Comments of the New Jersey Conservation Foundation
in the matter of
New Jersey Energy Storage Analysis

On March 6, 2018, the staff of the New Jersey Board of Public Utilities (Board or BPU) requested written comments in the above matter, which concerns the requirements of P.L. 2018, c. 17, (the Clean Energy Act or Act) for the Board to conduct an analysis of and make a report on, energy storage needs and opportunities in the state. The New Jersey Conservation Foundation (NJCF) respectfully offers the following comments, followed by answers to the staff's specific questions.

1. The Board's energy storage analysis should be carried out with the primary goal of advancing and supporting New Jersey's clean energy and global warming response goals.

NJCF urges the Board and its staff to conduct its analysis of energy storage in the context of the state's legal and policy goals for clean energy. These include:

- The Act's aggressive goals for renewable energy to supply 50% of all energy delivered to retail customers by 2030, much of which renewable energy is to be acquired under a strict cap on ratepayer costs;
- The requirements of the Global Warming Response Act of 2007, N.J.S.A. 26:2C-27, to reduce statewide greenhouse gas emissions, meaning the sum of annual emissions of greenhouse gases from all sources within the state and from electricity generated outside the state but consumed in the state, to 1990 levels by 2020 and to 80 percent or less than 2006 levels by 2050; and
- The goals of Governor Murphy's Executive Order 28 for the state's 2019 Energy Master Plan to provide a comprehensive blueprint for the conversion of the State's energy production to 100% clean energy sources on or before January 1, 2050, and to provide specific proposals to be implemented over the next ten years in order to achieve the 2050 goal.

This context for the analysis is critical, since cost-effective energy storage technologies are widely considered to be an essential component of any clean energy system that includes high percentages of energy production by wind, solar and other variable renewable energy (VRE) resources. This need is due to the electric system's need to continually balance the amount of electricity generated with the amount of electricity consumed. But VRE cannot always be available to increase the amount of energy it generates in response to increases in consumption (for example, when the sun is not shining or the wind not blowing). Without clean energy solutions to this need, such as flexible load, energy storage, and zero emission but highly dispatchable generation, fossil fuels will continue to be used for such balancing purposes.

Further, high levels of VRE resources are likely to produce more energy than is being consumed during periods of ample wind or sunshine but low energy consumption. Without the ability to shift energy consumption to such periods, including by increasing electricity used to charge energy storage resources, this overproduction can only be managed by curtailing VRE or other resources, including clean energy resources. High levels of such curtailment increase costs and reduce the amount of greenhouse gas reductions that clean energy could otherwise support. Energy storage can store VRE produced at times when production exceeds consumption, and release it at times when consumption exceeds production, helping ensure reliability while reducing costly curtailment and displacing or avoiding additional greenhouse gases from fossil generation. Achieving the right amount and types of storage to produce these benefits, however, and to do so cost effectively, is a significant challenge.

2. Careful analysis is needed as part of an integrated energy planning process to identify optimal levels, types and locations of energy storage as part of an increasingly clean energy system.

Different energy storage technologies are best suited to short, long, frequent or infrequent charging and discharging, and can have very different cost and performance capabilities in these applications. Three characteristics are particularly important for electric system uses:

(a) how much energy can be stored, measured in total watt-hours that can be delivered from the device on a single charge, and often referred to as the "rated energy capacity" or "rated capacity";[1]
(b) the maximum level of power that can be delivered from the device, measured in watts, which is often referred to as the "rated power"; and
(c) how long it takes to deliver all the available watt-hours at the rated power level, often call the "discharge time".

Figure 1 in the Appendix illustrates the rated capacity and discharge time different storage technologies, and their alignment, from a UK perspective, with key needs of an electric system with growing levels of VRE production. Figure 2 shows the relationship between rated power (maximum power output) and rated capacity (maximum energy output) under the maximum discharge time levels for a wide variety of storage technologies. Both figures give a good sense of what power sector needs various storage technologies are and are not technically capable of serving.

Beyond these key features, many other characteristics of storage technologies, including their energy efficiency, cost, their expected calendar lives and the number of charging cycles they can provide, their optimal depth of discharge, and their commercial maturity all can factor into determining which technologies are the best choice for a particular application. Figure 3 in the Appendix gives an indication of the complexity of the cost and operating parameters of many storage technologies and the power sector applications they may best be suited to, at least as of 2015.[2]

The substantial diversity of all these parameters of various storage technologies and of the types of services they might best provide suggests an efficient, step-wise process for the Board to assess storage needs and opportunities. First, the Board would focus on identifying the types and amounts of services that New Jersey's electric system is likely to need in the next 5 to 10 years to best support its clean energy goals. Then it could encourage and support the private sector and other stakeholders to bring forward technology proposals that would best provide these types and amounts of services, at the lowest cost, and in light of the ongoing development of improved storage technologies.

---

[1] Note this quantity is different from capacity as the term is used with respect to power plants, where it measures the total sustainable instantaneous power output of the plant, in watts. The analogue for that metric in storage devices is the *rated power*.

[2] In 2019, lithium-ion (LI) battery technologies appear to have eclipsed a number of other battery technologies. However, given the many types of LI technologies, along with the continued evolution of other forms of storage, the basic principles and parameters identified in the 2015 and 2017 resources in the Appendix remain relevant.

NJCF recommends three key steps in this process. The first step is to determine which storage functions, and how much of each, are likely to be most needed in New Jersey as it progresses towards its clean energy goals, in parallel with other states interconnected to the same electric grid and PJM's energy balancing market.[3] Initial framing of this task and indicative results could be done with the assistance of energy experts at Rutgers, along with the stakeholder input the Board is currently gathering.

More detailed analysis, to support any actual storage procurement deployment, however, would best be done through regional dispatch simulation of an increasingly clean energy system, using electric system planning tools that accurately and precisely account for wind and solar availability, variability and costs across the broad, interconnected regional electric grid that includes New Jersey. NJCF has previously recommend the use of such tools in integrated energy planning for New Jersey, which would help inform both the state's Energy Master Plan and its various clean energy goals and policies.[4]

Such tools can identify VRE resources from within the state and across the region, which, in combination, provide the best fit to meet New Jersey's energy consumption patterns at the least cost, reducing the need for and cost of storage. Such tools should also include commercially addressable flexible load, which in some cases may be a far cheaper alternative than either new generation or energy storage. Such tools can also then identify storage needs and opportunities still needed, in terms of both the quantity of storage needed and the time frame within which the various storage types would need to perform.

With the best insights into the types and quantities of storage functions and services likely to be needed, the next step would be to identify which specific storage technologies, in what amounts, can best meet the energy storage needs identified in the above analysis. This will involve considerable detailed evaluation of the costs, benefits and risks of various storage technologies. As such, it would be done best by private sector investors and storage companies with specialized knowledge, who face concrete investment opportunities that create strong incentives to manage both cost and risk, rather than by a state agency or a disinterested technical analysis.[5] This type of private storage investment could be incentivized, for example, by competitive procurement for the types and quantities of the various storage services identified in the first step. Periodically updating this planning and procurement process, with inputs to the planning process reflecting current commercial costs and performance capabilities of storage and other clean energy technologies, would result in a low-cost pathway towards an integrated clean energy portfolio for both the state and, increasingly for the entire region.

---

[3] Getting the quantity right is especially important for storage that serves a market function, since market prices typically respond to an oversupply by falling to very low levels, which then fail to compensate all resources, not just the newest entrants. This result can happen in most ancillary service markets, including frequency regulation.
[4] See, NJCF comments on the Energy Master Plan, October 12, 2018.
[5] While the staff questions seem to anticipate significant regulated utility ownership of energy storage systems, it seems likely from ongoing storage deployment that three forms of private sector ownership are emerging nationally and would likely thrive in New Jersey's relatively competitive electricity sector: competitive storage providers, as an analogue to competitive independent power producers (IPP), competitive aggregation of consumer-owned storage devices, and competitive storage projects developed under storage purchase agreements with load-serving entities (both competitive and regulated). By placing risks such as technology risk, execution risk, and performance risk on private investors, such approaches to storage have the potential to result in lower overall costs and lower costs to ratepayers, in particular.

3. Additional storage benefits may be attained, beyond integration of high levels of VRE supply.

Energy storage also has the potential to create other benefits, beyond this critical role of helping enabling high levels of VRE energy production. These benefits include enhancing the ability of the distribution system to deliver high peak demand levels at lower cost than increasing the size and voltage ratings of distribution transformers and switch gear; enhancing resilience for facilities where uninterruptible power supplies (UPS) are important; and improving power quality where needed for sensitive electronics and processes.

The first of these – supporting high, localized peak electricity loads -- may be particularly important for reaching the GWRA decarbonization goals, since it may potentially support and accelerate the electrification of key emitting sectors such as transportation, the built environment, and various types of industrial processes. For example, high speed electric vehicle charging, without lengthy queuing, can create very high peak demands at popular charging facilities. Battery or other suitable storage devices at such facilities could potentially meet this demand with energy stored at times of lower use, avoiding or reducing the need for expensive capacity upgrades to the distribution system's delivery and safety equipment. If cost-effective, such storage would reduce the ratepayer impacts of such upgrades, while allowing electric vehicle charging services to avoid high distribution system demand charges. Further, by allowing the energy for such uses to be stored at times of maximum renewable energy production, such applications could dramatically increase the ability of a clean energy system to reliably balance high levels of VRE production, even as they are also decarbonizing a major energy end use.

Similarly, widespread adoption of battery systems at the household or business level for resilience benefits could, in parallel, support a more cost-effective approach to maintaining voltage levels and the volt-var balance on the distribution system, while also supporting greater penetration of distributed solar. Such "stacked benefits" are widely thought to be one potential way for a given investment in energy storage technologies to produce commercial and social benefits above and beyond any one purpose. Figure 4 in the Appendix illustrates how such distributed storage and other distributed energy resources (DERs) could be configured on the state's low voltage electric distribution systems, several services and value streams they could provide, and key stakeholders for each service and deployment.

4. Distribution planning for batteries and other DERs to support the state's clean energy goals.

The examples above suggest that New Jersey needs to consider how best to achieve such "stacked benefits" from storage located on the lower voltage distribution system, whether in front of or behind the meter. In the examples, some of these potential benefits accrue directly to customers (such as increased resilience and the lower maintenance and operating costs of electric vehicles), while some result from selling reliability and balancing services to the wholesale energy market, and still others come from avoiding higher cost upgrades to the regulated distribution utility's distribution network. In addition, there can be broad social benefits, such as increased resilience at emergency services, new and growing business sectors in electrification and efficient flexible load, and rapid and globally replicable reductions in GHG emissions.

These considerations suggest another planning workstream needed to support the state's clean energy goal – namely, distribution system planning, with the goal of identifying barriers and solutions to achieving the direct customer benefits, distribution system cost reductions, and broader societal benefits of behind the meter and distribution system located storage and other, related distributed energy resources (DERs).

Such a distribution planning process should be a part of, and closely coordinated with, the broader integrated planning process, for two reasons. First, the amount, type and location of such storage and other DERs are of central importance to, and will be dictated by, what is necessary for achieving the state's clean energy goals at affordable cost levels. And second, to achieve this central goal, storage and other DERs must interact with, and produce benefits for, both the larger wholesale market and the local distribution system. Accordingly, as part of the overall integrated energy planning process, distribution planning should focus on identifying and improving the capabilities of the distribution system, and of the resources located on or behind it, to support and enhance the cost-effective achievement of the state's clean energy and global warming response goals.

Coupling such distribution planning with competitive procurement and other market-based approaches to attracting private investment in storage and other DERs will help minimize ratepayer costs, allocate the risks of innovation to investors rather than ratepayers, and focus the utility on infrastructure, information and energy management systems needed to support effective deployment, operation and benefit stacking of storage and other DERs.

6. Answers to specific staff questions.

Several of the staff question refers to "renewable electric energy storage systems," which is the same language used in the statute. It is not clear what the plain meaning of the statutory language is. Given that, it is important to note that in practice it would be extremely difficult to limit electric storage systems to storing renewable energy only. This is because a storage device that uses electricity from the interconnected electric grid as an input will store whatever mix of renewable and non-renewable energy is currently energizing the electric grid. Even an energy storage device that is co-located behind the meter with a renewable energy generating resource would frequently store non-renewable, grid-sourced electricity, unless it were operated so it only charges when, and to the extent that, the co-located renewable energy resource is generating more electricity that is being consumed behind that same meter. Such a requirement, however, would dramatically limit energy storage deployment and prevent many of the beneficial uses described above, which are very likely necessary to achieve the state's clean energy and global warming response goals.

Another more feasible and relevant approach would be to ensure electric energy storage systems facilitate and store increasing amounts of renewable and clean energy. This approach seems more consistent with the state's aggressive clean energy, renewable energy and global warming response goals. The planning and procurement recommendations above are based on achieving these goals in line with the Act's focus on using competition where possible and minimizing ratepayer costs. Accordingly, this view of what is meant by "renewable electric energy storage" is implicit in NJCF's answers to the following questions.

1. As discussed above, a variety of energy storage technologies would be needed to provide the various services needed as the state progresses towards its clean energy goals. Further, each service requires specific combinations storage operating characteristics, and may also require its own unique battery management system and interface with the customer, as well as potentially with the electric distribution system, and with the wholesale electric market. Thus, realizing net

benefits from the storage will require the right choices among all these options. In some, and perhaps most storage applications, these choices will be made by private parties, who will then bear the bulk of the costs and benefits, and who will naturally seek to ensure their benefits exceed their costs. If, however, any of the benefits of the storage systems that accrue directly to ratepayers are greater than any of their costs borne directly by ratepayers, storage systems that are more cost-effective than their alternatives will benefit ratepayers.

2. As discussed above, energy storage has the potential, if technologies with the right operating characteristics, performance and costs are available and implemented, to help make high speed EV charging less expensive and more commercially attractive and more available. However, this depends on the cost of such storage-enhanced systems being less than that of pure "wires-based" charging systems. Similarly, appropriate levels and types of energy storage could result in less curtailment of renewable energy production in the state, if the state were to develop enough in-state renewable energy production to exceed, at particular times, its own demand plus export capability to other parts of PJM. Storage could also help alleviate conflicts between state clean energy resources, such as high levels of offshore wind production during cool nights with low demand, coincident with high levels of nuclear output from the state's remaining nuclear reactors. If the combined output of these resources exceeded demand within the state, and exceeded either export capability or demand within the region, one of the two clean energy resources would need to be curtailed to prevent overproduction. But to know whether any of these situations are likely, whether they would be helped by storage, and what types of storage, in what amounts and in what locations would be cost-effective in terms of avoiding any such curtailments, will require the kind of analysis and planning recommended in these comments.

3. NJCF has no specific information on this question regarding New Jersey. Please see the resources cited in the Appendix draws on for an overview of storage technologies, key physical and operating characteristics, and applications for which they are most suitable.

4. This question assumes that storage investments will be made by regulated electric public utilities and local governments, with costs passed on to ratepayers and, presumably, taxpayers. Some storage applications may indeed be procured and financed this way. Under the planning approaches recommended above, which focus on finding the most cost-effective solutions to system balancing needs and, among those solutions, the least-cost utility owned or purchased storage solutions that create the biggest stack of benefits, any such ratepayer costs should generally be lower than the costs to ratepayers would be of achieving comparable levels of clean energy deployment and global warming response *without* the storage. However, many storage applications could readily be invested in privately, with the capital costs incurred by private investors, not regulated utilities, and with recovery of those costs based on providing competitive storage services (to the wholesale market and to end-use customers, not as part of utility rates) that make the customers better off than if they did not buy them. Additional benefits could be achieved by substituting such storage solutions for more expensive "wires-only" distribution solutions, which would also make ratepayers better off. For all these reasons, NJCF recommends the BPU consider focusing on competitively provided storage solutions wherever possible.

5. The right amount of storage for New Jersey, as well as the type and key physical and operational characteristics needed, can only be even approximately understood by a relatively detailed, regional dispatch simulation analysis that explores optimal paths for New Jersey's clean energy deployment over the next decade, along with reasonable assumption for parallel clean energy deployment throughout and interconnected into PJM. Such analyses should be a major focus for current energy planning at the BPU and for the evolving energy master plan.

6. There are two common paradigms for thinking about where DERs (including batteries) are best located on the distribution system. The first is where they create the most "stacked value" for their hosts (i.e., end customers), the distribution system and the grid. The second is where the distribution system can best accommodate them. This latter is sometimes called "hosting capacity analysis". Both these approaches can be used to target initial DER investment, but unfortunately, they both tend to miss the critically important question of what is needed for the DERs to actually operate and help integrate large volumes of VRE.

   Instead of simply looking at hosting capacity or value, it can also be important to work through such operational requirements in identifying early DER deployment opportunities. For example, some types of DERs simply shift load in time, which can dramatically help with VRE integration, stay well within the existing distribution system's operating parameters, and require little other than the ability to observe the price signal from the wholesale market, rather than actively participate in it. Smart thermostats and several other distributed services can operate in this mode. Batteries could, as well. Further, batteries could potentially also use their digital inverters to provide some degree of voltage control for the distribution system. This suggests a possible low cost, incremental pathway for DER and battery deployment on the distribution system, without attempting to simultaneously make massive investments in things like automated metering infrastructure (AMI), entirely new regulatory and utility business models, and other resource and time-intensive changes.

   Other types of DERs can have major interactions with the distribution system, including reversing flows on feeder lines, that would require more complex and significant system monitoring, analysis and control technologies to support, as well as potentially much more systematic reengineering of the distribution system and its current distribution management systems, and potentially of the regulated utility business model itself. This is why a significant effort in distribution system planning is needed in New Jersey – to identify low cost, high benefit DER applications, and avoid high cost, low benefit ones. This is especially true for early storage deployment.

7. Perhaps the greatest reason New Jersey needs to consider storage deployment through an integrated clean energy planning process, with market-based cost and performance inputs, is so it can answer this kind of question before it decides how much and what kind of storage to encourage, rather than after.

8. Instead of primarily focusing on integrating DERs into the electric system, NJCF encourages the BPU and its staff to also think about how to use DERs to help integrate VRE resources into the electric system.

9. See the answers to the previous questions.

10. We recommend the BPU consider defining energy storage, for the purpose of the ESA, as " systems electrically connected to the electric grid, whether behind the meter or in front of it, that convert electricity from or deliverable to the grid to some other form, store it for a period of time, and then reconvert the stored energy to electricity for either redelivery to the electric grid or for a direct end use." This would address flywheel, gravity-based, batteries, capacitor, compressed air, and similar forms of storage and which are the most prevalent and promising current storage technologies. It would not cover such intermedia time-shifting technologies as ice or molten salt thermal storage that is used for a direct end use such as heating or cooling. However, such uses are better treated as examples of flexible load, since they do not involve the additional step of converting the stored energy back to electricity.

11. NJCF recommends that the BPU base its implementation of the statutory storage goals on the results of its initial integrated planning, as described in these comments and in NJCF's comments on the Energy Master Plan of October 12, 2018. In particular, the rated power, rated capacity and discharge time dimensions of those goals should be informed by such analysis, since the likely needs, costs and benefits of those characteristics can best be determined by looking at the regional balancing market dynamics expected in and across typically high and low VRE producing hours in those years. The economic value of the mandated capacity in the PJM BRA certainly could matter for the 2021 goal, but should not be the only consideration. PJM's current Manual 21 requirement for storage to participate in PJM's BRA, namely that the storage resources eligible capacity (in the power plant sense) be based on how much energy the storage resource can discharge over 10 continuous hours, would certainly affect the capacity market value of the 2021 goals -- if it is maintained. It is not clear that the current Manual 21 requirement will be maintained or, indeed, that it is needed for reliability or efficient operation of the BRA. Accordingly, NJCF recommends the BPU look primarily at the implications of integrated energy planning in terms of the rated capacity, rated power and discharge times most likely to be needed in the 2020's, and use these results in further specifying the types of storage to be considered for the 600 MW 2020 goal. Indeed, any such planning results could be very helpful in supporting a more efficient treatment of storage in PJM's capacity market. The 2030 goal, in turn, would be better addressed in the mid-late 2020's, when more information is available about new storage technologies and new system needs.

12. NJCF does not, at this time, make a recommendation regarding the treatment of existing vs. incremental storage in terms of counting towards the statutory goals, other than the recommendations above that the type and quantity of storage to be developed in New Jersey be evaluated primarily on the basis of need and cost-effectiveness in supporting the state's renewable energy, clean energy and global warming response goals.

13. Please see our answer to question 11, above.

Appendix

Figure 1

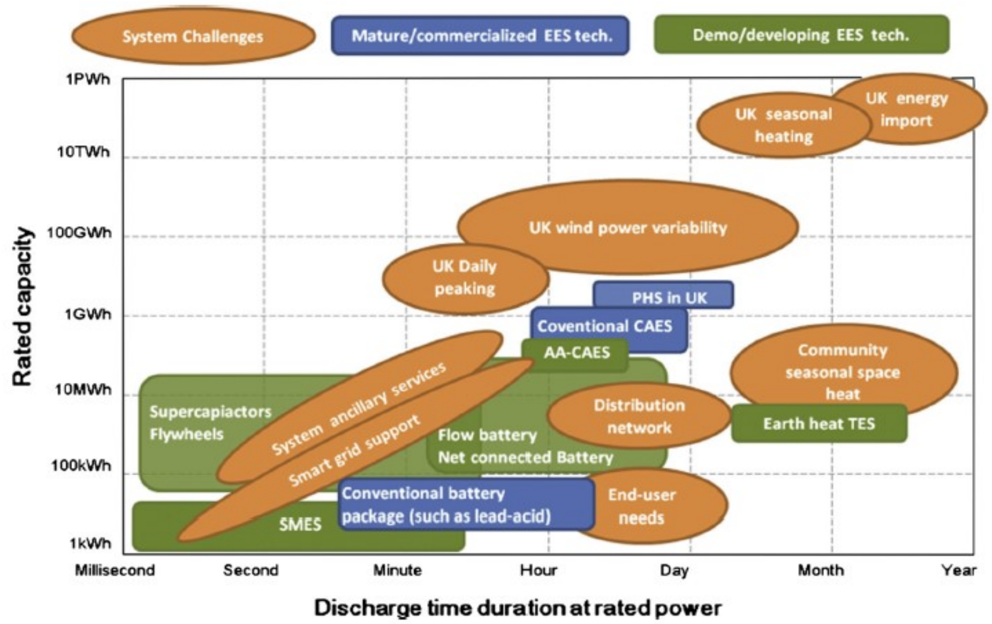

Fig. 1. Electrical energy storage technologies with challenges to the UK energy systems [4,6,7–9].

Figure 2

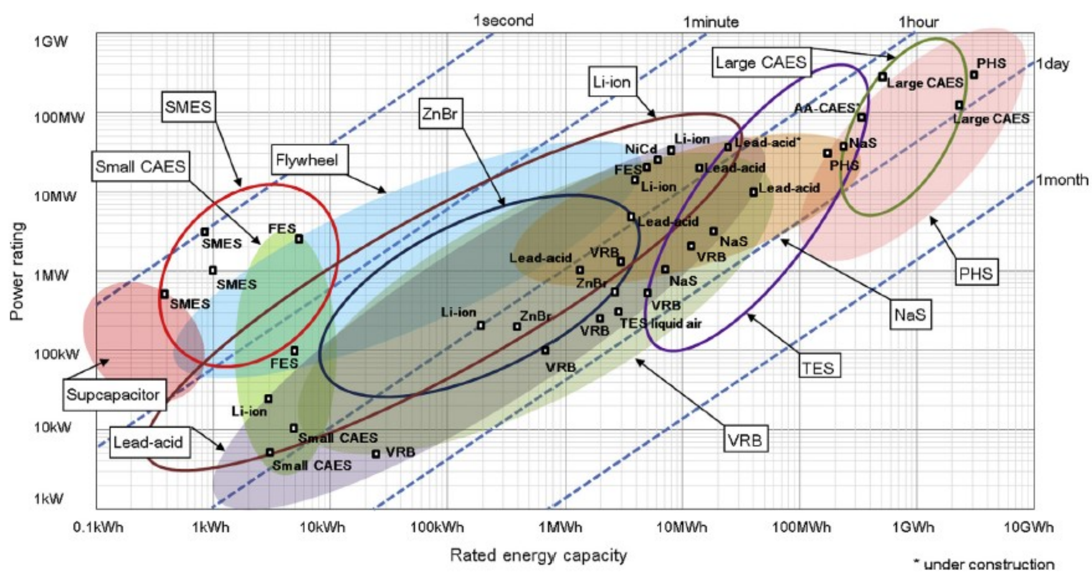

Fig. 16. Comparison of power rating and rated energy capacity with discharge time duration at power rating. The marked data of EES facilities from the cited references in Section 2 of the paper).

Source of Figures 1 - 3: Luo, X., Wang, J., Dooner, M. and Clarke, J. (2015) Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, Volume 137. pp. 511-536. Available at http://wrap.warwick.ac.uk/63615 . Accessed March 16, 2019.

Figure 3

Table 12
Other technical and economical characteristics of electrical energy storage technologies.

Technology	Suitable storage duration	Discharge time at power rating	Power capital cost ($/kW)	Energy capital cost ($/kW h)	Operating and maintenance cost	Maturity
PHS	Hours–months [4], long-term [27]	1–24 h+[4], 6–10 h [73] 10 h [175]	2500–4300 [73], 2000–4000 [175]	5–100 [4], 10–12 [114]	0.004 $/kW h [70], ~3 $/kW/year [72]	Mature
Large-scale CAES	Hours–months [4], long-term [27]	1–24 h+ [4], 8–20 h [73]	400–800 [4], 800–1000 [175]	2–50 [4], 2–120 [8], 2 [70]	0.003 $/kW h [70], 19–25 $/kW/year [72]	CAES commercialized, AA-CAES developing
Over-ground small CAES	Hours–months, long-term [27]	30 s–40 min [51], 3 h [216]	517 [114], 1300–1550 [216]	1MVA from £296 k [51], 200–250 [216]	Very low [51]	Early commercialized
Flywheel	Seconds–minutes [4] short-term(<1 h)[27]	Up to 8 s [4], 15 s–15 min [175]	250–350 [4]	1000–5000 [4], 1000–14,000 [8]	~0.004 $/kW h[70], ~20 $/kW/year [72]	Early commercialized
Lead–acid	Minutes–days [4], short-to-med. term	Seconds–hours [4], up to 10 h [14]	300–600 [4], 200–300 [114], 400 [206]	200–400 [4], 50–100 [57], 330 [206]	~50 $/kW/year [72]	Mature
Li-ion	Minutes–days [4], short-to-med. term	Minutes–hours [4], ~1–8 h [209]	1200–4000[4], 900–1300[57], 1590[73]	600–2500 [4], 2770–3800 [73]	–	Demonstration
NaS	Long term[82]	Seconds–hours [4], ~1 h [209]	1000–3000 [4], 350–3000 [8]	300–500 [4], 350 [206], 450 [217]	~80 $/kW/year [72]	Commercialized
NiCd	Minutes–days [4], Short and long term	Seconds–hours [4], ~1–8 h [209]	500–1500 [4]	800–1500 [4], 400–2400 [57]	~20 $/kW/year [72]	Commercialized
VRB	Hours–months [4], Long term [27]	Seconds–24 h+ [4], 2–12 h [106]	600–1500 [4]	150–1000 [4], 600 [217]	~70 $/kW/year [72]	Demo/early commercialized
ZnBr	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4], 400 [87], 200 [114]	150–1000 [4], 500 [71]	–	Demonstration
PSB	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4]	150–1000 [4], 450 [217]	–	Developing
Capacitor	Seconds–hours [4], ~5 h [210]	Milliseconds–1 h [4]	200–400 [4],	500–1000 [4],	13 $/kW/year [72], <0.05 $/kW h [210]	Commercialized
Super-capacitor	Seconds–hours [4] short-term(<1 h)[27]	Milliseconds–1 h [4], 1 min[209], 10 s[216]	100–300 [4], 250–450 [216]	300–2000 [4]	0.005 $/kW h [70], ~6 $/kW-year [114]	Developing/demo.
SMES	Minutes–hours [4] short-term (<1 h)[27]	Milliseconds–8 s[4], up to 30 min [209]	200–300 [4], 300 [114], 380–489[216]	1000–10,000 [4], 500–72,000 [114]	0.001 $/kW h [70], 18.5 $/kW/year [72]	Demo/early commercialized
Solar fuel	Hours–months [4]	1–24 h+ [4]	–	–	–	Developing
Hydrogen Fuel cell	Hours–months [4]	Seconds–24 h+ [4]	500 [114], 1500–3000 [154]	15 [114], 2–15€/kW h [204]	0.0019–0.0153 $/kW [154]	Developing/demo.
TES	Minutes–days [4], minutes–months [4]	1–8 h [4], 1–24 h+ [4], 4–13 h [203]	200–300[4], 250 [203], 100–400[203]	20–50 [4], 30–60 [4], 3–30 [4]	–	Demo/early commercialized
Liquid air Storage	Long-term [214]	Several hours [168,214]	900–1900 [214]	260–530 [214]	–	Developing/demo.

Table 12
Other technical and economical characteristics of electrical energy storage technologies.

Technology	Suitable storage duration	Discharge time at power rating	Power capital cost ($/kW)	Energy capital cost ($/kW h)	Operating and maintenance cost	Maturity
PHS	Hours–months [4], long-term [27]	1–24 h+[4], 6–10 h [73] 10 h [175]	2500–4300 [73], 2000–4000 [175]	5–100 [4], 10–12 [114]	0.004 $/kW h [70], ~3 $/kW/year [72]	Mature
Large-scale CAES	Hours–months [4], long-term [27]	1–24 h+ [4], 8–20 h [73]	400–800 [4], 800–1000 [175]	2–50 [4], 2–120 [8], 2 [70]	0.003 $/kW h [70], 19–25 $/kW/year [72]	CAES commercialized, AA-CAES developing
Over-ground small CAES	Hours–months, long-term [27]	30 s–40 min [51], 3 h [216]	517 [114], 1300–1550 [216]	1MVA from £296 k [51], 200–250 [216]	Very low [51]	Early commercialized
Flywheel	Seconds–minutes [4] short-term(<1 h)[27]	Up to 8 s [4], 15 s–15 min [175]	250–350 [4]	1000–5000 [4], 1000–14,000 [8]	~0.004 $/kW h[70], ~20 $/kW/year [72]	Early commercialized
Lead–acid	Minutes–days [4], short-to-med. term	Seconds–hours [4], up to 10 h [14]	300–600 [4], 200–300 [114], 400 [206]	200–400 [4], 50–100 [57], 330 [206]	~50 $/kW/year [72]	Mature
Li-ion	Minutes–days [4], short-to-med. term	Minutes–hours [4], ~1–8 h [209]	1200–4000[4], 900–1300[57], 1590[73]	600–2500 [4], 2770–3800 [73]	–	Demonstration
NaS	Long term[82]	Seconds–hours [4], ~1 h [209]	1000–3000 [4], 350–3000 [8]	300–500 [4], 350 [206], 450 [217]	~80 $/kW/year [72]	Commercialized
NiCd	Minutes–days [4], Short and long term	Seconds–hours [4], ~1–8 h [209]	500–1500 [4]	800–1500 [4], 400–2400 [57]	~20 $/kW/year [72]	Commercialized
VRB	Hours–months [4], Long term [27]	Seconds–24 h+ [4], 2–12 h [106]	600–1500 [4]	150–1000 [4], 600 [217]	~70 $/kW/year [72]	Demo/early commercialized
ZnBr	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4], 400 [87], 200 [114]	150–1000 [4], 500 [71]	–	Demonstration
PSB	Hours–months [4] long term [27]	Seconds–10 h+ [4], ~10 h [209]	700–2500 [4]	150–1000 [4], 450 [217]	–	Developing
Capacitor	Seconds–hours [4], ~5 h [210]	Milliseconds–1 h [4]	200–400 [4],	500–1000 [4],	13 $/kW/year [72], <0.05 $/kW h [210]	Commercialized
Super-capacitor	Seconds–hours [4] short-term(<1 h)[27]	Milliseconds–1 h [4], 1 min[209], 10 s[216]	100–300 [4], 250–450 [216]	300–2000 [4]	0.005 $/kW h [70], ~6 $/kW-year [114]	Developing/demo.
SMES	Minutes–hours [4] short-term (<1 h)[27]	Milliseconds–8 s[4], up to 30 min [209]	200–300 [4], 300 [114], 380–489[216]	1000–10,000 [4], 500–72,000 [114]	0.001 $/kW h [70], 18.5 $/kW/year [72]	Demo/early commercialized
Solar fuel	Hours–months [4]	1–24 h+ [4]	–	–	–	Developing
Hydrogen Fuel cell	Hours–months [4]	Seconds–24 h+ [4]	500 [114], 1500–3000 [154]	15 [114], 2–15€/kW h [204]	0.0019–0.0153 $/kW [154]	Developing/demo.
TES	Minutes–days [4], minutes–months [4]	1–8 h [4], 1–24 h+ [4], 4–13 h [203]	200–300[4], 250 [203], 100–400[203]	20–50 [4], 30–60 [4], 3–30 [4]	–	Demo/early commercialized
Liquid air Storage	Long-term [214]	Several hours [168,214]	900–1900 [214]	260–530 [214]	–	Developing/demo.

Figure 4

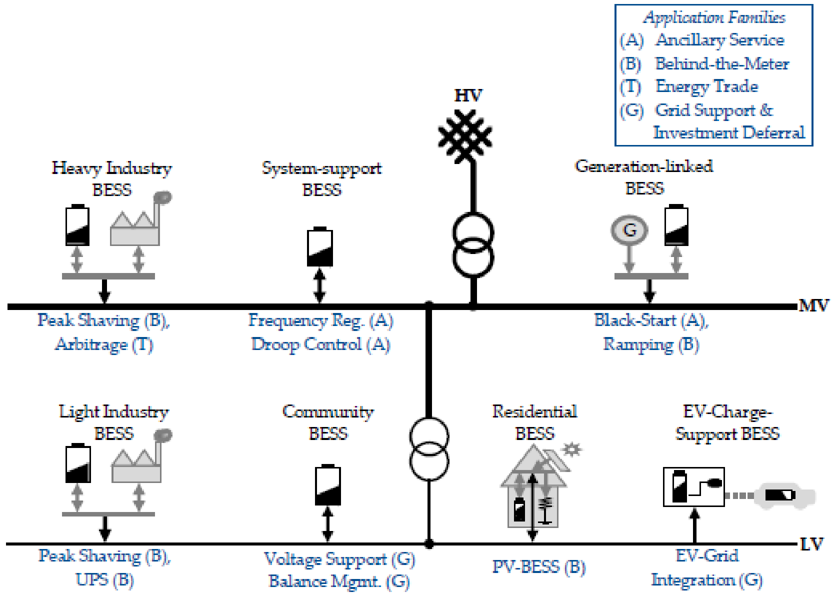

Figure 7. Variant types of stationary battery storage systems (black color) grouped according to their integration to Low-Voltage (LV) and Medium-Voltage (MV) grid levels. Typical applications are listed in blue color, letters in brackets link to *application families* as defined in the figure legend. Overlying High-Voltage (HV) connection and transformer links are depicted schematically.

Table 5. Application tasks of storage systems classified to application families. Source of revenue is listed for an exemplary (ex.) stakeholder via respective storage application.

Application Family	Application	Revenue Stream—$\mathbb{P}_{APL}$	Stakeholder (ex.)
Ancillary Service (A)	Frequency Regulation Black-Start Droop control	Auction Profit ISO Contract DSO/ISO Contract	Enterprise Electric Utility All Feeders
Behind-the-Meter (B)	PV-BESS Peak-Shaving UPS Ramping	Retail Tariff Savings Peak Tariff Reduction Reliability Value Enhancement DSO/ISO Regulation Compliance	Private Sector Industry Industry RES Feeders
Energy Trade (T)	Arbitrage	Energy Exchange Markets	Enterprise
Grid Support and Investment Deferral (G)	Voltage Support EV-Grid Integration Balance Management	Red. Utility Cost Red. Power Link Cost ISO contract	DSO/Enterprise Enterprise DSO
Combined Applications	Multiple Appl. Island-/Micro-Grid V2G	Value Stacking Reduced Fuel Cost Value Stacking	Various Grid Operator Various

Source of Figure 4: Hesse, H., Schipe, M., Kucevic,D., Jossen, A. (2017) Lithium-ion Battery Storage for the Grid – A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids. Energies vol. 10, p. 2107. Available at www.mdpi.com/journal/energies . Accessed March 16, 2019.