vogler-Finck and Früh, 2015). On the assumption that 5% of reserve margin compared with average load is required for the Brazilian electricity grid, about 8.5 GW of load could be used for reserve. However, due to the high share of hydroelectric power in Brazil, energy storage is likely to have a more limited role to play in this application.

Given that the future wind capacity could be seven times higher than the current, the role of energy storage for renewable integration will become more important. The Brazilian distributed generation program is aiming to deploy 24.5 GW of solar photovoltaics (PV) which may benefit from additional electricity storage (Lopez, 2015). The optimal size of energy storage for PV depends on installed conditions, such as irradiation, daily load pattern, grid connectivity, and the size of the distributed networks. However, it seems likely that increasing distributed generation will provide deployment opportunities to energy storage.

3.2.2 Thermal storage

In Brazil, 74% of households use electric shower systems for heating water - 24% (32 TWh) of the residential electricity consumption and responsible for 18% of peak demand. Air conditioning consumes about 20% of the residential electricity demand (27 TWh), and a half of the commercial demand (66 TWh) (Melo et al., 2014; Sgarbi et al., 2014). Despite the large potential of solar energy, the share of solar thermal energy for heating water, and space heating and cooling is not widely deployed (Naspolini et al., 2010). Solar heating systems with thermal energy storage could replace electricity demand for hot water and space heating. The required thermal storage capacity will be different by the consumption patterns, but typically require about 0.5 kWh.

Air conditioning for a commercial building can be transformed into solar cooling systems coupled with hot and cold storage (Otanicar et al., 2012; Pintaldi et al., 2015). Energy storage capacity for solar cooling systems cannot be defined simply by the energy requirement. However given that energy consumption for air conditioning in Brazil will increase (Sivak, 2009), increased thermal (both heat and cold) storage could help to reduce peak electricity consumption.

4 ENERGY STORAGE TECHNOLOGIES

Energy storage technologies can provide various services by their technological and economic characteristics (Figure 8). Different scales are suitable for different applications, with very large scale technology options more suitable for centralised storage facilities providing energy management, or for the storage of large amounts of renewable energy. Smaller scale facilities can be used in distribution networks, providing support for districts of the distribution network or even for individual houses.

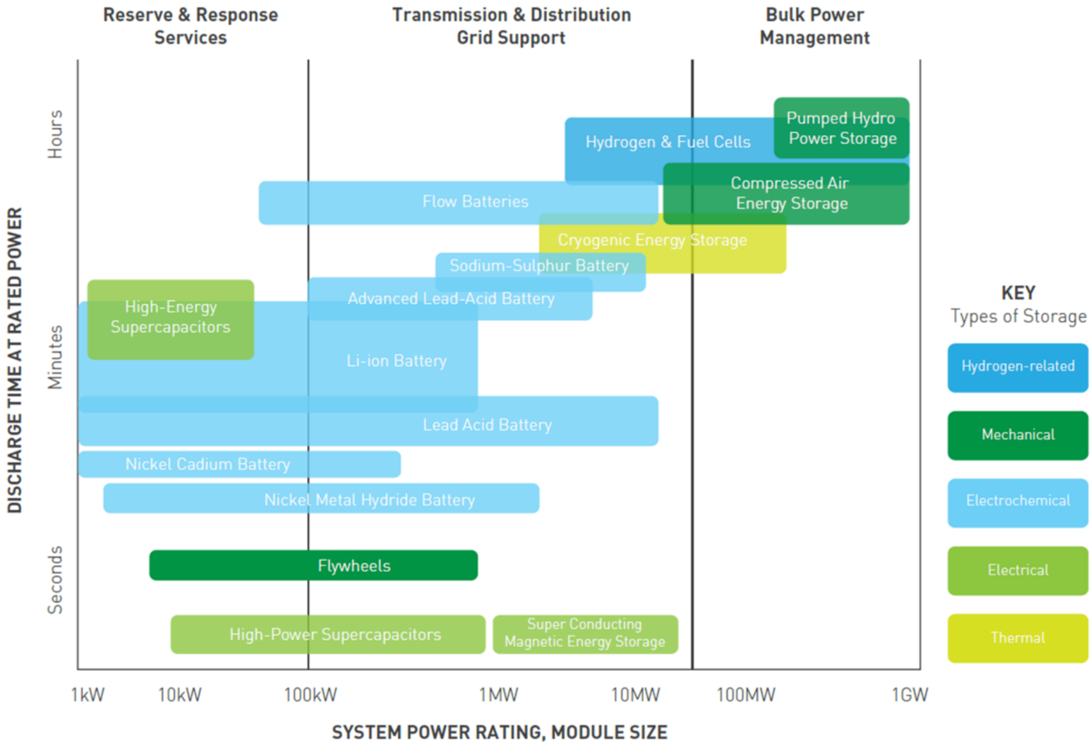

FIGURE 8 ENERGY STORAGE TECHNOLOGIES ACCORDING TO THEIR POWER RATING AND DISCHARGE TIME (CENTRE FOR LOW CARBON FUTURE, 2014)

As described above, existing electricity storage in UK and Brazil is dominated by pumped hydro storage, with 2.8 GW and 20 MW deployed respectively. Non-PHS electricity storage is mostly electrochemical battery demonstrators, with approximately 25 MW in the UK. New energy storage technologies have seen recent rapid decreases in cost and improvements in performance, but there is wide uncertainty as to future developments. Understanding the current state-of-the-art and research direction of energy storage can reduce these uncertainties.

Most energy storage technologies will experience significant technological and economic improvement during next decades. Figure 9 presents the future cost projection of lithium-ion batteries and liquid-air energy storage compared with currently widely accepted large-scale energy storage (PHS) and small-scale energy storage (Pb-acid batteries). The prospect of energy storage technologies following similar cost-reduction curves to solar PV would have a profound impact, but it is not clear that this would be the case in reality. Scaling-up of grid-scale battery manufacturing would be challenged by resource availability, competing applications, and the complexity of the manufacturing process (Ghadbeigi et al., 2015).

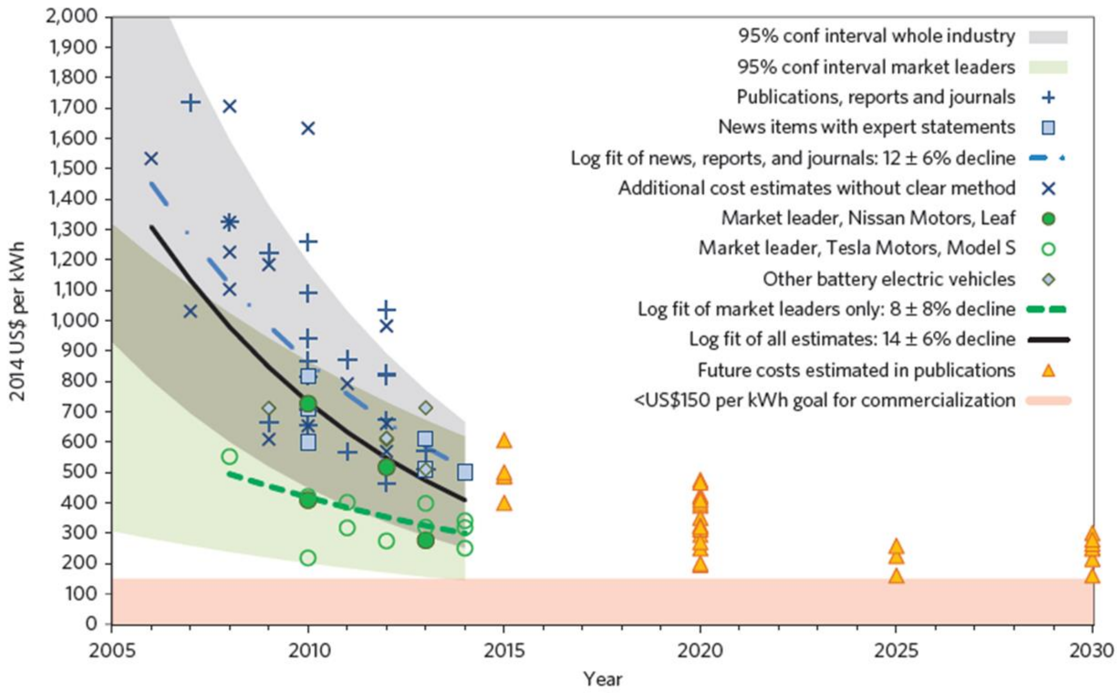

FIGURE 9 COST OF LITHIUM-ION BATTERY PACKS IN BEV (NYKVIST AND NILSSON, 2015)

4.1 LARGE-SCALE ELECTRICITY STORAGE (>100 MW)

Large-scale energy storage can reduce the additional capacity of hydroelectric and gas plants while providing other services, and minimise environmental impacts. Apart from pumped-hydro storage, technologies which can be applied at similarly large scales are:

- Compressed air energy storage (CAES): Air is compressed and stored either underground in caverns, or in high-pressure containers, at off-peak times. When required the expanding gas is used in a conventional gas-turbine.
- Liquid air/cryogenic energy storage (LAES): Off-peak electricity liquefies the air, which is stored at atmospheric pressure as a cryogenic. By using ambient or waste heat, the liquid is vapourised, and the expansion to the gas phase turns a turbine to generate electricity (Morgan et al., 2015).

An advantage of these technologies is the decoupling of stored energy from power generation capacity: increasing amounts of energy can be stored at relatively low cost, by expanding the reservoir or container size without affecting the more expensive electricity generation process.

Currently, large-scale CAES with rated power of 330 MW and discharge duration of 6 hours at the rated power output is being planned and constructed in Northern Ireland (Gaelctric, 2015).

At scale, LAES could also be an option for minimising environmental impacts, and avoiding geological limitations. A 5MW LAES pre-commercial demonstrator is being built by Highview Power Storage near Manchester in the UK, with a conceptual 200MW/1.2GWh having been showcased.

Although a hydrogen-based energy system also can provide the energy services for large-scale electricity networks, it requires an intensive investment in infrastructure for hydrogen production, distribution, and consumption and embeds environmental impacts during hydrogen production processes (Dincer, 2012).

In Brazil, large-scale energy storage could be used to defer the large transmission expansion by shaping peak consumption. The key role of energy storage for reducing and deferring the transmission expansion is that a relatively modest energy storage capacity can be installed to support a very small portion of peak demand. The lifespan of transmission equipment can be extended by avoiding the maximum load band, and the transmission charge can be reduced by reducing transmission use during the peak periods (Eyer et al., 2005).

With a large expansion of offshore wind power in the UK, large-scale energy storage could have an important role to play in integrating renewables into the national grid.

4.2 District-scale electricity storage (10kW ~ 100MW)

Energy storage for distributed electricity networks needs to be selected by characteristics such as the total electricity consumption and daily load patterns on the network. The key technology options are:

- Lithium-ion batteries (LiB): Dominant battery in small portable applications due to high energy density, light-weight and high efficiencies; the large-scale development and manufacturing of LiBs for the EV market has increased their use in stationary applications, but they remain expensive with limited lifetime (Centre for Low Carbon Future, 2014).
- Lead-acid batteries: Commercially mature re-chargeable batteries, used as DC auxiliary, and suitable for power quality, UPS and spinning reserve applications; but low lifecycle and energy density compared with other elector-chemical batteries (Centre for Low Carbon Future, 2014)
- Flow batteries: Flow batteries can release energy continuously at a high rate of discharge. Three main different electrolytes that form the basis of existing designs currently in demonstration or in large-scale project development. Electrolytes are stored in external tanks, decoupling power and energy (Centre for Low Carbon Future, 2014; Taylor et al., 2012).
- Liquid air energy storage: as above.

Small-scale renewable energy systems coupled with energy storage may be able to provide economically viable electricity options for remote communities in Brazil and the UK (Corrêa da Silva et al., 2016; Manchester et al., 2015).

In Brazil, there is significant distributed capacity relying on diesel generators used during peak hours by businesses and industries connected to medium voltage networks. In early 2015 this distributed generation capacity was targeted by a public call (Portaria MME no. 44/2015) and invited to provide energy to the National Interconnected System (SIN, in Portuguese). ANEEL regulated this option through Resolução Normativa no. 690/2015. Storage, such as electrochemical batteries (for smaller communities, < 10s MW) and liquid-air energy storage (for larger communities, 1s MW - 100s MW) coupled with renewable energy sources such as wind or photovoltaic, may be an option to replace these diesel generators with benefits.

In addition to the traditional application of energy storage, seasonal events such as Carnival and summer destinations and mega-sporting events could be potential markets that energy storage can reduce the capacity and electricity consumption. However, the economic viability and the value of energy storage compared with other approaches would need to be carefully evaluated.

4.3 Domestic-scale electricity storage (< 10 kW)

Electrochemical batteries are also being marketed to domestic users. For example, Tesla's Powerwall™ which is a lithium-ion battery (Tesla, 2016) and the Maslow system from Moixa in the UK (Moixa, 2016). They can be connected with photovoltaic to provide stable electricity and off-grid opportunities to a house. However, the system costs ($3,500 for a 6.4kWh Powerwall unit), and installation costs make a challenging economic case in markets where the variability of consumer electricity costs is low, and there is a limited supply of low-cost distributed generation.

4.4 Ancillary services (fast response)

Ancillary services, reconciling the differences between generation and demand, require a system that can provide or draw electricity in second, or sub-second timescales. The frequency of an electricity grid needs to be maintained within a certain range by controlling the difference between generation and load. Similar to frequency regulation, the voltage of a grid also should be maintained within a certain range. Energy storage systems can supply electricity if some electricity generation capacity is not available unexpectedly; or act as a source of demand in the case of over-generation. The main technology options are:

- Flywheels: Grid-scale flywheels have very short response time to reach the rated power output (< seconds). Although flywheels have long lifetimes and power density, a huge self-discharge rate is a major disadvantage (Andrade et al., 2007; Centre for Low Carbon Future, 2014).
- Supercapacitors: Lower energy density, but higher power density than batteries, often combined in hybrid systems. Supercapacitors store or deliver energy at a high rate, but have limited storage capacity when compared with most batteries (Centre for Low Carbon Future, 2014).
- Superconducting magnetic energy storage (SMES): stores electrical energy in the magnetic field. A continuously circulating current within the superconducting coil produces the stored energy. Due to the lack of energy transformation processes, the energy efficiency is very high (Taylor et al., 2012).
- Electrochemical batteries: as described above.

4.5 Thermal storage

Thermal energy storage (TES) stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time. The storage medium is a crucial item for any thermal energy storage technologies as it determines the heat capacity and heat exchange method. There are three approaches for the storage medium: (Radcliffe and Li, 2015)

- Sensible thermal storage materials store thermal energy by raising (heat storage) or reducing (cold storage) their temperature. They can be solid (like concrete) or liquid (like water) and tend to be cheap, though the amount of energy stored in a given volume is limited.
- Phase-change materials (PCMs) store more energy by heating a material which melts or boils (changes phase) at a specific 'transition' temperature. A number of such materials have been developed and deployed, but it is still an area of active research.

- Thermo-chemical materials (TCM) store large quantities of energy by means of chemical reactions which give off or soak up heat. The development of reversible thermo-chemical storage is still at a very early stage.

4.5.1 Heat

As with electrical energy storage, the TES applications for heat are varied:

- Large-scale seasonal thermal energy storage: Inter-seasonal storage systems can be applied to match the difference between seasonal energy production from renewable energy sources such as solar heating systems and seasonal heat demand which are higher during winter. This system can be integrated with heat pumps to provide higher heat pump efficiency (Eames et al., 2014).
- Tank thermal energy storage: Water is the storage medium. Pimlico in London has tank thermal energy storage for short term balancing (2,500 m^3 for 3256 houses, 50 businesses, and three schools). The seasonal balancing system is installed at Friedrichshafen in Germany (12,000 m^3 for 390 houses) (Eames et al., 2014).
- Pit thermal energy storage: Water and gravel water can be used as storage medium. Demark has a number of large-scale pit thermal energy storage (75,000 m^3 in Marstel) (Eames et al., 2014).
- Borehole thermal energy storage: Thermal energy can be injected into the ground through boreholes if appropriate geological conditions are provided. Such systems are often combined with heat pumps for buildings and houses (Eames et al., 2014).
- Aquifer thermal energy storage: If aquifers exist and geologically stable, thermal energy can be stored by injecting heated water. However, this system can cause geological changes and mineral dissolution. Due to the restriction of water temperature, the energy density is lower than the tank systems (Eames et al., 2014; Radcliffe and Li, 2015). Due to the lack of insulation, the heat loss is higher than the tank systems.

For both Brazil and the UK, TES has significant deployment potential. In Brazil especially, TES technologies can be used to store solar thermal energy for heating water either directly, or indirectly through another storage medium (such as phase-change materials). In the UK, the energy input may come from electrical heat pumps or resistive heating when demand is low, or there is excess generation. This household-scale application can shift electrical load for water heating away from peak demand times.

In the UK, the opportunities for large-scale seasonal thermal energy storage are limited compared with Brazil due to the limited land area for thermal storage installation close to demand areas, low solar irradiation, and largely established gas networks for heating. However, if the heat sector is electrified by deploying heat pumps, domestic or building-scale thermal energy storage can be deployed to increase the energy efficiency of heat pumps. An average house using a heat pump will need between 500L (with PCM) and 1000L of a hot water tank which is about 10 kWh (Arteconi et al., 2013; Kelly et al., 2014).

If community-scale district heating is established, large-scale sensible TES can be installed for intra-day use, or over seasonal times scales (Gadd and Werner, 2015). PCM and thermochemical energy storage that require further studies on material and fundamental sciences could reduce the footprint and increase the efficiency of systems.

4.5.2 COLD

Worldwide energy demand for space cooling will overtake space heating by 2060, and outstrip it by 60% at the end of the century, as cooling demand in the developing countries of the global south grows faster than heating demand in the developed northern economies (Figure **10**) (Birmingham Energy Institute, 2015).

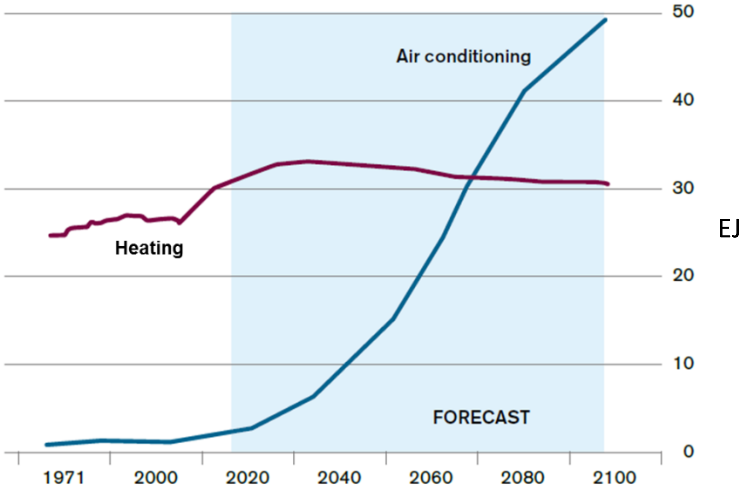

FIGURE 10 **WORLDWIDE FORECAST ENERGY DEMAND FOR SPACE HEATING AND SPACE COOLING (EXAJOULES) (ISAAC AND VAN VUUREN, 2009)**

Currently, the demand for refrigeration and air conditioning is about 16% of the total UK electricity demand. If about a half of the cold waste generated during the re-gasification of liquefied natural gas (LNG) in the UK was recycled, the total amount of recycled coolth is about 20 TWh (22% of the total cooling demand).

In Brazil, the future cooling demand is expected to increase due to economic growth and global warming (Shah et al., 2015). Increasing air-conditioning demand will increase the peak electricity demand during a hot day. Thermal energy storage, particularly PCM, linked with solar thermal collectors or PV could be able to provide clean cooling while reducing the peak consumption during a hot day (Osterman et al., 2012).

4.6 SUMMARY

Table 2 summarises the applications of energy storage for the UK and Brazil, and appropriate energy storage technologies for each application.

TABLE 2 APPLICATIONS OF ENERGY STORAGE AND POSSIBLE TECHNOLOGIES IN THE UK AND BRAZIL

Applications	UK Application (potential)		Brazil Application (potential)		Technologies
Electricity storage					
Large (>100MW)	Integrating large-scale offshore renewables	*H*	Transmission infrastructure deferral	*H*	PHS, CAES, LAES
	Transmission congestion relief	*M*	Generation capacity reduction	*H*	
District (10 kW - 100 MW)	Distributed grid	*M*	Remote communities	*H*	Batteries (small), LAES (large)
	Integrating district-scale renewables	*H*	Distributed PV networks	*H*	
Small (< 10 kW)	Integrating roof-top PV	*H*	Integrating roof-top PV	*M*	Batteries
Ancillary	Power output quality (voltage and frequency)	*H*	Power output quality (voltage and frequency)	*L*	SMES, Batteries, Supercapacitors, Flywheels
	Spinning and non-spinning reserve	*H*	Spinning and non-spinning reserve	*L*	PHS, CAES, LAES, Batteries
Thermal storage					
Heat	District heat network	*M*	Solar heating for hot water	*H*	Sensible, Latent, Thermochemical
	Heat pumps	*H*			
Cold	Integrating cold waste	*M*	Integrating cold waste	*M*	
	Solar cooling	L	Solar cooling	*M*	

5 COLLABORATION OPPORTUNITIES

5.1 RESEARCH

5.1.1 CAPABILITY

The research capability of the UK and Brazilian universities has been assessed by comparing the number of journal articles published between 2000 and 2015. The Web of Science Database was used to identify journal articles related to energy storage technologies (Thomson Reuters, 2016). Along with these publications, the major public sector investments related to grid energy storage were identified in the UK (EPSRC, 2016).

The total number of publications related to energy storage technologies between 2010 and 2015 is 574 in the UK and 93 in Brazil (Figure 11). The research capabilities of both countries are focused on electrochemical batteries such as lithium-ion batteries, supercapacitors, lead-acid batteries. Compared to Brazil, the UK has, also, published journal articles related to advanced energy storage including lithium-sulphur batteries, sodium-based batteries, and flywheels. The UK's research groups actively studied thermal energy storage such as phase-change material and molten-salt storage.

Overall, in terms of the number of publications of each energy storage technology, the UK institutes generally have more experience and diverse research interests compared with the Brazilian universities.

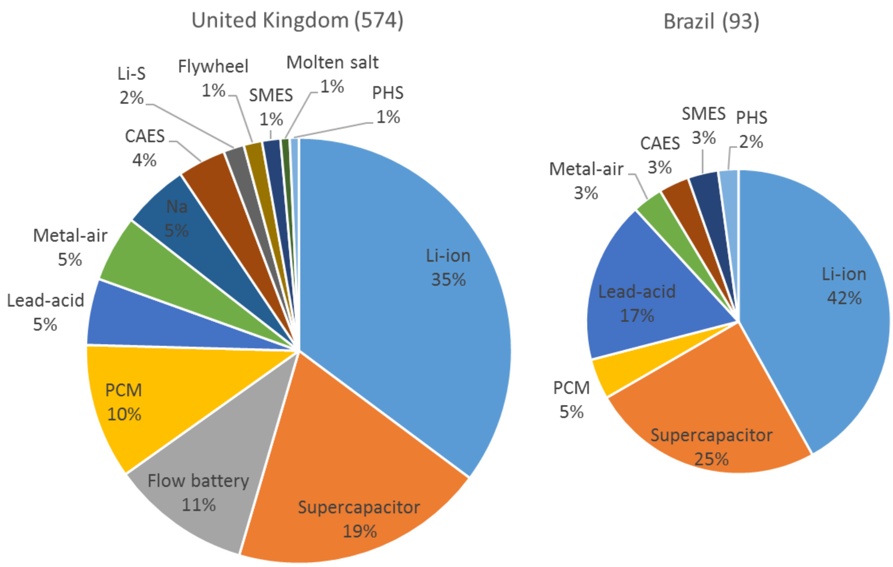

FIGURE 11 THE CUMULATIVE NUMBER OF PUBLICATIONS BY ENERGY STORAGE TECHNOLOGY (EXCLUDING POLICY AND MARKET ASPECTS) OF THE UK (LEFT) AND BRAZIL (RIGHT) BETWEEN 2010 AND 2015

In <u>electrochemical energy storage</u> UK universities have expertise in areas including lithium-ion batteries, metal-air batteries, sodium-based batteries, supercapacitors, and flow batteries. The University of Cambridge, Imperial College London, the University of Southampton, the University of Nottingham and the University of Oxford are leading the research for grid and transport purposes, In thermal energy storage, UK research groups focus on material development with improved thermal performance (Brandon et al., 2016). The University of Birmingham, the University of Nottingham, and the University of Warwick have expertise in phase change materials (PCM).

The UK Government recently funded £30m of university-based energy storage facilities under its 'Eight Great Technologies' call (Figure 12) (EPSRC, 2016). As part of these projects, energy storage pilot plants have been installed, covering electrochemical batteries, liquid air, and thermal energy storage. A new project Manifest[4], led by the University of Birmingham, will integrate these projects

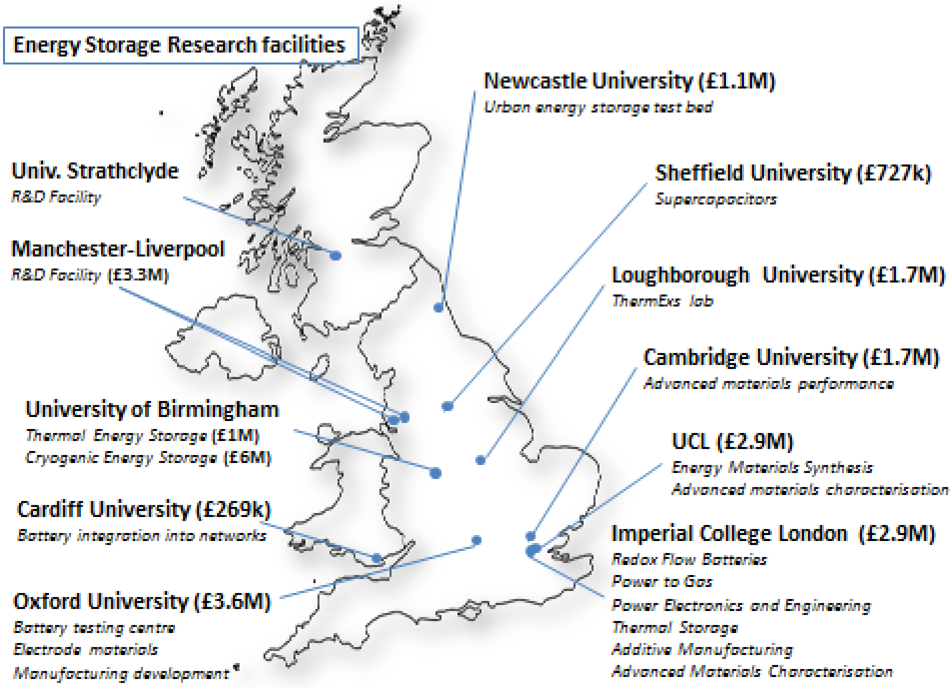

FIGURE 12 MAJOR PUBLIC-SECTOR INVESTMENTS IN ENERGY STORAGE RESEARCH FACILITIES IN THE UK (SOURCE: ENERGY STORAGE RESEARCH NETWORK)

Brazil has a limited research experience on some electric energy storage such as lead-acid and lithium-ion batteries, and supercapacitors, and thermal energy storage materials such as phase-change material. Most of the advanced energy storage technologies including lithium-sulphur, sodium-based and flow batteries and thermal energy storage technologies are not visible. The University of Campinas, the University of São Paulo, the Federal University of São Carlos and the Federal University of Minas Gerais published the most highly in the area. The University of Campinas is actively studying phase-change material, and the other universities are mostly focusing on electric energy storage (Figure 13). More granularity of capability in Brazil is given in Appendix III.

[4] See http://gtr.rcuk.ac.uk/projects?ref=EP/N032888/1.

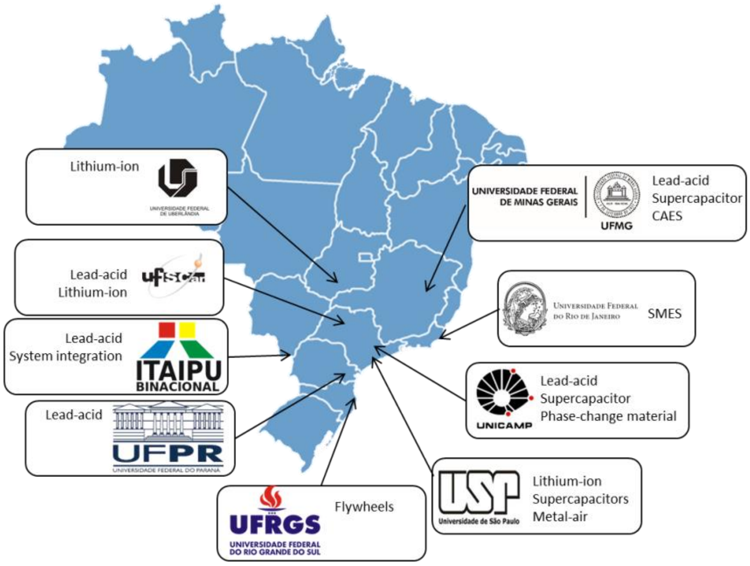

FIGURE 13 RESEARCH CAPABILITIES AND INSTITUTES ON ENERGY STORAGE IN BRAZIL

5.1.2 Drivers and barriers

The main drivers of research collaboration are knowledge sharing, cost reduction, and investment risk reductions in advanced technologies (IEA, 2015). It also provides the technology and scientific knowledge transfer opportunities from one country to another which can lead to economic growth of both countries (Lema and Lema, 2012). The different level of research capability and experience between the UK and Brazil will lead the technology transfer from the UK and Brazil. The changing market capacity of the UK and demand growth in Brazil encourages the technology drivers. The expansion of the science community networks will encourage creativity and collaborative activities to breakthrough common global challenges. The costs and facilities for high-risk early-stage projects, and natural resources such as scarce materials, can be shared between countries. Targeted research funding opportunities for early stage topics such as fundamental material science can help overcome barriers to collaboration.

5.1.3 Opportunities and activities

The main collaborative activities during the research and development periods of energy storage are sharing scientific understandings between universities and research centres in the UK and Brazil.

For more effective collaborative research activities, the high-level intergovernmental agreement between the UK and Brazil, cooperation programmes and research programmes need to be established (Jennings et al., 2015). Although some private funding bodies can be involved, public funding bodies such as governments and research councils provide the majority of research funding.

Currently, an energy storage roadmap for the UK is being developed by the University of Birmingham for the Supergen Hub. The experience can be shared to understand technologies that can provide and benefits from the collaboration between two parties. The potential technologies, research groups, and collaboration pathways should be identified and clearly defined in the research roadmap. Research capability including research outcomes, topics and funding opportunities should be analysed to identify the institutes that can make synergy.

International conferences and workshops for sharing findings, and identifying more collaboration opportunities are vital to the success of the early stage collaboration. Exchanging researchers and students between the UK and Brazilian universities are also an effective way for improving understanding each countries research needs and opportunities (Bordons et al., 2014).

5.2 Demonstration

5.2.1 Drivers and opportunities

Demonstrating energy storage technologies require investment to evaluate the feasibility of new technologies (Bossink, 2014). International collaboration can help to reduce costs and risks of a country, and increase market opportunities by leveraging limited research and natural resources (Jennings et al., 2015).

In particular, electricity storage on distributed networks and thermal energy storage benefits from demonstration projects and feasibility studies to de-risk further investment by assessing technology performance, gaining experience of operational challenges (including regulatory barriers), and quantifying market value. The UK has much experience of establishing and reporting on demonstration projects for new energy storage technologies, including electrochemical batteries, and liquid-air energy storage. Brazil can provide additional markets and the demonstration opportunities. In the long term, secondary life lithium-ion batteries from electric vehicles can be deployed for grid purposes in remote areas economically (Duan et al., 2013, p.).

5.2.2 Opportunities and activities

The major demonstration activities in the UK (Table 3) have been funded through the Low Carbon Network Fund (managed by Ofgem) and the innovation programme of the Department of Energy and Climate Change (DOE, 2015). The Gaelectric Compressed Air Energy Storage is being constructed in Northern Ireland funded by European Commission through European Project of Common Interest (PCI).

Some other smart city projects in the UK implemented energy storage (stationary energy storage or electric vehicles) and heat pumps (DECC, 2013). The representative projects are the Milton Keynes Smart Project led by the Open University (MK: Smart, 2016), Low Carbon London led by UK Power Networks (UK Power Networks, 2014) and Thames Valley Vision led by Ofgem (Thames Valley Vision, 2016) which are explained in Appendix IV.

Further potential demonstration sites in the UK and Brazil need to be identified and profiled. Particularly, cryogenic energy storage and flow batteries which are suitable energy storage for remote areas in Brazil require large-scale demonstration projects to reduce the installation costs and identify business cases. Some electrochemical and thermal energy storage technologies are already being demonstrated in the UK for grid and off-grid applications (Bossink, 2014). The lessons of the demonstration projects can be applied to Brazil to identify properly applicable sites.

Given that the electricity consumption of Brazil is more than twice compared with the UK, and it keeps growing, Brazil may be an ideal test bed for demonstration sites in different environments and applications. The projects can also directly influence communities in Brazil by replacing carbon-intensive power generation with low-carbon energy systems enabled by energy storage.

Name	Technology	Capacity (MWh)	Purpose	Developer	Location
330 MW - Gaelectric Compressed Air Energy Storage (CAES)	CAES	1980	Grid	Dresser-Rand	Larne, County Antrim
MASLOW - Distributed energy storage for essential consumer and grid-scale network needs	Electro-chemical	1	Grid	Moixa Technology Ltd; Kiwi Power Ltd; Good Energy Ltd;Northern Power Grid; G&P Batteries Ltd; Solar Fair ltd/AtmosClear SA;Aquion Energy Inc (USA)	various
EVEREST (Electric Vehicle Embedded Renewable Energy Storage and Transmission)			Transport - Grid	Evalu8 Transport Innovations Ltd (lead contractor); Future Transport Systems Ltd; Lotus Engineering Ltd; Goodwolfe Energy Ltd; APT Technologies Ltd; and Circontrol	
Liquid Nitrogen Cryogenic Energy Storage Demonstration Project:	Liquid-air storage	20	Grid	Highview	Greater Manchester
BSR and WPD Battery Storage Facility - RES	Lithium Iron Phosphate Battery	1.28	Grid	RES	Butleigh, Somerset
Smarter Network Storage	Lithium-ion battery	10	Grid	Samsung SDI; S&C Electric Europe; Younicos	Leighton Buzzard, Bedfordshire
Kilroot Station Battery Storage Array - AES	Lithium-ion Battery	40	Grid	LG Chem; Parker Hannifin; AES Energy Storage	Carrickfergus, Northern Ireland
Northern Powergrid CLNR EES1	Lithium-ion Battery	5	Grid	NEC Energy Solutions, Inc. (A123 Systems); Dynapower	Darlington, North East
Orkney Storage Park Project	Lithium-ion battery	0.5	Grid	Mitsubishi Heavy Industries, Ltd. (MHI)	Kirkwall, Orkney
WPD Falcon Project, GE Durathon	Sodium–nickel-chloride battery	0.5	Grid	GE Energy Storage; Princeton Power Systems	Milton Keynes, Buckinghamshire
Northern Isles New Energy Solution	Valve-regulated lead-acid battery	3	Grid	Scottish Hydro Electric Power Distribution (SHEPD)	Northern Isles, Scotland
Gigha Wind Farm Battery Project	Vanadium–redox-flow battery	1.68	Grid	REDT	Gigha, Scotland

TABLE 3 MAJOR UK ENERGY STORAGE DEMONSTRATION ACTIVITIES, WITH A RATED POWER OUTPUT OF > 500 KW (NOT INCLUDING EPSRC-FUNDED PILOT PLANTS). DESCRIPTIONS OF DEMONSTRATION PROJECTS ARE PROVIDED IN APPENDIX V.

Suitable demonstration projects in Brazil could include

- large-scale energy storage such as CAES, LAES and flow batteries;
- district-scale energy storage such as LAES and batteries;
- small-scale batteries for building; and
- thermal energy storage linked with solar heating and cooling systems.

For the effective collaboration, the findings of the demonstration projects in the UK and Brazil need to be shared. Energy storage database including energy storage demonstration facilities in the UK and Brazil can provide comprehensive information on currently operating energy storage and demonstration projects. Establishing international demonstration facilities can reduce the required high capital investment while maximising the effectiveness of facilities.

5.3 DEPLOYMENT

Economic analysis is a necessary first step which is needed to evaluate the potential role of energy storage in any system. Given Brazilian government plans to build additional 41 GW of electricity generation capacity that may require large transmission capacity (Almeida Prado Jr. et al., 2016), an analysis of options for reducing capacity, including by retrofitting currently existing hydropower plants to enhanced pumped hydro storage, may be advisable. The methods of UK-based groups who have estimated the value of energy storage by different market and operation conditions in the UK (Carbon Trust, 2016; Strbac et al., 2015) could also be applied to Brazil.

Despite the *a priori* case for integrating energy storage into the energy system, some policy and regulatory barriers may prevent its widespread deployment. In the UK, learning from demonstration projects is feeding into new policies and regulations[5]. Recent experience of some specific interventions would provide valuable lessons for Brazilian policymakers, including:

- The inclusion of energy storage in capacity markets, under a separate auction process for demand side response and energy storage
- Provision of ancillary services from energy storage under National Grid's Enhanced Frequency Response tender.

The UK Government is expected to launch a Call for Evidence to investigate the potential barriers to energy storage in 2016.

The deployment of energy storage technologies as part of the innovation process (Figure 14) will itself drive research, development and demonstration activities of relevance to UK and Brazil, including:

- Manufacturing: Energy storage manufacturers (UK) and energy providers (UK and Brazil) can collaborate to capture the maximum value of deployed energy storage in Brazil and the UK. Highview Power Storage is leading the global market of a liquid-air energy storage system. REDT Energy Storage manufactures and exports flow batteries. There are a number of electrochemical battery manufacturers for grid and transport applications including Johnson Matthey Battery Systems, Anesco, and Nexeon.
- Product lifecycle: End-of-the-life processes should be studied and prepared. For example, currently in developed countries, the recycling rate of lead-acid batteries is > 97%. However, due to low economic returns, there is a minimal recycling of lithium-ion batteries (Gaines, 2014). Increasing number of electric vehicles will provide a large number of lithium-ion batteries globally; these 'second-life' batteries can be reused for grid purpose (Duan et al., 2013). Warwick Manufacturing Group at the University of Warwick is leading the manufacturing and end-of-the-life studies (WMG, 2016) along with the University of Cambridge studying the battery recycling (R Vasant and Sonmez, 2013).

[5] The UK Government aims to level the playing field for the storage market, removing policy and regulatory barriers in the first instance, and is expected to publish a call for evidence on a smart systems routemap, including storage, in 2016.

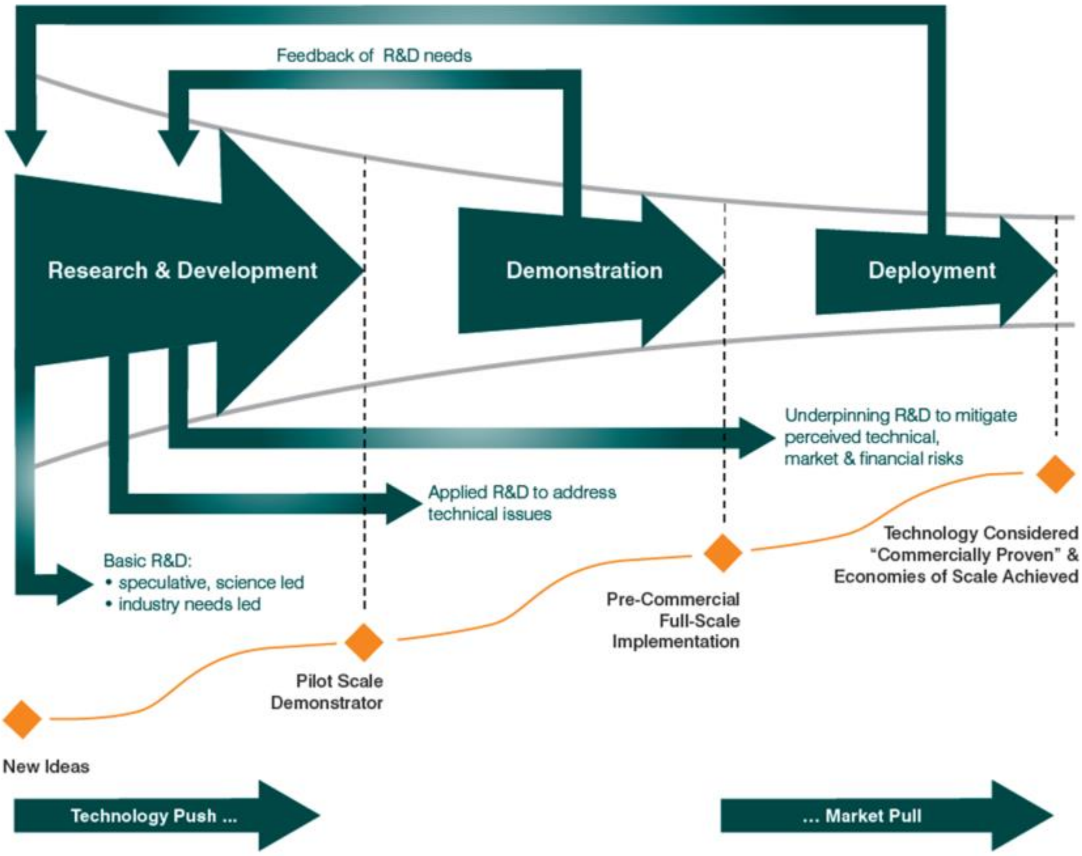

FIGURE 14 THE INNOVATION PROCESS (ENERGY RESEARCH PARTNERSHIP, 2010)

5.4 SWOT ANALYSIS

We have conducted an analysis based on a Strength-Weakness-Opportunity-Threat (SWOT) approach to identify the places where the UK and Brazil can collaborate in the area of energy storage (Table 4). In general, collaboration can be grown in areas where there are similar opportunities and threats, and different strengths and weaknesses. We compared research capability, technology development and deployment experiences, market capacity, natural and human resources, other political and social opportunities, and challenges.

Currently, research and demonstration capabilities and experiences in the UK are stronger than Brazil, while Brazil has natural resources and demonstration project opportunities. Given the non-linear nature of innovation, the lack of research capability in Brazil could limit the opportunities for deploying energy storage.

TABLE 4 SWOT ANALYSIS OF THE UK AND BRAZIL FOR ENERGY STORAGE TECHNOLOGIES

		UK	Brazil
Current	Strength	Existing international collaborations Research and demonstration capability and facilities Rapid integration of renewable energy	Natural resources Potential for hydroelectric plants to be retrofitted
	Weakness	Lack of policy and market support Gas-fuelled electricity and heat providing low-cost energy system flexibility Limited manufacturing capability with overseas competition	Research capability in few specific areas Lack of policy and economic support for energy storage and electric vehicles High hydroelectric share reduces opportunities for non-PHS energy storage
Future	Opportunities	Increasing demand for flexible generation options Growing EV fleet and infrastructure Increasing industrial capacity	Growing energy consumption Droughts reduce hydro capability Demonstration project opportunities Increasing solar PV and wind generation
	Threat	Uncertainty in development of the energy system	Bioenergy based transport policies

6 CONCLUSIONS

We have reviewed the potential application of energy storage as an important component of supporting flexible energy systems in the UK and Brazil. Energy storage could play important roles in both countries by providing energy system flexibility options for national networks and distributed grids, integrating renewable generation, and reducing capital investment for generation and transmission capacities.

For the UK, the potential of new district- or small-scale energy storage for both heat and electricity may be as important as that of large-scale energy storage. Thermal energy storage, in particular, could be important in the decarbonisation of heat consumption.

In Brazil, the system is under pressure from increasing demand and environmental concerns. Large-scale hydropower plants will also require increased transmission capacity between generation in the north of the country and demand in the south. Brazil, therefore, could represent an opportunity for deploying large-scale electrical energy storage technologies. Thermal energy storage connected with solar water heating systems could also reduce the peak residential demands.

Given the leading position of the UK in energy storage innovation, and Brazil's expanding energy market and natural resources, there is significant collaborative potential between the UK and Brazil. The energy storage community in the UK has benefited from recent investments in energy storage research programmes and facilities, alongside a suite of demonstration projects led by the energy industry. There is a willingness to engage internationally and seek opportunities in other markets where energy systems are coming under pressure.

Collaboration between the UK and Brazil would be beneficial for both countries across the innovation process:

6.1 RESEARCH AND DEVELOPMENT

Universities in the UK have particular expertise and facilities in areas that we have identified as also meeting energy system needs in Brazil, and where there are some research groups in Brazil which could benefit from collaboration:

- Electrochemical battery research for grid-scale applications (which would also be relevant to electric vehicles): lithium-ion batteries, metal-air batteries, sodium-based batteries, supercapacitors, and flow batteries.
- Thermal energy storage, including the development of phase change materials and improved thermodynamic processes.
- Energy system modelling and analysis to evaluate the role and value of energy storage across scales.

6.2 DEMONSTRATION

Scaling up technologies for testing in 'real' conditions is a key challenge for energy storage:

- Energy demonstration activities in the UK are providing valuable lessons on technology performance. An exchange of information on outcomes will also provide valuable lessons to Brazil when seeking to demonstrate and deploy energy storage.

- Brazil offers the potential of new demonstration opportunities, including in off-grid or remote locations, where technologies being developed in the UK could be tested.

6.3 Deployment

Encouraging the widespread take-up of energy storage in the UK and Brazil will present topics for collaboration:

- Governments and regulators in both UK and Brazil are investigating policies and markets which will allow energy storage to be deployed on a 'level playing field' alongside other flexibility options. Dialogue between policy-makers and industry stakeholders in UK and Brazil on these experiences will improve the policy-making process.
- Analysis of future energy scenarios, combined with energy storage 'roadmapping' can highlight opportunities for, and barriers to, deployment of energy storage in energy system transformations.
- Manufacturing of energy storage devices, where some natural resources important to the technologies are abundant in Brazil.
- End-of-use studies which consider options for re-use or recycling of energy storage technologies, in particular, Li-based batteries that will dominate a growing global EV market and may have 'second life' use as stationary devices.

6.4 Next steps

Establishing strong academic and industry networks between the UK and Brazil will allow specific project proposals to be formulated across the areas described above, and to explore other areas of mutual interest. The work of the British Embassy in Brasilia and officials across Brazil

Deeper engagement requires an expectation of outcomes which will lead to the provision of resource for substantive work. In the UK, the Newton Fund[6] and new Global Challenge Research Fund[7] offer such a prospect for academic involvement. Development of technologies and policies to deliver clean and sustainable energy, recognising the prospects for energy storage, should be a priority for these programmes.

In Brazil, the anticipated call to demonstrate the potential of energy storage by the regulator Aneel, allowing the inclusion of overseas expertise, will ultimately increase Brazilian capability and encourage inward investment.

[6] See http://www.newtonfund.ac.uk/.
[7] See http://www.rcuk.ac.uk/funding/gcrf/.

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Appendix I. ELECTRICITY STORAGE TECHNOLOGY CRITERIA

TABLE 5 ENERGY SERVICES AND THEIR CRITERIA (DNV GL, 2015)

	Rated power	Duration	Response
Bulk energy services			
1. Electrical energy time-shift	0 - 500 MW	2 - 6hr	msec - m
2. Power supply capacity	1 - 500 MW	2 - 6hr	min
Ancillary services			
3. Load following	1 - 100 MW	15 m - 1hr	- 1s
4. Regulation	10 - 40 MW	sec - hrs	- 1s
5. Frequency response	10 - 40 MW	2 m - 1 hr	msec
6. Reserve	10- 100 MW	m - hr	msec
7. Voltage support	1 - 10 MVAr	m - 1 hr	sec
8. Black start	5 - 50 MW	sec - hrs	m
Transmission infrastructure services			
9. Trans. congestion relief	1 - 100 MW	1 - 4 hr	msec
10. Trans. upgrade deferral	10 - 100 MW	1 - 8 hr	sec
Distribution infrastructure services			
11. Dist. upgrade deferral	0.4 - 10 MW	1 - 4 hr	sec
Customer energy management service			
12. Power quality	0.1 - 10 MW	msec - 15m	msec
13. Power reliability	0.05 - 10MW	1 - 8 hr	msec
14. Retail electricity time-shift	0.001 - 1 MW	1 - 6 hr	msec
15. Demand charge management	0.05 - 10 MW	1 - 4 hr	sec
Renewables integration			
16. Smoothing renewable output	0 - 500 MW	15m - 6 hr	msec - sec

Appendix II. ELECTRICAL ENERGY STORAGE TECHNOLOGIES

TABLE 6 CHARATERISTICS OF ELECTRICITY STORAGE TECHNOLOGIES (BRANDON ET AL., 2016; CENTRE FOR LOW CARBON FUTURE, 2014; IEA, 2014)

Type	Power Duration	Efficiency (%)	Lifespan (years)	Lifecycle	Comments
PHS	50MW - 3GW hours - weeks	75 - 85	> 50	High	97% of existing energy storage globally, but requires favourable landscape
CAES	50 - 300 MW hours - days	n/a	20 - 40	High	Two commercial plants operating. Requires suitable geology for large-scale underground CAES.
Lead acid	< 20 MW seconds - days	75 - 90	< 20	500-2000	Commercially mature re-chargeable batteries, used as DC auxiliary, and suitable for power quality, UPS and spinning reserve applications
Li-ion	< 50 MW seconds - hours	85 - 90	5-15	< 3000	Dominant battery in small portable applications due to high energy density, light-weight and high efficiencies; but high cost and limited lifetime
Na-S	< 10 MW seconds - hours	85 - 90	5-15	< 3000	316 MW installed globally. Due to the temperature requirements these type of cells become more economical with bigger size.
Metal-air	unknown	50	unknown	< 100	At R&D stage, but potential increase in energy density over conventional batteries, currently have poor efficiency and cycling capability
Flowbattery	500 kW - 15 MW hours - months	65-85	5-30	3000 - high	Flow batteries can release energy continuously at a high rate of discharge. Three main different electrolytes that form the basis of existing designs currently in demonstration or in largescale project development. Electrolytes are stored in external tanks, decoupling power and energy.
Flywheel	< 20 MW < seconds	85-95	20	high	Commercially deployed in US for grid frequency regulation. Long lifetimes but huge self –discharge.
Super-capacitor	< 300 kW < seconds	75-95	20	high	Lower energy density, but higher power density than batteries, often combined in hybrid systems.
SMES	< 40 MW < seconds	> 95	>20	high	Very quick response time, suitable for maintaining power quality. Very expensive and must be kept at very low temperatures.
CES	10 - 100s MW mins - hours	60 (expect)	20-40	high	In demonstration phase in UK. 'Liquid air' used as storage medium also has other transport / refrigeration applications

Appendix III. Research capability in Brazil

The numbers of papers related to energy storage technologies have been reviewed based on the publication and citation information between 2000 and 2015 provided by Web of Science (Thomson Reuters, 2016). These are not perfect metrics for evaluating research capability, but allow for some quantitative comparison.

Lithium-ion batteries

The number of papers has been increasing in Brazil since 2010; however at quite a low level, with 55 publications between 2000 and 2015 (ranked 29th globally) mostly in the fields of electrochemistry, physical chemistry and materials science.

The University of São Paulo leads the research in Brazil with 13 publications, followed by the Federal University of São Carlos (7 publications), the Federal University of Uberlândia and the Federal University of Minas Gerais (both 5 publications). A number of the other universities published a small number of journal articles during the period.

Lead-acid

In lead-acid related studies 38 papers were published between 2000 and 2015 (ranked 15th). Current studies are related to recycling and improving lead-acid batteries.

The University of Campinas leads the research in Brazil with 16 publications, followed by the Federal University of São Carlos (10 publications). Researchers from the Federal University of Parana and the University of the University of São Paulo have also published in the field.

Supercapacitors

The number of publications has increased since 2010 in Brazil, but limited to 32 between 2000 and 2015 (ranked 24th) in the areas as for Lithium batteries.

The University of Campinas leads the research in Brazil with 6 publications, followed by the University of São Paulo and the Federal University of Minas Gerais (both 5 publications). A number of the other universities published a small number of journal articles during the period.

Phase-Change Materials

The number of publications since 2000 is only 12, with 8 from the University of Campinas.

Other technologies

There were 6 journal articles in the field of metal-air batteries. The University of São Paulo has been the main contributor. Most of the studies focus on electrocatalytic activity and stability of metal-air battery cells.

5 journal articles prepared by Brazilian researchers are identified related to Superconducting magnetic energy storage SMES. Federal University of Rio de Janeiro is the main research group on SMES collaborating with the National University of San Juan.

Four publications are identified related to flywheel storage during 2000 and 2015, and all of them are published by the Federal University of Rio de Janeiro. However the most recent article was published about a decade ago (Andrade et al., 2007).

Three publications are identified related to CAES during 2000 and 2015. All of the journal articles are published in 2015 studying the performance evaluation of CAES for grid application. The Federal University of Minas Gerais published three articles evaluated the performance of CAES and cryogenic energy storage for grid application (Abdo et al., 2015).

Only one journal article has been identified in the fields of sodium-based batteries, flow batteries (from the University of São Paulo in collaboration with University of Warwick) (Leung et al., 2015), and pumped-hydro storage (Canales and Beluco, 2014).

Appendix IV. DEMONSTRATION PROJECTS IN THE UK

- **Gaelectric Compressed Air Energy Storage (CAES):** Advanced energy storage project deploying compressed air energy storage (CAES) technology. This facility will generate up to 330 MW of power for periods of up to 6 hours. It will create demand of up to 200 MW during its compression cycle. The project involves the creation of two storage caverns within salt deposits which are a feature of the east Antrim coastal areas of Northern Ireland. These caverns will be located at depths of greater than 1400 m below ground. The facility will be highly responsive and will be capable of providing a range of tools to system operators in their management of the transmission grid.

- **MASLOW - Distributed energy storage for essential consumer and grid-scale network needs:** Feasibility work for a proposed project to deploy 1MWh of storage across 750 domestic sites. The MASLOW system provides night storage for electricity through Meter Attached Storage, to power low voltage LED lighting and DC electronics during peak periods.

- **EVEREST (Electric Vehicle Embedded Renewable Energy Storage and Transmission):** This project demonstrates the viability of using energy storage to support electricity distribution networks, the integration of renewable generation and the rapid charging of electric cars.

- **Liquid Nitrogen Cryogenic Energy Storage Demonstration Project:** Highview and project partners, energy and waste management company, Viridor, were awarded funding from the British Government, to build a 5MW Liquid Air Energy Storage (LAES) technology system. The funding is supporting the design, build and testing of a pre-commercial LAES technology demonstrator alongside Viridor's landfill gas generation plant at Pilsworth Landfill facility in Greater Manchester. In addition to providing energy storage, the LAES plant will convert low-grade waste heat, from the GE Jenbacher landfill gas engines, to power.

- **BSR and WPD Battery Storage Facility – RES:** One of the first industrial-scale battery storage facilities is to be developed in the UK, thanks to an initiative between British Solar Renewables (BSR) and Western Power Distribution (WPD). This £1 million project will demonstrate the technical and commercial feasibility of directly linking a major battery storage facility, a solar park and the electricity network. WPD, the electricity distributor for the Midlands, South West and South Wales, is carrying out the project funded by Ofgem's Network Innovation Allowance, in conjunction with BSR and the National Solar Centre (NSC).

- **Smarter Network Storage:** The Smarter Network Storage (SNS) project aims to carry out a range of technical and commercial innovation to tackle the challenges associated with the low-carbon transition and facilitate the economic adoption of storage. It is differentiated from other LCNF electrical storage projects by its demonstration of storage across multiple parts of the electricity system, outside the boundaries of the distribution network. By demonstrating this multi-purpose application of 6 MW / 10 MWh of energy storage at Leighton Buzzard primary substation, the project will explore the capabilities and value in alternative revenue streams for storage, whilst deferring traditional network reinforcement.

- **Kilroot Station Battery Storage Array – AES:** AES has completed construction of a 10 MW / 40 MWh energy storage systems at its Kilroot power station in Northern Ireland. The ESS is connected to a large windfarm as well as a coal-fired generation plant. It will serve to store wind energy for later use as well as enhance grid reliability by providing fast response ancillary services, such as frequency response. The system is connected to the System Operator of Northern Ireland (SONI).

- **Northern Powergrid CLNR EES1:** Northern Powergrid's Customer-Led Network Revolution (CLNR) project is assessing the potential for new network technology and flexible customer response, to facilitate speedier and more economical take-up by customers of low-carbon technologies and the connection to the distribution network of increasing amounts of low carbon or renewable energy generation. The project is partially funded by Ofgem Low Carbon Networks Fund. It includes six NEC Energy Solutions GSS units commissioned in 2013 in three different areas. The strategic siting, both rural and urban, represents different grid situations, and it is estimated that the placements offer a representative sample of 80% of the entire UK power grid.

- **Orkney Storage Park Project:** Mitsubishi Heavy Industries, Ltd. (MHI), jointly with Scottish Hydro Electric Power Distribution (SHEPD), has begun an energy storage system demonstration project using the distribution grid in the UK's Orkney Islands, which has a high penetration of renewable energy. The project aims at demonstrating power supply stabilization in the region by introducing a container-housed large capacity energy storage system using lithium-ion rechargeable batteries, with a power output/input capability of 2MW (megawatts). The storage system will be handed over for operation in the middle of 2013.

- **ABB & UK Power Networks Energy Storage Installation:** An electricity distribution company has commissioned the first of a new type of dynamic power-control system with energy storage at a site north of Hemsby in Norfolk, so that energy from a nearby wind farm can be fed into the local grid.

- **Demonstrating the Benefits of Short-term Discharge Energy Storage on an 11kV Distribution Network:** Electrical storage offers one means to manage intermittent demand and intermittent generation on a distribution network within existing network constraints, principally thermal capacity. UK Power Networks has previously explored with Durham University and ABB the benefits that storage can offer in managing intermittent generation.

- **WPD Falcon Project, GE Durathon:** The system is to be used in Western Powers distribution substation located in Milton Keynes. Five 50kW (100kWh) Sodium Nickel Chloride Durathon batteries were supplied by GE. These have been installed to investigate using energy storage to defer costly network reinforcement and evaluate using a number of smaller batteries distributed across a network, rather than a single unit at a single location.

- **Northern Isles New Energy Solution:** Shetland is not connected to the main electricity network in GB. This means that the islands rely entirely on local sources of generation, and the supply and demand on the islands must be balanced locally. The project is led by Scottish Hydro Electric Power Distribution (SHEPD), which is the owner and operator of the energy distribution network in Shetland. To implement and trial the new technologies, NINES has attracted £34m funding from Ofgem, DECC and Hjaltland Housing Association.

- **Gigha Wind Farm Battery Project:** The Scottish island of Gigha is to be the focus of a £2.5m experiment aimed at solving a major technological problem 'how to store energy generated by wind, tide and wave power plants'. The project, which will involve building giant batteries containing 75,000 litres of sulphuric acid mixed with vanadium pentoxide, is intended to allow power generated by the island's wind turbines to be stored for later use.

- **Milton-Keynes Smart City Project:** Over the last decade Milton Keynes has made major strides towards becoming an energy efficient city and reducing carbon emissions in line with European and UK targets. Milton Keynes hosts a range of advanced energy installations, such as the Falcon smart grid, an extensive electric vehicle charging infrastructure, and a district heating system. In the context of the existing energy infrastructure, the work on energy management in MK:Smart has two goals: i) to develop and demonstrate innovative energy services enabled by the smart analytics capabilities of the MK Data Hub and ii) to demonstrate the business value of the MK Data Hub for the energy sector.

- **Low Carbon London – led by UK Power Networks:** UK Power Networks has completed Low Carbon London, its £28m, 4 year innovation project to investigate the impact of a wide range of low carbon technologies on London's electricity distribution network. Low Carbon London has delivered successfully in accordance with the requirements of Ofgem's Low Carbon Networks Fund, facilitating the development of viable solutions for Distribution Network Operators to support the low carbon transition in the UK.

- **Thames Valley Vision (TVV):** The Thames Valley Vision (TVV) is a £30 million project established to ensure a high quality and affordable electricity network in the future. Customers in Bracknell and the surrounding area will benefit from this project that will help the UK achieve a low carbon economy. The £30 million project is part of wider UK programme funded by the Low Carbon Network Fund (LCNF) run by Ofgem, the UK energy regulator.