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Technology Strategy Assessment

Findings from Storage Innovations 2030

Supercapacitors

July 2023

About Storage Innovations 2030

This technology strategy assessment on supercapacitors, released as part of the Long-Duration Storage Shot, contains the findings from the Storage Innovations (SI) 2030 strategic initiative. The objective of SI 2030 is to develop specific and quantifiable research, development, and deployment (RD&D) pathways to achieve the targets identified in the Long-Duration Storage Shot, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer of energy storage within the coming decade. Through SI 2030, the U.S. Department of Energy (DOE) is aiming to understand, analyze, and enable the innovations required to unlock the potential for long-duration applications in the following technologies:

- Lithium-ion Batteries
- Lead-acid Batteries
- Flow Batteries
- Zinc Batteries
- Sodium Batteries
- Pumped Storage Hydropower
- Compressed Air Energy Storage
- Thermal Energy Storage
- Supercapacitors
- Hydrogen Storage

The findings in this report primarily come from two pillars of SI 2030—the SI Framework and the SI Flight Paths. For more information about the methodologies of each pillar, please reference the SI 2030 Methodology Report, released alongside the ten technology reports.

You can read more about SI 2030 at https://www.energy.gov/oe/storage-innovations-2030.

Acknowledgments

DOE acknowledges all stakeholders who contributed to the SI 2030 industry input process. Further information about the stakeholders who participated in the SI Framework and SI Flight Paths activities can be found in Appendix A. Stan Atcitty and Rob Hovsapian were key to the Flight Paths listening session that helped inform this effort. This report involved significant engagement with subject matter experts and others who are familiar with supercapacitors and energy storage more broadly. Thank you to all of the industry, academic, National Laboratory, and DOE participants who contributed insights that supported this effort.

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Background

Introduction

Electrochemical capacitors, which are commercially called *supercapacitors* or *ultracapacitors*, are a family of energy storage devices with remarkably high specific power compared with other electrochemical storage devices. Supercapacitors do not require a solid dielectric layer between the two electrodes, instead they store energy by accumulating electric charge on porous electrodes filled with an electrolyte solution and separated by an insulating porous membrane. Supercapacitors offer large specific capacitance and high power output. They can be charged and discharged very quickly, offer excellent cycle life and long operational life, and operate over a broad temperature range. The major drawbacks of supercapacitors are low energy density and a high self-discharge rate. For example, a supercapacitor passively discharges from 100% to 50% in a month compared with only 5% for a lithium-ion battery [1]. The high capital cost and low energy density of supercapacitors make the unit cost of energy stored ($/kWh) more expensive than alternatives such as batteries. Their attributes make them attractive for uses in which frequent small charges/discharges are required (e.g., ensuring power quality or providing frequency regulation). Their attributes and cost make them less attractive for long-duration energy storage, which favors technologies with low self-discharge that cost less per unit of energy stored.

High-Level History

Modern supercapacitor principles were first observed in 1957 by General Electric's engineers experimenting with devices using porous carbon electrodes immersed in an electrolyte solution, and then developed by researchers at Standard Oil of Ohio in 1966 [2]. A primary application is in consumer electronic devices where they have a wide range of uses, including filtering signals and storing small amounts of energy for power backup. Advances in supercapacitor materials, construction, and manufacturing techniques improved the performance of supercapacitors. Their key attributes are high power density, high charge and discharge rates, an extreme cycle life (on the order of millions) with high round-trip efficiency, and reliability. These advances and attributes now lead them to be used in a broad range of applications, including providing electric grid services. For example, supercapacitors were used in 2021 to provide a hydropower-based distribution utility with black-start support when in a temporary microgrid configuration as part of a DOE-funded field demonstration [3]. Supercapacitors also have been deployed in combination with solar photovoltaic generation to power the West Thumb Ranger Station in Yellowstone National Park [4].

Current Commercial Uses

Supercapacitors can be used in stand-alone applications or as part of a hybrid energy storage system composed of two or more energy storage technologies. Their applications include the following:

1. **Medical:** Supercapacitors are used in devices such as defibrillators, medical implants (e.g., pacemakers), patient monitoring equipment, and other assorted equipment.
2. **Critical infrastructure:** Supercapacitors are sometimes used to provide ride-through power in critical infrastructure that is typically backed up by large generators, which often take more than 15 seconds to start up.
3. **Industrial and manufacturing:** Supercapacitors often are used on variable-frequency drives that operate critical manufacturing processes to ensure constant voltage. They also

are used in industrial applications that require quick peaking power, such as seaport cranes and forklifts.

4. **Microgrids:** Supercapacitors can be used along with battery energy storage in microgrids and off-grid remote facilities to provide and absorb inrush currents during equipment start-up and during line faults. This reduces the discharge rate and extends the life of the system by maintaining ideal operating temperatures for batteries.
5. **Internet of things devices:** Supercapacitors often are used in devices such as smart door cameras, security cameras, and portable point-of-sale devices to reduce battery cycling and extend the life of such devices. This also results in reduced maintenance.
6. **Electric and hybrid vehicles:** Supercapacitors can be used as part of the energy storage system to provide power during acceleration and capture braking energy by regeneration. They are used in parallel with the batteries and reduce wear by absorbing and providing energy during the constant cycle of multiple braking and accelerating events.
7. **Bulk power systems:** Supercapacitors are used in a flexible alternating current transmission system (FACTS) and in high-voltage direct current transmission to alter the impedance of the line in order to regulate power factor and transmission capabilities by injecting or absorbing reactive power (Figure 1(a)) [5]. They are used in renewable systems integration for improving the power quality of fluctuating renewable generation (Figure 1(b)) [6].

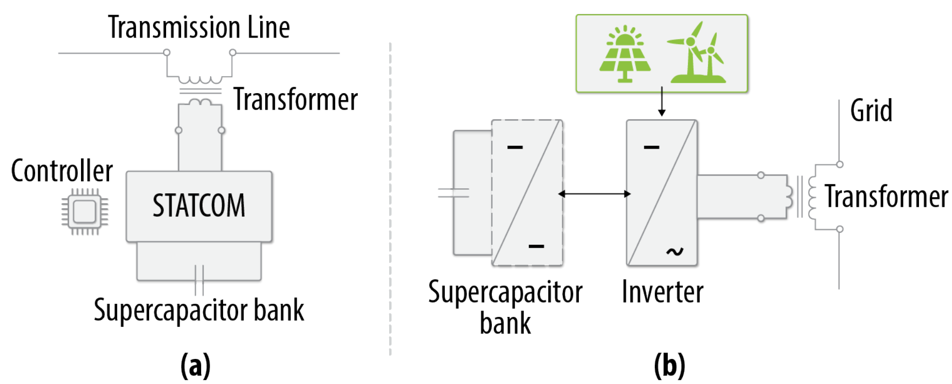

Figure 1. Supercapacitor applications in the bulk-power systems: (a) a schematic of a volt/VAR control using a static compensator with supercapacitors, and (b) a schematic of renewable energy regulation using a supercapacitor bank. (Adapted from [5], [6].)

The global supercapacitor industry was valued at $1.5 billion in 2021 and is expected to experience a compound annual growth rate of 30% from 2021 to 2030 to become a $15 billion industry [7]. The primary driver for this growth is the automotive and consumer electronics sectors, which currently make up 32% and 30% market share, respectively, followed by the energy sector at 21% market share [7]. Hybrid electric vehicles, such as Toyota Yaris-R and the Lamborghini Sián, developed in collaboration with the Massachusetts Institute of Technology, have employed a hybrid gasoline-supercapacitor powertrain to take advantage of the high power density, quick charge/discharge capability of supercapacitors during acceleration and deceleration, and energy recovery from braking system applications [2], [8]. Europe, especially Germany, has been utilizing supercapacitors in their transportation sector for their low-floor trams for a decade. These trams have no overhead lines and rapidly recharge at every stop, which not only reduces the need to build overhead lines but also improves efficiency by 10% to 25% [8]. The addition of a combination of flywheels and a supercapacitor module to the lead-acid battery storage installed in a microgrid on the Scottish Isle of Eigg has improved the life and reduced maintenance of the lead-acid battery storage system. This energy storage system helped with frequency control for smooth grid operation and helped Eigg achieve its 100% renewable energy goal in 2015 [8]. A superior response time and a high discharge rate are the primary reasons that supercapacitors are replacing lead-acid batteries in wind turbine pitch control applications and a combination of supercapacitor and Li-ion battery storage systems in grid storage applications [9].

Types of Supercapacitors

Supercapacitors can be divided into three types based on the charge storing mechanism (Figure 2, Table 1): electrochemical double-layer capacitors, pseudocapacitors, and hybrid electrochemical capacitors.

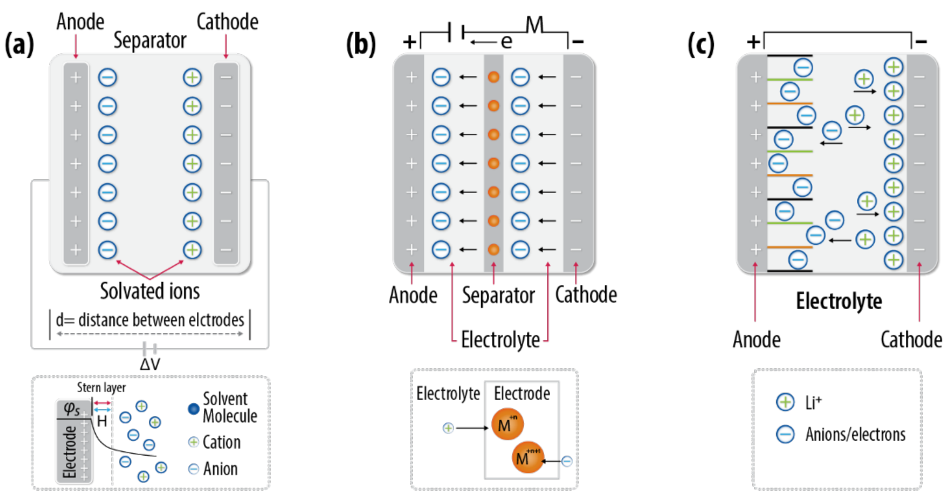

Figure 2. Schematics of three types of supercapacitors: (a) electrochemical double-layer capacitor, (b) pseudocapacitor, and (c) asymmetric/hybrid electrochemical capacitor. (Adapted from [10].)

Electrochemical double-layer capacitors (EDLCs) use two similar electrodes based on active carbon to form two capacitors with the electrolyte (Figure 2(a)). Charges are distributed on the surfaces by physical processes involving no chemical reactions. They exhibit a fast response to charge/discharge and good cycling stability; however, they also exhibit a higher self-discharge rate. The performance characteristics of an EDLC can be adjusted for different applications by changing the electrolyte.

Pseudocapacitors (PCs) use transition metal oxide-based electrodes to form highly reversable redox (faradaic) reactions, which store energy by transferring charge between the electrode and the electrolyte (Figure 2(b)). These faradaic processes allow PCs to achieve greater capacitances and energy densities than EDLCs, which involve only the electric double-layer effect at the electrode/electrolyte interface and no reactions at the electrodes.

Hybrid electrochemical capacitors (HECs), also called *asymmetrical capacitors*, use different anode and cathode materials. The cathode is similar to EDLC and the anode is like that used in a metal oxide-doped carbon electrode (Figure 2(c)). This asymmetry implements both faradaic and non-faradaic processes to store charge, leading to energy and power densities greater than EDLCs without sacrificing the cycling stability and affordability that have limited the success of PCs.

Table 1. Comparison of attributes for three types of supercapacitors

Type	Charge Mechanism	Advantages	Disadvantages
Electrochemical double-layer capacitor (EDLC)	Physical surface adsorption and desorption	Fast charge/discharge; excellent cycle life (up to 1M cycle life); easy to fabricate, leading to a lower cost	Low energy density (less than 8 Wh kg^{-1}), higher self-discharge rate
Pseudocapacitor	Highly reversible surface redox (faradaic) reactions	Higher energy density (more than 10 Wh kg^{-1}) and capacitance compared with EDLCs, higher cost compared with EDLCs	Slightly lower cycle life (up to 200,000 cycles) [11]
Hybrid (composite, asymmetric, or battery-type) capacitor	Adsorption and desorption at one electrode and faradaic reactions at the other	Higher power and up to 10 times the energy density of EDLC [12], lower discharge rate	Lower cycle life compared with other types (up to 100,000 cycle life) [12]; complex design, leading to a higher cost

Baseline Cost

EDLCs are the most mature of the three supercapacitor types [13]. Unlike the other technologies studied under Storage Innovations 2030 that use 2030 estimates as the baseline [14], the latest estimates for the baseline cost and performance parameters for EDLCs are based on 2025 estimates [15] (see the cost and performance parameters in Table ES.2) [15]. The size of the supercapacitor used to estimate the cost has a power rating of 1 MW, is able to discharge for 45 seconds, and is able to cycle 1 million times; these parameters are consistent with the K. Mongird et al. report [15]. The lower estimate of $240/kW was used for the DC storage block cost, which when divided by the duration of 0.0125 hour (45 seconds) provides $19,200/kWh. A similar technique was used to convert cost to kilowatt-hours for the balance of plant costs.

The cost components for controls and communication, power equipment, system integration, project development, engineering procurement, construction, and grid integration were outdated according to the K. Mongird et al. report, and hence were derived using the 2025 estimates for lead-acid battery from the V. Viswanathan et al. report [14]. The 2025 estimates were developed based on the learning rates for each of these cost components [14]. Lead-acid battery numbers for these parameters were chosen because the requirements are similar between supercapacitors and lead-acid batteries in some grid applications [16].

EDLCs are best suited for short-duration applications, such as primary and secondary responses that require 30 minutes or less of operation per day [17]. The EDLC considered for this study is assumed to cycle 40 times per day, corresponding to a daily operational time of 30 minutes per day. Note that increasing the number of cycles per day would decrease the assessed levelized cost of storage (LCOS). EDLCs have very high round-trip efficiency (92%) and are capable of 100% depth of discharge [17]. The LCOS for EDLCs depends on the usable cycles during its 16-year shelf life.

Table 2. EDLC cost and performance estimates for 1 MW, 45 seconds of storage (2025 estimates)

Parameter	Value	Description
Storage block calendar life	16	Deployment life (years)
Cycle life	1,000,000	Baseline total number of cycles
Cycles per day	40	Number of charge-discharge cycles per day
Round-trip efficiency (RTE)	92%	Baseline RTE
Storage block costs	19,200	Baseline storage block costs ($/kWh)
Balance of plant costs	7,600	Baseline balance of plant costs ($/kWh)

Controls and communication costs[a]	33.04	Controls and communication costs ($/kW)
Power equipment costs[a]	142.5	Power equipment costs ($/kW)
System integration costs[a]	7,824	System integration costs ($/kWh)
Project development costs[a]	11,058	Project development costs ($/kWh)
Engineering, procurement, and construction (EPC) costs[a]	8,731	EPC costs ($/kWh)
Grid integration costs[a]	27.73	Grid integration costs ($/kW)
Fixed operations and maintenance (O&M) costs	1	Baseline fixed O&M costs ($/kW-year)
Variable O&M costs	0.0003	Baseline variable O&M costs ($/kWh)
Levelized cost of storage (LCOS)	0.443	Baseline estimate of LCOS ($/kWh-cycle)

Pathways to $0.05/kWh

A subgroup of the authors of this report worked individually with 15 subject matter experts (SMEs) to understand the supercapacitor innovations that are currently being investigated, cost projections, and possible DOE interventions to achieve technical advancements and cost reductions. The group of SMEs included representatives from universities, consultants, startups, and large industry manufacturers (the names and affiliations of the SMEs are provided in Appendix A). Then, based on information gathered individually from these SMEs, the research team identified 14 potential interventions/innovations where DOE support could be useful (see Table 3, the innovations in italics are ones that were identified as being important but did not receive enough data for analysis; the details of the innovations are provided in Appendix B). Most of the innovations and interventions provided correspond to EDLC-type capacitors. Therefore, simulations on pathways to achieve $0.05/kWh only are conducted for EDLCs. Qualitative descriptions of innovations for PCs and HECs are provided in the latter portion of this report.

Table 3. List of innovations identified for supercapacitors based on SMEs' input

Innovation Category	Innovation
Raw materials sourcing	Alternative sources of activated carbon
Supply chain	Controlled overseas manufacturing
Technology components	Module development
	Hybrid components
Advanced materials development	High-voltage electrolytes
	High-carbon electrodes
	Processes for creating sustainable activated carbon[b]
	Hybrid supercapacitors[b]
Manufacturing	Cell packaging
	Automated manufacturing
	Advanced materials manufacturing
Deployment	*Demonstration support*[b]
	Policy support[b]
	Human resources development[b]

The parameters of each innovation (e.g., cost of innovation, time to achieve, cost and performance gains) provided by the SMEs were fit to a distribution and used as input to a Monte Carlo simulation. The impact on LCOS was then evaluated based on combining multiple innovations in a portfolio and calculating the collective impact within a given portfolio. Each portfolio is formed by using all possible

[a] These cost estimates were not available for supercapacitors and were taken from the 2021 cost estimates for a 1-MW lead-acid battery [14].

[b] These innovations were identified during the initial interviews with SMEs but did not receive feedback regarding impact, investment requirements, and timeline from the follow-up. Hence, these innovations were not included in the Monte Carlo simulation and analysis.

combinations of two to eight innovations as described in the Methodology report. The LCOS impact of each portfolio was applied to the 2025 estimates of EDLC storage baseline parameters shown in Table 2; 2025 is used here rather than 2030 because of limitations in the availability of the cost and performance estimates.

The range of LCOS for portfolios performing in the top 10% (i.e., producing the lowest LCOS) is $0.330 to 0.344/kWh-cycle, which is a 23% to 26% reduction relative to the baseline 2025 projections (Figure 3). These portfolio LCOS values are constructed using the means of the distribution of the Monte Carlo simulation results for the given portfolio. Therefore, if the realized innovation impacts are larger than the mean of the output, LCOS reductions could be even larger than shown here. More than 80% of the portfolios achieve at least a 12% reduction in LCOS, which corresponds to a final LCOS of $0.39/kWh-cycle.

The Monte Carlo simulations suggest that the mean investment for portfolios performing in the top 10% is $86 million and would take between 4 and 7 years to realize their potential (Figure 4). Most of the innovations provided by the SMEs are refinements of current technology that produce incremental gains rather than radical departures that create very large costs or performance improvements. Thus, the distribution of these top-performing portfolios is relatively flat.

The SMEs also provided their individual insights on how these innovations should be funded (Table 4). Cells with asterisks (*) represent the most preferred channels of funding. The SMEs believe that most of the innovations are best achieved through research and development (R&D) grants. Innovations under the Manufacturing category show a preference for both loans and grants, which makes sense given that these are innovations with a higher technology readiness level. Most of the manufacturing occurs overseas and, therefore, loans and financial assistance for domestic companies could incentivize onshoring.

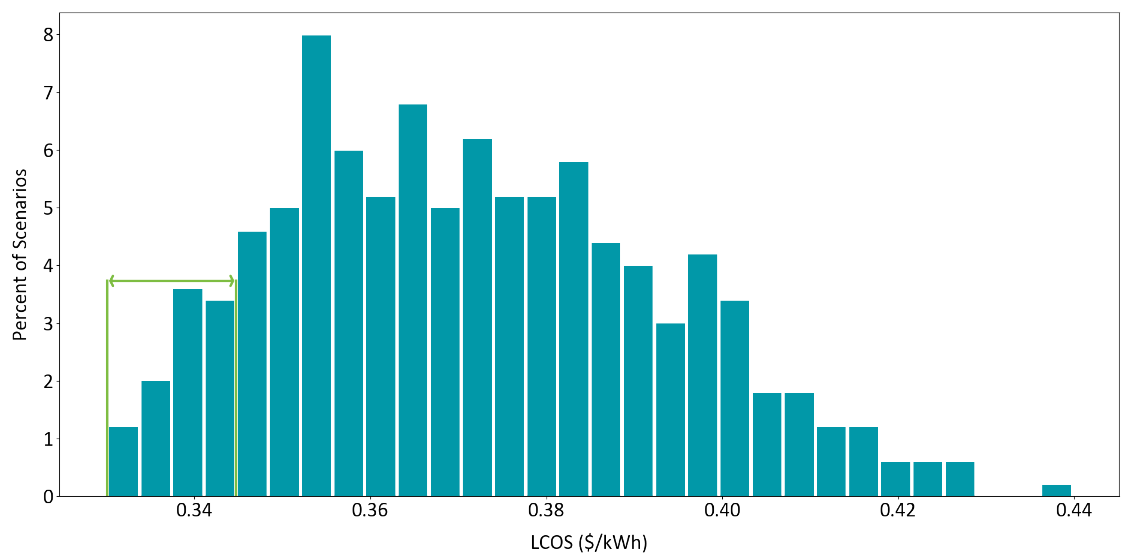

Figure 3. Distribution of effective LCOS based on the impact of all portfolios containing two to eight innovations/interventions per portfolio. The marked region shows the top 10% of the portfolios that achieve the greatest LCOS reductions.

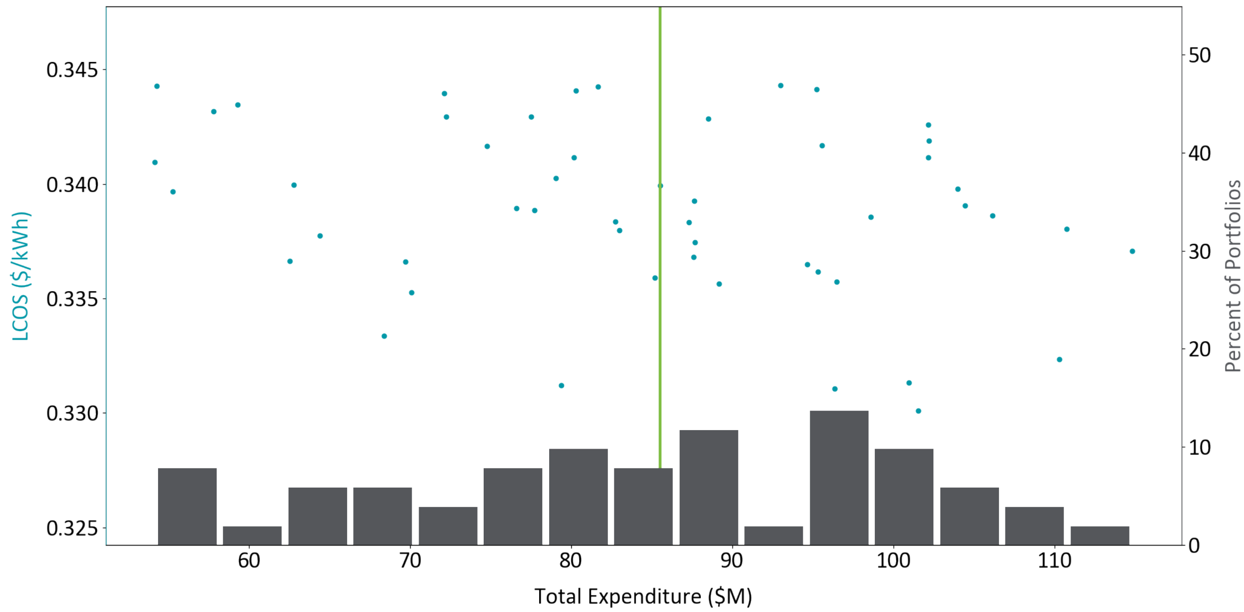

Figure 4. Scatter plot where each dot represents LCOS with respect to the expenditures of a portfolio performing in the top 10%, aligned with the histogram representing the percentage of top-performing portfolios (y-axis on the left) and the percentage of portfolios within an expenditure bin (y-axis on the right)

Table 4. SMEs' preferences for investment mechanisms. (Technical Assistance includes advice or guidance on issues or goals, tools and maps, and training provided by government agencies or National Laboratories to support industry.)

Innovation	National Laboratory Research	R&D Grants	Loans	Technical Assistance
Alternative sources of activated carbon	0%	67% *	33%	67% *
Controlled overseas manufacturing	0%	67% *	33%	33%
Module development	50%	50%	50%	0%
Hybrid components	50%	50%	50%	0%
High-voltage electrolytes	75%	100% *	0%	25%
High-carbon electrodes	75%	100% *	0%	25%
Cell packaging	50%	75% *	50%	25%
Automated manufacturing	0%	67% *	67% *	33%
Advanced materials manufacturing	0%	67% *	67% *	33%

The primary driver for the reduction in LCOS for supercapacitors is the use condition with many cycles per day. Innovations in supercapacitor technology to reduce storage block cost and LCOS are listed in Figure 5. Cell packaging and hybrid components were the most commonly present innovations in portfolios performing in the top 10%. As mentioned earlier in this report, each portfolio consists of two to eight innovations; therefore, the portion of the portfolios in the top 10% in which a given innovation is contained is indicative of its importance to achieving the largest LCOS reductions.

Manufacturing is key to storage block costs and, thus, LCOS reductions because three of the top four innovations among the top-performing portfolios come from this innovation category. Most of the innovations are oriented toward improving the carbon material because it is the most important and expensive component of a supercapacitor. A detailed description of how each of these innovations interact with one another within the Monte Carlo model is presented in Appendix C.

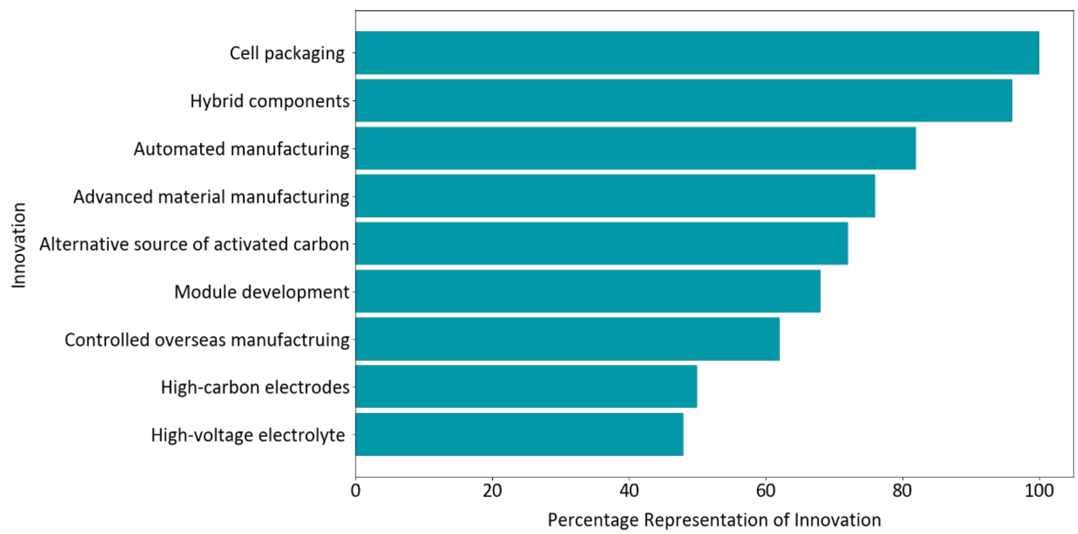

Figure 5. Representation of innovations in portfolios performing in the top 10% (resulting in the lowest LCOS)

R&D Opportunities

The Framework and Flight Paths sessions with multiple industry members and SMEs identified R&D opportunities for each of the three types of supercapacitors. This section summarizes these opportunities based on each type.

Electrochemical Double-Layer Capacitors

The most significant challenges for EDLC adoption in the power system are poor energy density and high costs. Most of the innovations identified during the Framework and Flight Paths sessions center on improving these weaknesses.

When the SMEs were asked how to improve the specific energy (E_{cap}) from supercapacitors, the majority of the innovations were directed toward increasing capacitance (C) rather than voltage (V), even though capacity scales with the square of voltage:

$$E_{cap} = \frac{CV^2}{2} \qquad (1)$$

One of the critical reasons that SMEs do not focus on voltage is that they believe increasing voltage will decrease reliability. The current standard for voltages for supercapacitors is 2.7 to 3.0V for commercial EDLCs [2]. However, some SMEs did suggest improving the electrolytes to withstand voltages over 3.6V.

The active material used in a supercapacitor determines the capacitance of the device. The most commonly used electrode material in EDLCs—activated carbon—is derived from coconut shells and is manufactured in Japan and other Southeast Asian countries. Complete dependency of the most critical component of an EDLC on a single material that is manufactured overseas may increase the risk of cost and supply chain instability.

Materials make up 71% of the cost to manufacture an EDLC; of this percentage, the most significant cost component is the active material [18]. During a listening session, an industrial manufacturer pointed out that the activated carbon must be below $10/kg for EDLCs to be economical (currently $15/kg). SMEs highlighted the need to develop activated carbon material from diverse sources. Diverse sourcing will introduce competition and price stability. Purifying the active material and processing it for use also is expensive and energy intensive. The specific processing required varies depending on the type of active material. Therefore, manufacturing and processing innovations are needed in order to adopt new active materials.

Graphene and carbon nanotubes are promising active materials that were mentioned by multiple SMEs. Graphene is a highly conductive material derived from a single layer of graphite that increases the surface area of the electrode and hence the capacitance. SMEs claimed that using graphene increases the energy density by 72% [19]. Manufacturing graphene at scale is a significant challenge that both the lithium-ion battery and supercapacitor industries are investigating. However, industry and manufacturing SMEs expressed that many improvements in graphene manufacturing are required for it to be cost competitive in large quantities. Unless the graphene costs are competitive with those of the activated carbon, the increase in energy density would not significantly affect LCOS.

By far, the most cost-effective innovations identified were improvements to cell packaging and module development. Cell packaging has been identified as the most common innovation among the top-performing portfolios (Figure 5). Developing pouch cells is important for increasing the surface area when compared with cylindrical aluminum cells. This innovation would both improve energy density and reduce costs. Industry and manufacturers are already looking into this; however, most of the SMEs stated that improvements to manufacturing would accelerate the development of these high energy density pouch cells.

Module development is seen as another cost-reducing innovation that industry is already examining but where additional support could accelerate and enhance development. Participants mentioned that these module innovations are already becoming attractive for pitch control in wind turbines, leading to significantly reduced maintenance and replacement costs and increased safety relative to the traditionally used lead-acid batteries [9], [16]. DOE support could focus industry on identifying additional power system use cases for EDLCs and helping set the design requirements to meet the needs for these use cases.

There has been substantial discussion around the hybridization of EDLC supercapacitors and other energy storage devices, such as lithium-ion batteries or pumped storage hydropower, to meet long-duration storage needs. This hybrid setup takes advantage of the high power density of the supercapacitors and high energy density of other energy storage technologies. Theoretically, these hybrid pairings are beneficial; however, more work is needed on the power electronics and controls to assess and prove that hybridization will provide benefits in practice. Research also is required to develop hybrid modules that could be directly integrated in systems to make hybridization mainstream.

Hybrid Supercapacitors

Hybrid electrochemical supercapacitors (HEC) have a cathode like that of an EDLC and a carbon anode that is doped with metal oxides such as lithium titanate. The asymmetry in the electrode properties gives them increased energy density. The type of electrolyte determines the voltage level that can be achieved with these types of supercapacitors. Some SMEs believe that aqueous asymmetrical supercapacitors (AASCs) that incorporate liquid electrolyte with a battery electrode are a promising variety of HEC. While AASCs have higher energy density, they have lower cycle life and reliability than EDLCs.

SMEs believe that HEC can compete with batteries for applications where high charge and discharge rates are valuable. For example, HEC may be cost competitive for providing frequency regulation but not for providing multi-hour energy shifting. In general, the tradeoff with HEC is that increasing the energy density leads to a reduction in the cycle life. The cycle life and energy density benefits depend on the materials used, such as electrolytes and electrodes. HEC with Zn-based electrode chemistries have been shown to have cycle lives of up to 100,000 (ten times less than EDLCs) and energy densities more than over 30 times those of EDLCs in the range of 180 to 220 Wh kg^{-1} [12].

Another promising trend with regard to AASCs is the use of thicker electrodes to increase the energy density [20]. A thick electrode could increase the loading of the active material and provide more charge accumulation sites. However, increasing the electrode thickness may make it difficult to transport electrons and ions in the direction of the electrode thickness and separator, and may decrease the specific capacitance. Careful design of the electrode structure and selection of materials are needed for improved performance. SMEs expressed that AASCs with thick electrodes using low-cost carbon materials are a very promising area of research in supercapacitors for grid-scale energy storage applications. This is the industry perspective, and it is independent from the Monte Carlo analysis conducted for this report.

Another industrial HEC manufacturer and SME mentioned combining a supercapacitor electrode with a lead-acid battery to improve the response time for automotive and grid applications. It also was mentioned that this technology is expensive and is not competitive with other technologies in the market, such as lithium-ion battery, and adoption has been slow due to cost constraints.

Pseudocapacitors

Pseudocapacitors (PCs) rely on highly reversible surface redox (faradaic) reactions, which involve the transfer of charge between the electrode and electrolyte to store energy. Such reactions, however, are often limited to the surface so that the reaction rate is not limited by the ion diffusion into the bulk of the electrode material. While PCs have promising characteristics, they are still in an early stage and therefore not much information on innovations was gathered from the SMEs. Thus, the discussion on PCs is limited to challenges.

Higher specific capacitance can be reached with PCs because the density of the redox sites on the electrode surface can be significantly larger than the density of the ions absorbed in a traditional EDLC. This results in PCs being able to store 10 to 100 times more electrical energy per surface area than a pure EDLC [2]. The two electrode materials used to store charge in PCs are conducting polymers and transition metal oxides. The most frequently used conducting polymers are polyaniline, polypyrrole, and derivatives of polythiophene [21]. Ruthenium oxide is the most explored metal oxide for PCs. The two challenges associated with these materials are that the resulting PCs swell and contract during charging or discharging, causing degradation and potential safety issues, resulting in a cycle life of approximately 200,000 (five times less than for EDLCs). Other possible metal oxides are nickel oxide, cobalt oxide, vanadium oxide, manganese oxide, and zinc oxide [21]. More foundational R&D is needed in this area to determine which, if any, metal oxides are promising and will substantively impact the LCOS of the resulting PC.

Additional Opportunities and Discussion

SMEs cited a lack of awareness about supercapacitor benefits and capabilities for the power system and the significant challenge of integration into the broader energy storage conversation. Supercapacitors are developed within a small industry relative to other types of energy storage, such as batteries. Lithium-ion batteries have become the dominant storage technology for most grid applications through significant investment in innovation and scale-up of deployment, as well as the corresponding increased power densities at less cost. SMEs believe that awareness of supercapacitors and their capabilities is important for deploying supercapacitors for use cases where they can be competitive. Awareness about supercapacitors can be improved by including them in conversations at storage conventions on par with other storage technologies and also funding demonstration projects. A challenge for grid applications is that most of the active supercapacitor companies and all of the manufacturing are found in Asia. Within the United States, it is currently challenging to acquire the supercapacitors appropriate for grid applications.

A large part of the cost of supercapacitors comes from the active carbon material that is produced from char (incomplete combustion of natural gas and oils) and biochar products. Biochar is the carbon produced by pyrolysis of biomass sources. Currently, coconut shells are the primary source of material to produce activated carbon via biochar. There are several other potential agricultural sources, such as hardwood, nutshells, corn stalks, and hemp stalks, which could be used in the future as well. Sourcing these materials from the United States can support U.S. manufacturing of supercapacitors and increase investment in historically underserved communities and promote rural economic development [22].

Policy and market rules play an important role in how supercapacitors are used in the current power system. While supercapacitors can provide valuable electrical functions for the grid, sometimes rules and regulations are defined in such a way that supercapacitors do not meet the criteria. For example, while supercapacitors have high charge and discharge rates and therefore may be well suited to provide frequency regulation in the grid [17], regulation markets often have requirements regarding the minimum duration of a participating resource, which is often longer than what supercapacitors can economically provide [23], [24]. Lithium-ion batteries can have a higher LCOS compared with supercapacitors for certain regulation services but are still used for this because of these market barriers [17].

For example, a supercapacitor with a 45-second duration, 16-year shelf life, and a million-cycle life would outlast the shelf life by four times when cycled 40 times a day and have an LCOS of $0.44/kWh-cycle. If the same supercapacitor were to cycle 160 times a day, the baseline LCOS would be $0.11/kWh-cycle. Based on this principle, SMEs individually provided suggestions to analyze the market design to determine whether there were alternative structures that would meet grid requirements at a lower cost based on a wide spectrum of existing technologies, including supercapacitors. SMEs suggested that the revenue evaluation for regulation services be designed for a smaller time period (less than 5 minutes) rather than the 15 minutes that many markets currently employ.

Demonstration support is key to any technology going from laboratory to manufacturing scale-up for mass adoption. In the case of supercapacitors, demonstrations also would help educate customers about the capabilities of supercapacitor storage. An objective of such a demonstration would be to increase demand and therefore help supercapacitors achieve economies of scale. SMEs from both the sessions (Framework and Flight Paths) suggested providing financial support for demonstrations across multiple sectors, including mobility, telecommunications, power, and industry.

SMEs also called out financial support for U.S. manufacturing as key to improving price stability. This also would require investing in U.S. sources of active materials. Industrial incentives for importing or developing advanced manufacturing equipment for supercapacitor packaging for improved energy density and reduced costs also are identified.

As mentioned multiple times in this report, supercapacitors have not been traditionally well suited for stand-alone, long-duration energy storage but may have substantial benefit when hybridized with complementary storage technologies. Ideal combinations are those in which the strengths of one technology offset the weaknesses of another. For example, supercapacitors have a very high cycle life and fast charge/discharge rates but low energy density; lithium-ion batteries have lower cycle life and slower charge/discharge rates but much higher energy density. Therefore, hybridization of supercapacitors and lithium-ion batteries may provide benefits if the controls and hybrid system are optimized for a specific use case.

Key Innovations

Even though supercapacitors have been around for more than 50 years and are ubiquitous across a range of applications, they have remained underutilized within the power system. The three main reasons cited for this are the low energy density, high costs, and lack of knowledge of supercapacitor benefits. In summary, the key innovations that address these challenges are as follows (also see Table 5):

- **Cost Reductions**
    - Diversification of active materials and development of the corresponding cost-effective ways in which to purify and process the activated carbon
    - Development of modules and cell packaging techniques that can be efficiently manufactured and are designed for specific use cases
    - Design of HEC cells of various capacities and cycle life that are tailored to specific power system use cases
- **Energy Density Improvements**
    - Development of carbon nanotubes and graphene-based electrodes
    - Development of curved graphene manufacturing technologies for the mass market
- **Increased Awareness**
    - Analysis to find where supercapacitors are well suited to serve the grid needs
    - Analysis of potential hybridized energy storage technologies with respect to the combined cost and performance relative to the grid need
    - Funding of demonstration projects

Table 5. Key opportunities identified from the Framework and Flight Paths sessions

	R&D Physical Components	R&D Non-Physical Advances
Flight Paths	Active materials Aqueous electrolytes	Demonstration support Policies and incentives development for supercapacitors Development of standards and regulations specific to supercapacitors Knowledge of power system applications: power and energy curves
Framework	Graphene manufacturing Activated carbon Hybrid components Cell and modules development	Demonstration support Customer education about the benefits of supercapacitors Capital support to ramp up manufacturing Policy and regulatory changes to take advantage of supercapacitors

Appendix A: Industry Contributors

Table A.1. List of SMEs contributing to the Framework analysis

Subject Matter Expert	Affiliation
Alex Nichols	Florrent Technologies
Andrew Burke	University of California, Davis
Dave Wright	UCAP Power, Maxwell Technologies
Jason Plee	Eaton Industries
Jeremy Wilkes	Rell Capacitors
Jose LaSalle	Florrent Technologies
Linghong Li	DAE Technologies, Inc.
Lun Jiang	Rell Capacitors
Marty Mills	LICAP Technologies
Michael Liedtke	Self-Employed
Ray Ragonese	LICAP Technologies
Scott Jorgensen	Hyrax Intercontinental
Sebastian Pohlmann	Skeleton Technologies

Appendix B: Innovation Matrix and Definitions

Table B.1. List of innovations by innovation category. Some innovations apply to cavern storage and tank storage; however, some only apply to tank storage.

Innovation Category	Innovation
Raw materials sourcing	Alternative sources of activated carbon
Supply chain	Controlled overseas manufacturing
Technology components	Module development
	Hybrid components
Advanced materials development	High-voltage electrolytes
	High-carbon electrodes
	Sustainable activated carbon
	Hybrid ultracapacitors
Manufacturing	Cell packaging
	Automated manufacturing
	Advanced materials manufacturing
Deployment	Demonstration support
	Policy support
	Human resources development

Alternative sources of activated carbon: Researching alternative sources of raw materials that are cheap and sustainable in order to extract activated carbon other than the existing coconut shell and graphene.

Controlled overseas manufacturing: Investing in controlled sourcing and manufacturing of activated carbon material from overseas factories.

Module development: Developing modules that can be ready for integration in a system, specifically designing modules that cater to the power system/stationary system use case.

Hybrid components: Researching and developing software and power electronics for hybrid ultracapacitors with other storage technologies that can be integrated in the system.

High-voltage electrolytes: Researching and developing separators/electrolyte material that can support voltages above 3.6V and yet be dependable for high cycle life.

High-carbon electrodes: Developing high-carbon electrodes that improve surface area and can withstand even high voltages reliably.

Sustainable activated carbon: Creating new or modified processes for developing activated carbon from raw materials that are sourced from sustainable agricultural products in the United States or prepared from other biomaterials in the laboratory with high purity and controlled porosity.

Hybrid ultracapacitors: Improving the number of cycles and the reliability of lithium or other metal oxide-based hybrid capacitors while still achieving a high charge-rate.

Cell packaging: Innovating cell packaging that opens up an opportunity to improve surface area, such as a pouch cell, and allows the ability to automate manufacturing.

Automated manufacturing: Funding and providing capital support for manufacturing equipment that can improve and automate the processing of activated carbon.

Advanced materials manufacturing: Funding and providing capital support for manufacturing graphene and carbon nanotubes on an automated-factory scale to improve the capacitance of ultracapacitors.

Demonstration support: Funding demonstration projects that will educate the power grid infrastructure and automobile sectors about the capabilities of ultracapacitors.

Policy support: Funding policy studies that demonstrate the importance of ultracapacitors in grids, which will result in regulations that allow the participation of ultracapacitors.

Human resources development: Funding and investing in knowledge development about ultracapacitors—from university research to manufacturing skills development.

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Alternative sources of activated carbon	Controlled overseas manufacturing	Module development	Hybrid components	High-voltage electrolytes	High-carbon electrodes	Cell packaging	Automated manufacturing	Advanced materials manufacturing
Alternative sources of activated carbon	–	0.50	1.00	1.00	1.00	0.25	1.00	1.00	0.50
Controlled overseas manufacturing	0.50	–	1.00	1.00	1.00	1.00	1.00	0.75	0.75
Module development	1.00	1.00	–	1.00	1.00	1.00	0.75	1.00	1.00
Hybrid components	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00	1.00
High-voltage electrolytes	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00	1.00
High-carbon electrodes	0.25	1.00	1.00	1.00	1.00	–	1.00	1.00	1.00
Cell packaging	1.00	1.00	0.75	1.00	1.00	1.00	–	1.00	1.00
Automated manufacturing	1.00	0.75	1.00	1.00	1.00	1.00	1.00	–	1.00
Advanced materials manufacturing	0.50	0.75	1.00	1.00	1.00	1.00	1.00	1.00	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation	Budget_low	Budget_high	Budget_mean	Budget_std	Timeline_low	Timeline_high	Timeline_mean	Timeline_std	sbc_low	sbc_high	sbc_mean	sbc_std	cyc_low	cyc_high	cyc_mean	cyc_std
Alternative sources of activated carbon	2	20	7.75	5.99	1.5	8	4.06	2.18	-0.3	-0.1	-0.20	0.09	0	0	0	0
Controlled overseas manufacturing	1.5	20	9.88	7.59	1.5	5	3.33	1.47	-0.15	-0.08	-0.11	0.03	0	0	0	0
Module development	1	30	9.75	10.14	1	10	3.75	2.92	-0.12	-0.05	-0.09	0.04	0	0	0	0
Hybrid components	2	20	7.67	6.59	2	5	3.33	1.51	-0.12	-0.08	-0.10	0.02	0	0	0	0
High-voltage electrolytes	3	50	21.88	19.10	2	10	5.38	2.83	-0.1	0.1	-0.01	0.10	0	0	0	0
High-carbon electrodes	3	40	15.63	13.26	2	8	4.50	2.14	-0.15	0.1	-0.03	0.12	0	0	0	0
Cell packaging	2	20	9.38	7.65	2	5	3.25	1.49	-0.35	-0.1	-0.21	0.10	0.1	0.1	0.1	0
Automated manufacturing	2	40	12.50	15.00	2	5	3.17	1.47	-0.15	-0.05	-0.10	0.03	0	0	0	0
Advanced materials manufacturing	3	20	7.67	6.28	2	5	3.67	1.51	-0.25	-0.1	-0.19	0.08	0	0	0	0

sbc = storage block cost

Innovation	rte_low	rte_high	rte_mean	rte_std	bpc_low	bpc_high	bpc_mean	bpc_std	fom_low	fom_high	fom_mean	fom_std	vom_low	vom_high	vom_mean	vom_std
Alternative sources of activated carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Controlled overseas manufacturing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Module development	0	0	0	0	-0.15	-0.05	-0.083	0.058	0	0	0	0	0	0	0	0
Hybrid components	0	0	0	0	-0.25	-0.1	-0.200	0.087	0	0	0	0	0	0	0	0
High-voltage electrolytes	0	0	0	0	0	0	0.000	0.000	0	0	0	0	0	0	0	0
High-carbon electrodes	0	0	0	0	0	0	0.000	0.000	0	0	0	0	0	0	0	0
Cell packaging	0	0	0	0	-0.3	-0.15	-0.233	0.076	0	0	0	0	0	0	0	0
Automated manufacturing	0	0	0	0	-0.15	-0.05	-0.100	0.050	0	0	0	0	0	0	0	0
Advanced materials manufacturing	0	0	0	0	0	0	0.000	0.000	0	0	0	0	-0.15	-0.07	-0.11	0.04

rte = round-trip efficiency, bpc = balance of plant cost, fom = fixed operations and maintenance, vom = variable operations and maintenance

References

[1] Battery University, "BU-209: How does a Supercapacitor Work?," Battery University Group, [Online]. Available: https://batteryuniversity.com/article/bu-209-how-does-a-supercapacitor-work.

[2] M. E. Sahin, F. Blaabjerg, and A. Sangwongwanich, "A comprehensive review on supercapacitor applications and development," *Energies,* vol. 155, no. 674, 2022.

[3] S. M. Shafiul Alam, R. Bhattarai, T. Hussain, V. Gevorgian, S. Shah, Y. N. Velaga, M. Roberts, T. M. Mosier, J. A. Alzamora, B. Jenkins, and P. Koralewicz, "Enhancing Local Grid Resilience with Small Hydropower Hybrids: Proving the concept through demonstration, simulation, and analysis with Idaho Falls Power," Idaho National Laboratory, Idaho Falls, ID, 2022.

[4] L. Cohn, "US Utility Invests in Kilowatt Labs to Boost Service with Microgrids," Microgrid Knowledge, 19 Nov. 2018. [Online]. Available: https://www.microgridknowledge.com/google-news-feed/article/11430095/us-utility-invests-in-kilowatt-labs-to-boost-service-with-microgrids.

[5] F. Bensmaine, O. Bachelier, S. Tnani, G. Champenois, and E. Mouni, "LMI approach of state-feedback controller design for a STATCOM-supercapacitors energy storage system associated with a wind generation," *Energy Conversion and Management*, vol. 96, pp. 463-472, 2015.

[6] M. F. Elmorshedy, M. R. Elkadeem, K. M. Kotb, I. B. M. Taha, and D. Mazzeo, "Optimal design and energy management of an isolated fully renewable energy system integrating batteries and supercapacitors," *Energy Conversion and Management,* vol. 245, 2021.

[7] Verified Market Research, "Global Supercapacitors/Ultracapacitors Market Size by Product (Electric Double-layered Capacitors (EDLCs), Pseudo Capacitors, & Hybrid Capacitors), by Application (Automotive, Energy, Consumer Electronics, & Industrial), by Geographic Scope and Forecast," Verified Market Research, 2023.

[8] InnoEnergy Scandinavia, "Unlocking New Possibilities Through Innovative Energy Storage: The Role of Ultracapacitors in the Energy Transition," InnoEnergy and Frost & Sullivan, 2020.

[9] A. Castaignet, "Skeleton's modules are replacing lead-acid batteries for a global leader in wind power," Skeleton Technologies, 26 April 2021. [Online]. Available: https://www.skeletontech.com/skeleton-blog/skeletons-modules-are-replacing-lead-acid-batteries-for-a-global-leader-in-wind-power.

[10] S. W. Bokhari, A. H. Siddique, P. C. Sherrell, X. Yue, K. M. Karumbaiah, S. Wei, A. V. Ellis, and W. Gao, "Advances in graphene-based supercapacitor electrodes," *Energy Reports,* vol. 6, pp. 2768-2784, 2020.

[11] A. Burke, "Ultracapacitor technologies and application in hybrid and electric vehicles," *Int. J. Energy Res.,* vol. 34, pp. 133-151, 2010.

[12] C. Wang, Z. Pei, Q. Meng, C. Zhang, X. Sui, Z. Yuan, S. Wang, and Y. Chen, "Toward flexible zinc-ion hybrid capacitors with superhigh energy density and ultralong cycling life: the pivotal

role of $ZnCl_2$ salt-based electrolytes," *Angewandte Chemie* (International Edition), vol. 60, no. 2, pp. 990-997, 2021.

[13] K. Mongird, V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, and B. Hadjerioua, "An evaluation of energy storage cost and performance characteristics," *Energies*, vol. 13, no. 3307, 2020.

[14] V. Viswanathan, K. Mongird, R. Franks, X. Li, V. Sprenkle, and R. Baxter, "Grid Energy Storage Technology and Performance Assessment," Pacific Northwest National Laboratory, Richland, WA, and Mustang Prairie Energy, PNNL-33283, 2022.

[15] K. Mongird, V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, and B. Hadjerioua, "Energy Storage Technology and Cost Characterization Report," Pacific Northwest National Laboratory, Richland, WA, 2019.

[16] LICAP Technologies, "LICAP Wind Retrofit," LICAP Technologies, July 2021. [Online]. Available: https://assets.website-files.com/5d95f0142ae9df7b4153629a/611077af4f960bf1b99fee21_GE30NmWindRetrofit_July2021.pdf.

[17] O. Schmidt, S. Melchior, A. Hawkes, and I. Staffell, "Projecting the future levelized cost of electricity storage technologies," *Joule,* vol. 3, pp. 81-100, 2019.

[18] H. Dura, J. Perry, T. Lecacou, F. Markoulidis, C. Lei, and S. Khalil, "Cost Analysis of Supercapacitor Cell Production," in *2013 International Conference on Clean Electrical Power (ICCEP)*, Alghero, Italy, 2013.

[19] A. Castaignet, "Skeleton's New Graphene Supercapacitors Offer 72% Increase in Energy Density," Skeleton Technologies, 16 Sept. 2021. [Online]. Available: https://www.skeletontech.com/news/skeletons-graphene-supercapacitors-offer-72-increase-in-energy-density.

[20] P. Sun, Z. Deng, P. Yang, X. Yu, Y. Chen, Z. Liang, H. Meng, W. Xie, S. Tan, and W. Mai, "Freestanding CNT–WO3 hybrid electrodes for flexible asymmetric supercapacitors," *Journal of Materials Chemistry A,* vol. 3, pp. 12076-12080, 2015.

[21] Y. Kumar, S. Rawal, B. Joshi, and S. A. Hashmi, "Background, fundamental understanding and progress in electrochemical capacitors," *Journal of Solid State Electrochemistry*, vol. 23, no. 1118, pp. 667-692, 2019.

[22] M. Nematian, C. Keske, and J. N. Ng'ombe, "A techno-economic analysis of biochar production and the bioeconomy for orchard biomass," *Waste Management,* vol. 135, no. 5, pp. 467-477, 2021.

[23] B. W. Griffiths, "Revenue for Energy Storage Participating in ISO-NE Energy and Reserves Markets," Massachusetts Attorney General's Office, Boston, MA, 2020.

[24] PJM Interconnection, "Electric Storage Resource Participation Model," PJM Interconnection, Valley Forge, PA, 2018.