Unlocking New Possibilities Through Innovative Energy Storage

The Role of Ultracapacitors in the Energy Transition

Funded by the European Union

An EIT InnoEnergy White Paper
in collaboration with Frost & Sullivan

Contents

Foreword

The challenge is big, but our goal is simple: to achieve a sustainable energy future for Europe. Innovation is the solution. New ideas, products and services that make a real difference, new businesses, and new people to deliver them to market. At EIT InnoEnergy we support and invest in innovation at every stage of the journey – from classroom to end-customer – and covering eight key transformative areas, including transport and mobility, renewable energy, circular economy and energy storage.

The way we generate and distribute power is changing. Energy storage is vital in the transition to a sustainable energy system. EIT InnoEnergy encourages innovation in large and small-scale storage that supports the integration of renewable energy into the electricity grid, enables a more decentralised and responsive grid and creates business opportunities for new actors in the energy ecosystem. The industry's attention regarding storage technologies has mainly been focused on batteries, and in particular Li-ion, but recent breakthroughs have made ultracapacitors (also known as supercapacitors) a viable, reliable, faster and potentially safer power storage. In some cases to replace batteries but also in an efficient combination with batteries

In line with an ever-increasing emphasis on climate change and sustainability, EIT InnoEnergy recognises a strong case for ultracapacitors to serve as a key technology for both environmental and cost reasons. Ultracapacitors can provide the short bursts of high power at virtually endless number of cycles that vehicles, industrial and grid applications require. However, it is acknowledged that there is a general lack of awareness, understanding and references around those use cases. EIT InnoEnergy and Frost & Sullivan have jointly created a white paper on ultracapacitors with a focus on unlocking new possibilities for storage for the energy transition.

The aim of this whitepaper is to provide a document with an independent, accurate and balanced view to serve market development. The objective is to shed light on the case for ultracapacitors and highlight the main areas of application. The automotive, transportation and power grid sectors are given, but industrial applications, such as cranes, elevators, data centres, connected IoT devices, etc make for an ever-widening perspective. Ultracapacitors can play an essential role already today but perhaps even more so in the future to help build a more efficient and sustainable energy system

This effort has benefited from the guidance and feedback of Skeleton Technologies, NAWA-Technologies and C2C-NewCap that provided useful insights and contributions for this work.

Our hope is that this whitepaper will be a clear and accessible step towards supporting all actors that want to have a better understanding on the role of ultracapacitors.

Johan Söderbom

Thematic Leader for Smart Grids and Energy Storage at EIT InnoEnergy

Introduction

Ultracapacitors are not new; they were invented in the late 1950s by General Electric. The technology was eventually commercialised by NEC of Japan in 1978, where it was used as a backup power device for computers.

Due to an increased focus on cleaner power sources at the turn of this century, there have been several attempts to commercialise the technology as an energy storage device on a wider scale, but this has had somewhat limited success. Early innovations included cell-based ultracapacitors to power wristwatches and other micro electric items, eventually graduating to powering applications in hybrid electric vehicles (HEV). Industry attention, however, has remained on existing conventional technologies such as batteries and innovations focusing on new battery chemistries such as lithium-ion.

However, advances in new materials and manufacturing technologies in the late 20th and early 21st centuries have led to significant increases in ultracapacitor performance and lower costs. Coupled with an ever-increasing emphasis on climate change and sustainability, there is a strong case for ultracapacitors to serve as a key technology for both environmental and cost reasons.

In particular, ultracapacitors potentially unlock and open a new horizon for the energy transition. As the technology advances, it can move from specific, niche areas to more mainstream applications as a power source, which can enhance the capability of existing solutions, e.g. batteries, or replace these power sources altogether.

Organisations across the world are recognising the need for innovative solutions to cater for ever-increasing energy demands and are increasing the energy efficiency of their products and services, subsequently lowering environmental footprints. These innovations and breakthroughs push the boundaries of technology every day, leading to an increased demand for short-term, high-intensity power; a case in point is in mobile devices, where ultracapacitors can be a game-changer. This has driven companies to search for new and alternative sources of energy that can fulfil these demands while catering to customer needs, even as they adhere to strict energy-efficiency and pollution norms.

However, challenges exist in the industry, partly due to the lack of awareness of where ultracapacitors can be used, especially when there is a strong case being put forward for batteries.

This leads to a catch-22 situation wherein, with low adoption, there is limited economies of scale, which leads to ultracapacitors not being as competitive. This inevitably leads to a scenario where the overall industry, and thus society, loses due to the benefits of the technology not being fully realised, especially at a critical time defining our energy future.

This white paper is intended to shed new light on the case for ultracapacitors and highlight the areas where they can play an essential role to help build a more efficient and sustainable future.

An Overview of the Technology: Pros and Cons

Ultracapacitors are double-layer capacitors with higher capacitance than a regular capacitor. They store energy using a static charge instead of an electrochemical reaction compared to batteries and have an operational voltage between 2-3 volts. They store energy via electrostatic double-layer capacitance and electrochemical pseudo-capacitance.

There are three types of ultracapacitors:

1. Electrostatic double-layer capacitors (EDLCs)
2. Electrochemical pseudo-capacitors
3. Hybrid capacitors

Electrostatic double-layer capacitors (EDLCs):

EDLCs store energy in an electrical double layer called the Helmholtz double layer that is created at the interface between an electrolyte and a conductive electrode. The conductive electrode is made of activated carbon and the space between the two electrodes is filled with an electrolyte. Electricity is generated by the process of adsorption and desorption of ions from the electrode surfaces. The ultracapacitor does not have a solid dielectric or have any chemical reactions, leading to a lower impact on lifespan due to charging and discharging time in seconds. In addition, the ultracapacitor does not need special circuits to control charging and discharging. However, leakage of electrolyte is a concern as is high internal resistance, which makes it unusable for AC circuits. EDLCs offer high cycle life in excess of a million cycles with moderately higher operating voltage.

Electrochemical pseudo-capacitors:

These ultracapacitors use conducting polymer or metal oxides with high pseudo-capacitance as electrodes. Electricity is stored in an electrochemical process, which is generated via a charge transfer achieved through redox reactions, intercalation or electrosorption. They bridge the gap between EDLCs and batteries as they can store higher energy while operating faster. They can charge and discharge between seconds to minutes. Electrochemical capacitors have a life cycle of 500,000 cycles.

Hybrid capacitors:

These capacitors use electrodes of different capacities, one with electrostatic capacitance and the other exhibiting an electrochemical capacitance. They combine the benefits of both EDLCs and pseudo-capacitors along with a longer and pollution-free lifespan. They have operating temperatures between -25 degrees Celsius and +60 degrees Celsius and have 95% efficiency, compared to only 70% for batteries. This makes them suitable for use in high-power applications in the automotive and transportation space.

Figure 1: The different types of ultracapacitors

Source: Frost & Sullivan

EDLC	PSEUDO-CAPACITORS	HYBRID CAPACITORS
▪ Have carbon electrodes ▪ Higher energy density than low level capacitors but not equal to batteries ▪ High cycle stability	▪ Have metal oxide or conducting polymer electrodes ▪ Higher capacitance and energy density than EDLCs ▪ Lower cycle stability ▪ Lower power density than EDLC	▪ Electrodes can be composite or polymer based ▪ High energy and power density ▪ Moderate cycle stability

The advantages and challenges of ultracapacitors compared to other technologies

Ultracapacitors have clear advantages over batteries; they have a short charge and discharge time due to minimal internal resistance (less than 2 minutes), whilst batteries take between 10-60 minutes. In addition, ultracapacitors have a charge/discharge cycle of between 100,000 to a million, whilst batteries have 500 to 10,000 cycles, so they hardly need replacing and users save on operating costs.

Critically, the specific power output of an ultracapacitor is nearly 10 times as high as batteries, enabling a high-power discharge in short periods. Storing energy in an electric field instead of chemicals also leads to increased safety, lower fire hazard and explosion risk, increasing the service life of the capacitor to between 10-15 years.

On the other hand, ultracapacitors have lower specific energy densities of 5-10 Wh/kg compared to 100-250 Wh/kg for batteries. Also, batteries offer a steady voltage throughout their life, while ultracapacitor voltage decreases with increasing discharge. Ultracapacitor voltage charge increases with increased charging and the current starts dissipating once charging stops and the voltage level drops. Increased voltage beyond a certain point may also damage ultracapacitors with voltage dropping upon discharge. Finally, ultracapacitors currently cost significantly more than batteries, with battery costs ranging from $100 to $1,000 per kilowatt-hour (kWh) compared to $5,000 to $10,000 per kWh for ultracapacitors.

Figure 2: The pros and cons of ultracapacitors

Source: NREL

ADVANTAGES

- Charge/Discharge time: 1-10 seconds, minimum internal resistance
- High Specific Power: 10,000 W/kg
- Cycle life: 100,000 to 1 million
- Service life: 10-15 years
- Charge/Discharge temperatures: -40 degrees Celsius to +65 degrees Celsius
- Efficiency: > 95%
- Low maintenance
- No chemical substances

CHALLENGES

- Cost: $5,000-10,000 per kWh, when compared to $180/kWh for Lithium-ion batteries and $100/kWh for Lead Acid batteries.
- Cell Voltage: 2 to 3 volts
- Low Specific Energy: 35 Wh/kg compared to 100-250 Wh/kg for batteries.
- High self-discharge
- Voltage drops with increasing discharge unlike batteries where voltage is stable

Given the differences between energy storage technologies, it is obvious that they are not always in direct competition. In other words, ultracapacitors may replace batteries for those applications that require short-duration, high-specific power, e.g. pitch control for a wind turbine, but not for those applications that require a steady stream of energy over a long time, e.g. electric vehicles. However, in the latter application, ultracapacitors will have a crucial role to play to support those devices in electric vehicles that need short-term power to take the load off batteries and preserve their lifetimes.

Ultracapacitor cells for a wide range of applications from NAWATechnologies

Why will capacitors potentially be a game-changing technology?

Two key elements are expected to change in the coming years as research and investment into ultracapacitors gains momentum. The most important one is cost. The production cost of ultracapacitors has dropped considerably in the past 15 years - by 65% -75% as per analysis done by various ultracapacitors manufacturers, such as Skeleton Technologies and IOXUS - and this is expected to decrease by another 30% from 2019 to 2030. In comparison, battery costs are also expected to decrease, especially Li-ion battery costs, as increased volume of production is expected to reduce costs significantly over the decade, mirroring the costs of lead-acid batteries.

Another important development will be the increasing energy density of ultracapacitors in the coming decade. The industry expects this to increase 10- to 30-fold, which will make ultracapacitors more competitive with batteries as increased research leads to the development of new types of ultracapacitors.

However, a key argument for ultracapacitors is the high degree of flexibility that hybrid storage systems, which combine ultracapacitors and batteries, will bring to various applications.

Figure 3: Cost forecast of ultracapacitors and Li-ion batteries

Source: BloombergNEF and Frost & Sullivan

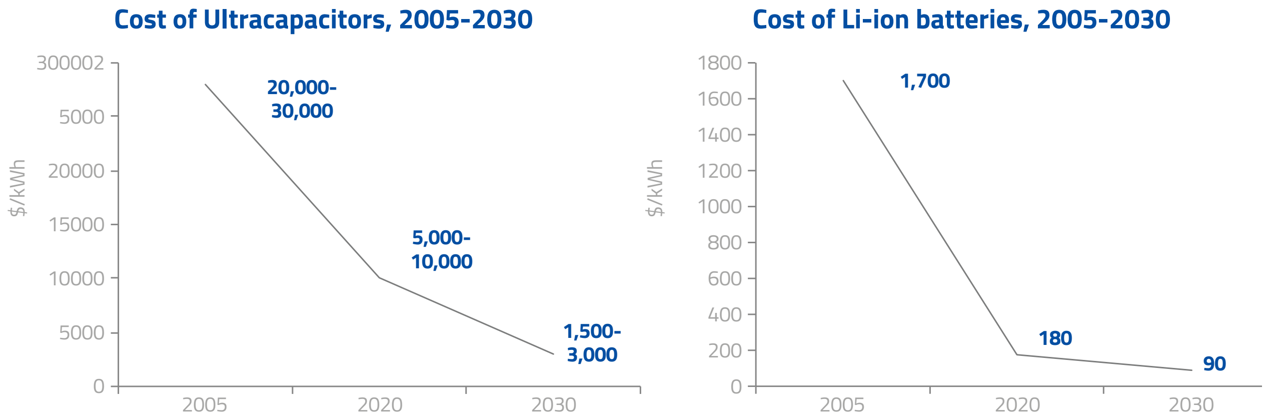
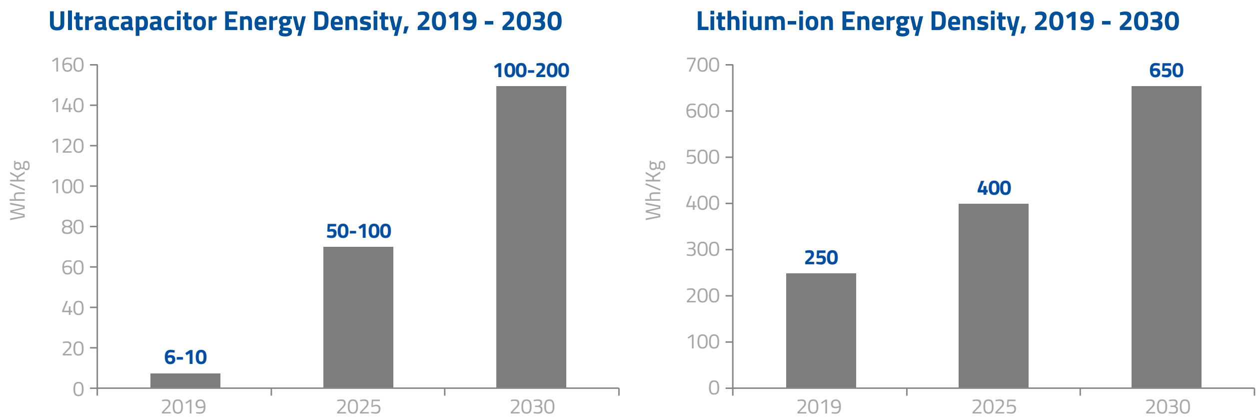


Figure 4: Energy density projections for ultracapacitors and Li-ion batteries

Source: NASA



Key Market Segments

As energy storage devices become crucial to fulfil increased energy demand more efficiently, there is a high opportunity for ultracapacitors across a wide variety of industries, such as automotive, transportation, and power generation and distribution, and industrial segments (such as cranes, elevators, data centres, Internet of Things (IoT) devices, etc.).

The increasing electrification of automobiles and other transportation infrastructure such as railways, trams, trucks, and buses has increased the demand on batteries for power while the emergence of renewable energy has led to higher grid fluctuations, which need balancing in short periods. Furthermore, the increase in IoT devices and sensors that require low downtime and rapid charging, and the expansion of data centres that have critical power requirements, all drive the need for ultracapacitors.

Ultracapacitor cells from Skeleton Technologies

Figure 5: Key drivers by market sectors

Source: Frost & Sullivan

AUTOMOTIVE

- Increased electrification and automation drives drive demand.
- Increased pressure on batteries leads to the need for alternative and secondary sources of power.
- Energy savings seen as key to vehicle efficiency and reduced fuel consumption.

TRANSPORTATION

- Increased need for higher efficiency and lower emissions pushes electrification of railways, trucks and marine industry.
- As loads increase secondary power sources become mandatory to supplement primary batteries.

POWER GRID

- Higher Renewable Energy (RE) penetration and a decrease in generation from traditional fossil fuels leads to less grid stability.
- Need to compensate for grid stability during peak demand times drives use of alternative sources of power.

INDUSTRIAL

- Increased power requirements from industrial equipment such as cranes, and elevators for heavy lifting and for backup power.
- Penetration of IoT devices leads demand for smaller power sources that have much longer cycle times.

Automotive Sector

Ultracapacitors can provide significant benefits and value to the automotive sector, which includes commercial vehicles such as fossil-fuel-based passenger cars, electric and hybrid vehicles and light utility vehicles.

The technology can address two critical challenges in the industry - reducing the total cost of ownership and lowering the environmental impact of vehicles.

In addition, the industry is being deeply affected by the transformation towards electrification and automation. This is driving change in vehicle architecture and the adoption of new energy storage systems to reduce dependence on primary energy systems such as batteries.

Today, ultracapacitors can be used alongside batteries, which results in a drastic improvement in battery lifetimes (as ultracapacitors can replace batteries for high-discharge activities), leading to lower operating expenditure and environmental costs (recycling costs and pollution). For example, they can be used in engine starting and stopping operations (Start/Stop), where short bursts of energy are needed, which eliminates the need for high load on batteries and results in less frequent replacements. The energy stored by ultracapacitors can also be used to support batteries in a variety of other applications across the vehicle, including power steering (where 5% fuel savings are possible), electric catalyst heating to purify exhaust gases, etc.

Another key benefit of ultracapacitors in the automotive industry is through energy recovery systems where kinetic energy caused during braking is stored and used in vehicle acceleration; this results in fuel savings (and hence emissions reductions) of 30%-40%. Car manufacturers such as Honda began incorporating ultracapacitors at the start of the century, but there was a slower adoption by US manufacturers. Recently, Lamborghini introduced ultracapacitors in its latest hybrid vehicle, Sian, and is collaborating with Massachusetts Institute of Technology (MIT) to develop ultracapacitors to fulfil the power requirements of high-power vehicles.

All of these benefits drive considerable value for the industry and can help overcome many challenges.

Figure 6: Use cases* and key value drivers for ultracapacitors in the automotive industry *Source: Frost & Sullivan*

APPLICATIONS	AUTOMOTIVE
Engine Start-up/Engine Cranking	HIGH
Hybrid and Electric Vehicles	HIGH
Energy Storage/Backup Power Bridging	HIGH
Power Steering	MEDIUM
Ebrake/Kinetic Energy Recovery System (KERS)	HIGH
Lead-acid Battery Hybridisation	HIGH
Autonomous Driving	MEDIUM
Electric Catalyst Heating	LOW
Start/stop	HIGH

**Relative Attractiveness Measure – see Appendix for Rating Rationale*

AUTOMOTIVE INDUSTRY VALUE DRIVERS

- Fast Charging/Start-Stop: 1 to 10 seconds
- Increased battery life (which can be as low as 12-24 months) and hence lower operating costs
- Fuel savings: 1% to 5%
- Lower maintenance: 10 to 15 years ultracapacitor life
- Lower pollution: 30-40% less emissions

However, challenges remain in the industry. Lead-acid batteries are still much cheaper than ultracapacitors and environmental legislation is not strong enough in many countries to push adoption.

In addition, the technology needs to be improved to enable easy plug-and-play installation for retrofitting existing fleets, especially in large commercial vehicles such as trucks. Further, manufacturers need to reduce the much longer starting times compared to batteries to incentivise customers to switch to the technology.

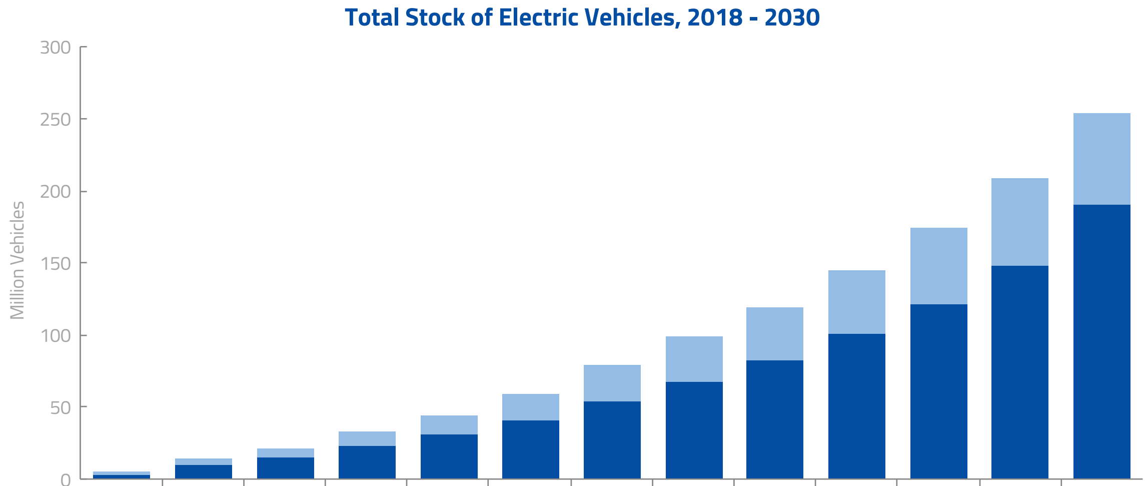
The Future - Electrification and Automation will Drive Value

Despite these challenges, the future looks bright for ultracapacitors in the automotive industry. Electric vehicles will increasingly become common on our roads with Frost & Sullivan forecasting that 125 million vehicles will be sold by 2030. Ultracapacitors can be charged in seconds compared to hours with batteries, which will help overcome the slow charging challenge in the industry.

Currently, the amount of power delivered by a charging station is designed for charging lithium-ion batteries in electric vehicles. As automakers increase their focus on ultracapacitor technology, charging infrastructure is expected to be revamped to enable fast charging of ultracapacitors. By overcoming this constraint, the use of ultracapacitors will help drive the roll-out of electric vehicles in the coming decade. Ultracapacitors are seeing increased usage in engine starting, start/stop, energy recovery and storage applications for all types of vehicles. Japanese automakers led early adoption in the past decade, with North American automakers have been adopting ultracapacitors for start/stop, energy recovery from braking systems and engine starting applications over the past five years. This trend is expected to continue over the first half of the next decade as automakers increase the scope of applications that can be powered using ultracapacitors.

Figure 7: Electric vehicle sales forecast, 2018-2030

Source: IEA



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
PHEV	2.0	4.0	6.0	10.0	13.0	18.0	25.0	31.0	36.0	44.0	52.0	61.0	74.0
BEV	3.0	10.0	15.0	23.0	31.0	41.0	54.0	68.0	83.0	101.0	122.0	148.0	179.0

As automation in automobiles increases through the middle of the next decade, more electronics such as Wi-Fi, 5G, video streaming, and other automated systems will become integrated.

An increasing number of applications, such as power steering and engine starting, will move completely towards ultracapacitors and away from batteries. Vehicles will increasingly become connected, leading to higher short-term power requirements driving the appetite for more energy.

Furthermore, as autonomous vehicles gain ground, more sensors and IoT devices are expected to be incorporated into the vehicle architecture to read traffic and road signals, thereby drastically increasing power requirements. There is, therefore, a strong case for automobile manufacturers to redesign the architecture of existing vehicles and adopt ultracapacitors to cater to these short-term, high-power uses. Ultracapacitors, with their short-duration, high-discharge-intensity power, are well-suited to fulfil these requirements, and their light weight is also a benefit for manufacturers that are trying to increasingly accommodate additional devices in vehicles.

Increased electrification and hybridisation of vehicles gives an impetus for the adoption of ultra capacitors as a secondary power source. The need to charge the main power source while on the move, thereby providing

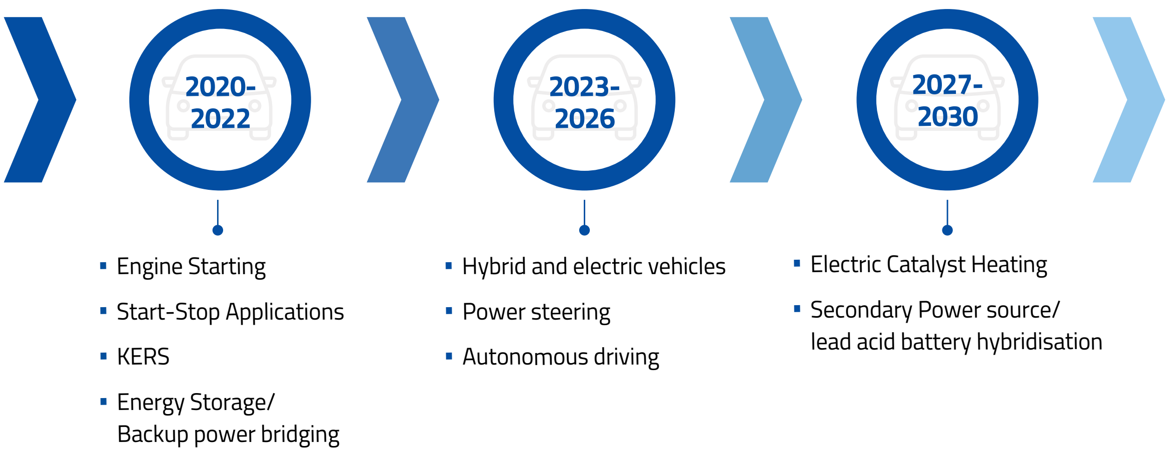
12V ultracapacitor module for engine start from Skeleton Technologies

a higher mileage to electric and hybrid vehicles, will drive the integration of ultracapacitors within these vehicles. This will also lead to a change in the charging infrastructure, which will accommodate the demands from ultracapacitors for fast charging.

As vehicle architecture evolves, the systems that are expected to adopt ultracapacitors include safety and powertrain, engine throttle, cooling fans, oil pumps, doors, seating, electrical windows, car heating and air conditioning, and audio and video. Use of ultracapacitors as a hybrid power source along with batteries will take shape with increased adoption towards the end of the decade as companies move towards increasing fuel efficiency and mileage and reducing pollution by increasing adoption of electric catalyst heating. There will be increased collaboration between vehicle manufacturers and ultracapacitor companies as vehicle architecture evolves; this is already beginning with the recent $100 million deal signed between ultracapacitor manufacturer Maxwell Technologies and Volvo automobiles to supply ultracapacitors for its electric and hybrid vehicles.

Figure 8: Anticipated impact of ultracapacitors in the automotive industry

Source: Frost & Sullivan



Transportation Sector

The transportation sector includes railways, trams, buses, trucks, marine vessels and off-road equipment such as mining vehicles. These vehicles are involved in the bulk transportation of goods and passengers. Rail includes urban and regional rail networks, while trams include city-based tram systems. Similarly, buses include both urban and rural buses, while trucks include heavy commercial vehicles used for long-distance goods transportation. The marine sector includes ships and offshore platforms, and off-road equipment refers to mining vehicles such as large mining dump trucks, excavators, etc.

As urban populations increase, so does the need for clean and efficient transportation services. Rising infrastructure spending by governments and the private sector has increased connectivity and transport options, leading to an increase in rail and tram networks, trucking, bus networks, and the spread of other heavy equipment such as mining equipment. Current transportation modes are mostly based on vehicles with combustion engines, which cause pollution and congestion, and there will be a shift towards more energy-efficient means of transport (such as trains) and electric-powered vehicles. These will lead to the adoption of alternative sources of energy, which increase engine efficiency and lower emissions.

The potential for ultracapacitors in the transportation industry is high with rail expected to be the most impacted. Ultracapacitors are used to capture and store energy generated from braking systems in rail, buses, trucks and trams, which is then used for other applications such as engine starting or acceleration. This reduces the power requirement from the battery while also stabilising power output. This energy-saving measure leads to increased battery and engine life as well as lower emissions. Ultracapacitors are usually combined with a primary battery power source, which reduces the load on the battery and the need to design heavy and large batteries for transportation networks; again, this leads to lighter vehicles, which consume less energy and have a lower environmental impact.

A case in point is ultracapacitor-based buses, which are estimated to consume 2 kWh per mile of operation; this reduces the overall cost of operating the buses and facilitates complete removal of CO2 emissions. Ultracapacitors also enable catenary-free (electrical wire-free) operation for buses, trams and electric rails, which can be charged during stops at stations or while braking. This is especially helpful in reducing overhead power lines in densely populated areas. In electric rails, ultracapacitors are either located on the train or on the tracks, which is known as way-side energy storage. This helps reduce energy consumption from the grid, increases voltage stabilisation for the train, and provides fuel efficiency of 10% to 25% for various forms of transport. For example, several cities in China have adopted trams made by CRRC Corporation that run on ultracapacitors and charge at stations.

Ultracapacitors are usually combined with a primary battery power source, which reduces the load on the battery and the need to design heavy and large batteries for transportation networks; again, this leads to lighter vehicles, which consume less energy and have a lower environmental impact.

The marine industry has enacted stringent fuel-efficiency norms that mandate a reduction in sulphur emissions, which will lead to increased electrification and hybridisation of systems. Ultracapacitors are used as peak load-shaving applications that supply power, allowing for the generators to operate at constant load and for absorption of excess generated power. They are also used in active heave compensation, which is a technique used to reduce the influence of waves lifting equipment in offshore vessels and platforms, and they absorb any excess power generated by the cranes on ships and in ports.

Ultracapacitors can also be used to store renewable energy produced by solar or wind energy onboard marine and offshore platforms, which helps reduce the demand on the primary power sources. Off-road equipment such as mining equipment and heavy trucks require constant operation as any downtime leads to losses; in such cases, ultracapacitors can be placed alongside batteries to operate high-power requirements such as engine starting and heavy load movement.

Challenges exist in the form of high cost of adoption of ultracapacitors and redesign of existing systems to accommodate the technology. Also, higher spending on research and development (R&D) of several battery types increases competition for ultracapacitors. The low cost of electricity and lower diesel prices also hinder alternative power source development as companies stick to tried-and-tested systems instead of moving to innovative ones.

Figure 9: Use cases* and value drivers for ultracapacitors in transportation

Source: Frost & Sullivan

	TRANSPORTATION				
APPLICATIONS	RAIL	BUS	TRUCK	MARINE	OFF-ROAD EQUIPMENT
Engine Start-up/Engine Cranking	HIGH	HIGH	HIGH	MEDIUM	HIGH
Generator Control Gradient				LOW	
Hybrid and Electric Vehicles	HIGH	HIGH	HIGH	MEDIUM	MEDIUM
Energy Storage/Backup Power Bridging	HIGH	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Catenary-free Operation	MEDIUM				
Ebrake/Kinetic Energy Recovery System (KERS)	HIGH	MEDIUM	MEDIUM		HIGH
Lead-acid Battery Hybridisation		MEDIUM	LOW		LOW
Start/Stop	HIGH	HIGH	HIGH		LOW
Heave Compensation				MEDIUM	

**Relative Attractiveness Measure – see Appendix for Rating Rationale*

TRANSPORTATION VALUE DRIVERS

- Reduced emissions
- Lower operational costs for vehicles: ~20% cost reduction
- Fuel Efficiency: 10 to 20% in case of larger vehicles
- Reduced overhead power line for trains and trams
- Voltage stabilisation for trains: less than 20 milliseconds
- Heave Compensation in marine vessels

The Future - Increased Electrification and Emissions to Drive Adoption

As vehicles move towards increased electrification over the next decade, the need for secondary power sources increases to reduce emissions and increase efficiency. Along with the development of new technologies such as connected trucks and machines and the spread of sensors and IoT devices, the demand for power is expected to increase exponentially, putting a strain on existing power sources. Subsequently, ultracapacitors will be deployed in various transport applications to replace many of the current battery functions to extend system life but also to reduce emissions coming from combustion engines.

Ultracapacitors are expected to increasingly play a role in applications such as start/stop and engine starting, and in energy recovery systems. Energy generated via braking systems is captured and stored in ultracapacitors using a Kinetic Energy Recovery System (KERS) to be used when needed.

Trains and trams are expected to move towards catenary-free operations as planners look for ways to reduce their dependence on overhead lines in urban areas. Energy recovery from braking and charging using an overhead line at stations require fast-charging systems such as ultracapacitors.

Marine and offshore platforms will also see increased ultracapacitor adoption to capture wave energy and offshore renewable energy. The need for safe operations in such platforms is an added driver for ultracapacitors as they have a lower risk of fires and improved safety compared to batteries.

The size of engines and batteries may decrease as ultracapacitors become the norm with higher energy density and lower costs. New vehicle architecture is expected in off-road and heavy equipment as the sector increasingly adopts electrification and hybridisation, incorporating ultracapacitors in their energy mix by the end of the decade. For example, autonomous trucks used for mining, such as the one launched by Volvo, will seek to increase energy efficiency by incorporating ultracapacitors.

Figure 10: Anticipated impact of ultracapacitors in transportation applications

Source: Frost & Sullivan

2020-2022
- Start/Stop application for buses, rail, truck and trams.
- KERS for rails, trams, trucks and buses.

2023-2026
- Increased penetration in off-road and mining equipment.
- Increasing presence in marine and off-shore platforms.
- Increased usage in start/stop applications in buses, trucks, rail and off-road vehicles.

2027-2030
- Used along with batteries in electric buses, off-road and mining vehicles and trains.
- Increased adoption across marine systems and offshore platforms as energy storage and supply device.

Power Sector - Generation, Transmission and Distribution (T&D)

The power industry is undergoing a seismic shift towards more efficiency and less-polluting technologies. The power generation industry includes sources such as fossil (power plants and standalone power sources used in industries such as diesel gensets) and renewable energy (RE)-based sources, including microgrids used in industries and communities. In addition to power generation, the industry caters to the transmission and distribution grid networks, which move electricity over long distances.

Climate change and sustainability are driving investments in renewable energy sources (wind, solar) and replacing fossil fuels such as coal and oil. This has led to less centralised, large power plants and more decentralised systems feeding power to the grid. A side effect of this change is reduced grid stability due to an increased, bidirectional electricity transmission. Ultracapacitors serve a number of functions within this context; they can be used to remove grid fluctuations caused by the intermittency of renewable energy production, thereby reducing the need for costly backup power sources or risking damage to the grid due to high-power and voltage fluctuations. They can also help absorb the excess power generated during high availability of renewable energy.

At the same time, ultracapacitors can be used to provide smooth functioning of conventional backup power generators by balancing the generator gradient while ensuring smooth power supply. Backup power generators are on standby to ramp-up or down power, depending on demand and supply. With ultra-low response time in milliseconds, ultracapacitors can cater to these changing needs, thereby helping ramp-up fossil fuel generators and extending engine life. Ultracapacitors can also maintain the quality of power supply by injecting high power at times of voltage drops, reducing downtimes. At peak load, where the demand on the grid is at its highest, there is a need to have backup capacity - this is usually done through large plants such as a gas plant - and ultracapacitors are emerging as a key technology along with batteries to provide short bursts of high-energy for 'peak shaving'.

The increasing use of microgrids, which are interconnected power supplies that work independent of the grid (mostly based on renewable energy sources) in industrial and commercial establishments as well as remote communities, has led to grid stabilisation requirements. Ultracapacitors can fulfil the function of providing frequency and voltage stabilisation to such grids, thereby providing high-power quality as well as an active energy storage system. They are also incorporated with batteries in a hybrid system to take over high-power applications of microgrids, which lessen the load on batteries and enable longer battery life. Ultracapacitor manufacturers such as Maxwell Technologies and Suneron Energy have introduced cells, modules and storage systems that cater to the energy requirements of grids.

170V ultracapacitor module for power grids, transportation and industrial applications from Skeleton Technologies

Pitch control for wind turbines is a key use case for ultracapacitors in power generation as it helps control the wind turbine and prevents damage during peak wind conditions; this will be discussed further in the paper. Ultracapacitors are also used as energy storage devices in times of peak power production by RE power sources, to smooth generator gradients, and for peak load-shaving applications, as deemed fit by various industries and power suppliers. The benefit is not only a reduction in overall costs but also less equipment damage due to unwanted power surges. For example, SKELGRID ultracapacitors by Skeleton Technologies serve as energy storage systems, which improve power quality for industrial applications. Installed on the Scottish Island of Eigg, which is supplied with power from its own renewable energy-based microgrid system, SKELGRID enables fast-response backup power to the microgrid, thereby helping the island reduce its dependence on lead-acid batteries during peak power times.

Figure 11: Use cases* and value drivers for ultracapacitors in the power industry

Source: Frost & Sullivan

	POWER		
APPLICATIONS	GENERATION	T&D	INDUSTRIAL
Engine Start-up/Engine Cranking	**HIGH**		**HIGH**
Pitch Control for Wind Turbine	**MEDIUM**		
Generator Control Gradient	**MEDIUM**		
Frequency Response/Synthetic Inertia		**MEDIUM**	
Energy Storage/Backup Power Bridging	LOW	LOW	**MEDIUM**
Peak Load Shaving	**MEDIUM**		**MEDIUM**
Variable Speed Drive (VSD) Backup			**MEDIUM**

**Relative Attractiveness Measure – see Appendix for Rating Rationale*

GRID INDUSTRY VALUE DRIVERS

- Frequency Response and Voltage Stabilisation
- Generator Gradient Control: Response time in less than 20 milliseconds
- Peak load shaving: 30 to 40% reduction in peak demand energy
- They offer low costs for usage in pitch control for wind turbines along with long life and simpler monitoring systems
- Low operating temperatures: -40 degrees to +65 degrees Celsius

The Future - Intermittent Renewable Energy and Microgrids to Drive Adoption

The move towards renewable energy is expected to accelerate (especially solar and wind) and there is higher risk for grid fluctuations due to the intermittent nature of renewables. Hence, there will be a stronger need for devices such as ultracapacitors in the coming years. According to Frost & Sullivan, solar PV installations are expected to increase from 99 GW in 2019 to 128 GW in 2025, while wind power is expected to see annual additions between 55-70 GW between 2021 and 2025. These large RE additions to the global grid will lead to the increased need for power sources to address the frequency and voltage fluctuations and peak power requirements.

Many wind turbine manufacturers and operators have already installed ultracapacitors in their wind turbines for pitch control functionality, and adoption is expected to continue, leading to a complete replacement of battery systems with ultracapacitors by the end of the decade. In such an application, the ability to withstand temperature extremes and requirement for minimal service is an absolute technological advantage over batteries.

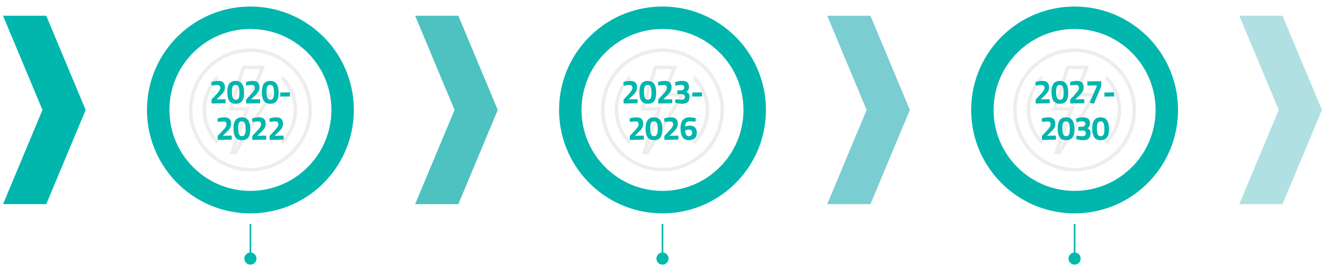
The proliferation of distributed power generation and microgrids in industrial and remote communities provides a good opportunity for ultracapacitors as they will have increasing power quality and energy storage requirements. Additionally, the adoption of IoT devices, smart meters and sensors that monitor power quality will require prime power sources of their own that are long-lasting and do not need frequent replacement.

Smart cities will also drive the adoption of alternative sources of power as governments seek to reduce energy consumption levels. Building energy management systems and increased energy controls will drive the implementation of solutions such as batteries and ultracapacitors to increase overall energy efficiency.

Cost remains a key issue as battery costs are being reduced through recyclability, which leads to higher adoption, creating direct competition for ultracapacitors. However, the end of the decade will witness increased ultracapacitor and battery usage as a hybrid power supply for grid networks, with ultracapacitors used for several key functions, such as voltage and frequency stabilisation, rather than batteries and generators.

Figure 12: Anticipated impact of ultracapacitors in the power industry

Source: Frost & Sullivan



2020-2022
- Engine Starting
- Frequency Response
- Generator gradient control
- Pitch control for wind

2023-2026
- Powering IoT devices in the grid
- Peak load shaving
- VSD Backup

2027-2030
- Hybrid power source along with batteries
- Primary source of power for voltage and frequency stabilisation

Industrial Sector

Within industry, ultracapacitors can serve highly diverse applications, including cranes (such as industrial, construction and port-based cranes), elevators (used in offices, commercial buildings and residential apartments), logistics equipment (e.g. forklifts and autonomous guided vehicles), medical devices (e.g. CT scan machines, ECG machines), oil and gas facilities, power tools, data centres of all sizes (including enterprise, colocation and cloud data centres) and IoT devices (including sensors used in all industries and that require constant power supply with minimal replacement).

Energy sources with fast response times and high-power density are key to fulfilling modern-day industrial power requirements and providing back-up power bridging to expensive, sensitive equipment in case of power disruptions. As industries move towards higher levels of automation, this leads to an increase in power requirements. Reductions in overall power demand during peak hours and the ability to store energy generated on-site for future usage help with efficiency of operations and reduces operational costs; these are key value drivers for the industry.

The shift towards automation has resulted in autonomous vehicles (e.g. autonomous guided vehicles) and IoT devices, which are used in industries and warehouses. These vehicles and devices are small, operate in relatively small and defined footprints, require continuous running power and need to avoid downtime. The use of batteries in such systems leads to long charging time and heavy discharge due to wireless communication of such devices, which may drain smaller batteries. This makes such applications ideal for ultracapacitors, especially, when they are connected to an energy-generating source such as solar power. IoT devices are often located in hard-to-reach areas and cannot be removed for charging and maintenance, often leading to the need for permanent and long-life power sources, which batteries cannot provide but which suit ultracapacitors. Faster charging also drives the use of ultracapacitors in power tools, which leads to the replacement of batteries and increases the efficiency of equipment.

Equipment used in medicine is critical and cannot afford downtime; this requires the installation of several backup power sources for short-term power loss. Ultracapacitors not only provide high power for the short term but also ensure delivery of quality power to medical equipment, thus preventing damage during short-term power outages before the main backup power comes online. The light weight of ultracapacitors and long life also make sense for replacing batteries in medical devices, leading to higher levels of adoptions in mobile medical units.

Ultracapacitors can provide exceptional benefits by capturing energy generated by industrial equipment such as cranes or elevators (during braking) and recycling it, leading to reduced emissions and operating costs. This excess energy generated from regenerative braking can be stored in ultracapacitors to be used when required, resulting in reduced energy consumption.

Data centres is another application that offers good opportunity as the industry moves backup power supplies closer to the server level; smaller and micro ultracapacitors are installed at the source to take care of short-term power outages and minimises downtimes. As edge data centres (smaller facilities located close to the populations they serve that deliver cloud computing resources and cached content to end users) propagate, companies are looking for ways in which they can employ alternative power sources to reduce dependence on uninterruptible power supplies (UPS) for short-term power outages. The advent of 5G technology will help increase the spread of multi-edge access sites, which are micro data centres with unique power requirements mandating smaller and modular power sources. The increased use of advanced electronics, which have higher processing power, also demands increased backup power sources at the server level, driving the need for ultracapacitor-supplied backup power.

An increase in horizontal drilling in the Oil & Gas industry and the need for high-power drilling and communications make ultracapacitors an attractive proposition given the extreme operating environments. Here, ultracapacitors are used in drill heads for communication, where extreme heat is commonplace. For example, an MIT-based start-up, FastCap, has launched a new type of ultracapacitor which can withstand temperatures within the range of -110 to 300 degrees Celsius, suitable for operation in high-pressure environments.

The increasing digitalisation of industries will lead to explosive growth in IoT devices and smart sensors over the next few years that require power for periodic pulses of high current to send back data; this makes them an ideal use cases for ultracapacitors. IoT devices are often located remotely and require power sources that can last a long time without frequent replacement. They also require light-weight power sources, which cannot be provided by batteries. Ultracapacitors fulfil these requirements by reducing the overall weight of IoT devices while ensuring continuous power supply in harsh working environments. This increases the life of the sensor and also increases the frequency of data transfer of IoT devices.

Figure 13: Use cases* and value drivers for ultracapacitors in industrial applications *Source: Frost & Sullivan*

	INDUSTRIAL							
APPLICATIONS	CRANE	ELEVATOR	LOGISTICS	MEDICAL	OIL & GAS	DATA CENTERS	POWER TOOLS	IoT DEVICES
Engine StartUp/Engine Cranking	HIGH		MEDIUM					
Powering Autonomous Guided Vehicles (AGVs)			HIGH					
Hybrid and Electric Vehicles	MEDIUM		MEDIUM					
Energy Storage/Backup Power Bridging	MEDIUM	HIGH		HIGH	MEDIUM	MEDIUM	MEDIUM	HIGH
Peak Load Shaving	MEDIUM							
Ebrake/Kinetic Energy Recovery System (KERS)	HIGH	HIGH			HIGH			
Lead-Acid Battery Hybridisation	LOW							
Start/Stop		MEDIUM	MEDIUM					
Heave Compensation					MEDIUM			
Prime Power for IoT Devices & Tools							HIGH	HIGH

Relative Attractiveness Measure – see Appendix for Rating Rationale

INDUSTRIAL VALUE DRIVERS

- Energy Efficiency: 34% reduced energy consumption for cranes and 70% in elevators
- No hazardous materials: reducing risk of fire
- Long lifetime: >10 years
- Fast charging/discharging: <10 seconds
- Ability to operate in extreme temperatures e.g. drill heads in Oil and Gas
- Start/stop: 20% less starting time
- Higher power output improves communication range (e.g. below earth surface)

The Future - Automation and Miniaturisation to Drive Power Needs

As industries move towards automation, the demand for sensors and IoT devices is set to explode as they enable live tracking and control of industrial equipment. The increased use of cloud computing and the advent of 5G will lead to a higher use of sensors over the next decade, impacting energy demand and leading to higher energy efficiency.

The increasing need to reduce pollution and emissions will also result in higher RE penetration in industries, which will require alternative power sources to balance the intermittency of RE power and also to act as an energy storage device. To increase the efficiency of existing systems, industries will move towards capturing energy from their machines (energy harvesting), which will use ultracapacitors as they are easily integrated into systems of energy capture and storage. Energy efficiency, extending the life of primary power sources and reducing machine damage due to high loads are all key factors driving industries to adopt alternative sources of energy such as ultracapacitors. With their higher power density, faster discharge cycles, long life span and increased safety, ultracapacitors are the ideal choice for industries looking to reduce costs, lower the need for frequent maintenance, and provide safe power supplies to industrial machines. Companies like NAWATechnologies and CAP-XX are launching ultracapacitors that help power IoT platforms.

Heavy industrial equipment such as cranes and elevators will be first adopters for ultracapacitors in the first half of the decade as they seek to reduce fuel consumption and emissions and aim to recycle energy released during operations. IoT, autonomous guided vehicles (AGVs) and other warehouse equipment are expected to favour ultracapacitors to reduce weight and shift away from heavy batteries. New products catering to these industries are being launched, which will ensure higher adoption.

Ultracapacitor cells for a wide range of applications from NAWATechnologies

Horizontal drilling for shale oil and gas is expected to increase and spread from the US to other countries, including Argentina. Horizontal drilling in the Oil and Gas industry results in the need for a constant power supply for drilling equipment and sensors in hard-to-reach places. These are well-suited to move towards ultracapacitors as companies seek to adopt power sources that do not need constant replacement and reduce the risk of fire or other hazards. Horizontal drilling requires communication networks to be robust and reach deep into the earth, and ultracapacitors are well-suited to provide the high-power requirement for such communication networks.

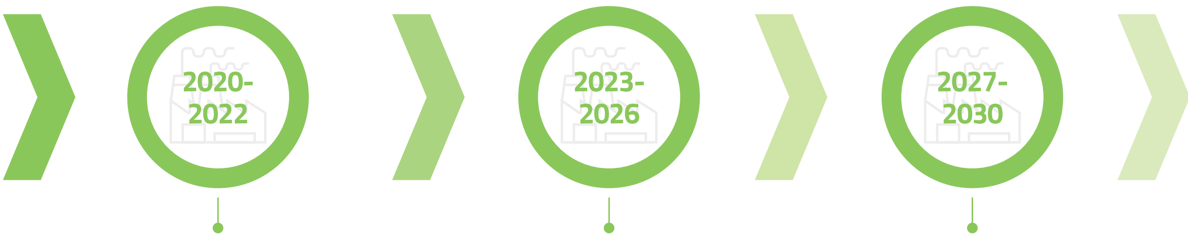
Data centres are expected to reduce their use of UPS and batteries for backup power and move towards ultracapacitor, as catering to short-term power requirements increases the pressure on existing systems, which can be alleviated by ultracapacitors.

Increased automation of Oil and Gas platforms and the need to reduce pollution in the industry have forced companies to develop innovative ways in which energy storage using alternative sources of power can be incorporated to reduce overall pollution and increase the efficiency of sites. Ultracapacitors and renewables will replace polluting battery and generator technologies, which will reduce costs and increase efficiency, even as oil companies are expected to battle low oil prices over the next decade.

With their higher power density, faster discharge cycles, long life span and increased safety, ultracapacitors are the ideal choice for industries looking to reduce costs, lower the need for frequent maintenance, and provide safe power supply to industrial machines.

Figure 14: Anticipated impact of ultracapacitors in industrial applications

Source: Frost & Sullivan



2020-2022
- Increased presence in cranes and elevators.
- Introduction to IoT, medical devices, data centers, fast charging for AGVs.

2023-2026
- Higher adoption in Oil & Gas space due to increased horizontal drilling.
- Replace batteries in autonomous vehicles and IoT devices.
- Hybrid structure along with batteries in data centers.

2027-2030
- Replace batteries in Oil & Gas drilling and increased presence in offshore platforms.
- Data center usage as backup power replacing batteries and UPS.

Use Cases

Lead-Acid Battery Hybridisation in Vehicles

Key reasons for using lead-acid batteries

Invented in the 19th century, the lead-acid battery is an energy storage device that generates electrical energy using a chemical process. In automobiles, it is used to provide electrical charge for starting, lighting and ignition systems. Apart from starting, the batteries also provide electrical power when the vehicle's electrical requirements exceed the supply from the charging system and also act as a voltage stabiliser when voltage fluctuations take place in the automobile. There are two types of lead-acid batteries, the flooded-cell type and the sealed type, and they are used to supply 12V for passenger vehicles and 24V for heavy trucks and mining equipment. Key benefits include low cost and high recyclability rate, with lead-acid batteries being 99% recyclable compared to only 5% for lithium-ion batteries. Costs of lead-acid batteries vary from $130 to $250 per kWh compared to $250 to $1,000 per kWh for Li-ion batteries (Source: NREL). High operating temperatures, ease of manufacture and low self-discharge also make batteries an ideal source of power for automobiles. They are used in hybrid and electric vehicles but only to support primary Li-ion batteries. These benefits make lead-acid batteries well-suited for automobiles and especially difficult to displace from a technological standpoint.

The case for ultracapacitors

Ultracapacitors can be used as a secondary power source in tandem with batteries to cater to short-term power requirements for various applications in vehicles, which relieves the load on batteries and extends battery life. Key benefits of ultracapacitors include their ability to store energy generated from braking systems, high-energy discharge, fast charging and operations at low temperatures, such as -40 degrees Celsius, which can be used for applications such as engine starting, even in harsh weather environments. By providing power for these short-term requirements, they help balance the load of the primary power source in an automobile. For example, GM became the first US-based manufacturer to adopt ultracapacitors for its Cadillac range of automobiles in 2015 to power start-stop systems.

Increasing performance expectations from automobiles are pushing power requirements. To cater to these higher requirements, manufacturers deploy large vehicle batteries, which increase costs and add to the weight of the vehicle. This can be a drag on the vehicle performance and lowers overall fuel efficiency. To meet these challenges, automobile companies have turned to incorporating alternative sources of power that can cater to peak electrical demands. Ultracapacitors, with their high-energy discharge and long life of 12-15 years, help lower maintenance costs while balancing the load on the batteries. Cost is a key challenge for ultracapacitors as initial costs vary between $2,000 and $6,000 per kWh (Source: NREL) and the need to redesign vehicle architecture to accommodate ultracapacitors can increase overall costs. Lower energy density compared to other battery types further hinders the increased adoption as a vehicle power source.

Lead-acid battery pollution provides further reasons for the replacement of such batteries with environmentally friendly power sources. Increased usage of lead and sulphur contaminates soil and groundwater if not properly disposed or recycled. Accidental leaks lead to poisoning and fires, including explosions, which have led many manufacturers to move towards alternative and safer sources of power such as ultracapacitors.

Unlocking the value potential

By incorporating ultracapacitors and batteries in a hybrid set-up, manufacturers extend battery life while allowing the vehicle to operate in wide temperature ranges. The focus on emission reduction and fuel efficiency drives the adoption of start-stop systems within vehicles featuring ultracapacitors, which increase fuel efficiency by 5% to 10%. Lower battery replacement cycles reduce operating costs for vehicles as they need not replace batteries for two years. This is especially significant for large commercial vehicles, such as trucks, that have an average of two batteries, which are often replaced more frequently and hence have a better cost-saving potential.

Policies from various governments on energy savings also lead to the adoption of ultracapacitors to increase vehicle efficiency, and increased electrification drives the demand for fast-charging applications. New forms of capacitors such as Li-ion or graphene-based ultracapacitors have higher energy density and costs that are comparable with Li-ion batteries, which will drive higher adoption of this technology in the future. As older batteries are replaced, these new types of ultracapacitors will see higher adoption rates via the battery aftermarket channel.

Several Japanese manufacturers such as Toyota and Honda have already incorporated ultracapacitors in their vehicles, while western manufacturers such as GM and Tesla are also increasing their use of ultracapacitors. It is expected that more research will go into ultracapacitors over the next decade, with vehicle manufacturers investing heavily in alternative sources of power. This will lead to the development of new products with costs and energy density comparable to batteries, driving higher adoption.

Figure 15: Key value drivers in lead-acid battery hybridisation

Source: Frost & Sullivan

LEAD ACID BATTERY HYBRIDISATION VALUE DRIVERS

- Long lifetime: > 10 years substantially reduces operating costs due to frequent battery replacements
- Fast charging/discharging: < 10 seconds
- Higher efficiency: > 95%
- Lower weight helps reduce vehicle drag
- Lower operating temperatures: -40 degrees to +65 degrees Celsius
- Increases fuel efficiency in vehicles by 5% to 10%
- Carbon materials used by ultracapacitors offer low pollution and good electrical conductivity thereby increasing sustainability of power source

Frequency Control and Pitch Control for Wind Turbines

Ultracapacitors are a critical reliability component of the turbine pitch control system, managing the pitch for each blade individually and performing critical functions by 'feathering' the blades to enhance the efficiency of wind energy conversion, as well as shutting down the system by pitching the blades to zero in case of high winds or a grid failure for fail-safe operation. They adjust the blades to capture maximum power while maintaining high levels of safety and preventing the turbine from spinning out of control. Traditional power systems for pitch control have depended on hydraulics or batteries to supply power, both of which have their drawbacks, including being complex systems that require frequent maintenance and replacement of parts, leading to downtimes. Manufacturers also have to replace the batteries every two to three years and they have lower efficiency as the battery discharges. The large number of components in a battery also leads to increased complexity, adding to maintenance and costs. Further, batteries are unable to operate in harsh weather conditions and have a narrow band of operating temperatures.

A low operating temperature can result in larger battery systems, leading to extra weight, less efficiency, higher costs and the inability to service such systems in offshore wind turbines, which will become a key growth area for renewable energy in the future.

The case for ultracapacitors

Ultracapacitors can store energy with a high-efficiency output. They can operate in harsh weather conditions and have reaction time in milliseconds.

The lack of chemical substances leads to high levels of safety and reduces the risk of fire, which is an advantage in remote sites, where turbines are often located. Ultracapacitors also have low maintenance

requirements compared to batteries and have a long replacement time of 15 years; this is a key benefit since the wind turbine industry is highly focused on minimising operating costs to be competitive as a technology. Operating temperatures for ultracapacitors are between -40 degrees Celsius to +65 degrees Celsius, which can help wind turbines function smoothly in low temperatures. This is valuable because it allows wind park developers to potentially access previously unfavourable sites.

The energy required for electrical pitch control systems is low and the duration takes seconds, which is a good fit for ultracapacitors because they deliver high power in short periods. Ultracapacitors also require less of monitoring and maintenance systems compared to batteries. They do not need heating or cooling systems, resulting in lower hardware requirements and redesign costs for the manufacturer.

Unlocking the value potential

Ultracapacitors have high initial costs but have reduced or equivalent total cost of ownership when compared to batteries over the lifetime of the system. This leads to higher acceptance from manufacturers as they can spread the costs over a long time. Less maintenance and fewer replacements add to the lower costs for ultracapacitors, especially in remote and offshore wind turbines, where maintenance is difficult and infrequent. It is estimated that nearly 20% to 25% of all downtime in wind turbines is due to pitch system failures, which is a significant cost for wind park operators. These failures can be reduced by using a less complex and highly efficient power source such as ultracapacitors instead of batteries, which require more components for operation.

Ultracapacitors can offer efficiency in excess of 95%. It is estimated that nearly 30% of all wind turbines globally are installed with ultracapacitor systems the first systems were installed by Enercon in 2006 for pitch control and emergency power. According to Maxwell Technologies, it is estimated that ultracapacitors will be able to replace batteries and hydraulic systems for pitch control by the end of the decade. Maxwell Technologies has introduced ultracapacitors in turbines in China and Europe, with retrofits introduced in North America.

Figure 16: Key value drivers for pitch control in wind turbines

Source: Frost & Sullivan

PITCH CONTROL VALUE DRIVERS

- Higher reliability resulting in reduced downtimes, which are up to 25% with more complex battery operated pitch control systems
- No chemical substances leading to lower fire hazard and higher safety
- Lower operating temperatures: -40 degrees to +65 degrees Celsius able to operate in more hostile, offshore environments
- Low maintenance requirement and long replacement time reduces operating costs given the remote locations of many wind farms

Elevators, Cranes and Power Tools in the Industry

As mentioned, the potential applications of ultracapacitors in industrial applications are diverse, but some of the most promising ones include elevators, cranes, and power tools.

Elevators generate energy from their movement and are grid-dependent for their primary power requirements. Increasing building efficiency norms drive energy storage requirements, which reduce grid dependence and lead to lower costs. Similarly, cranes also generate their own power and are in the process of incorporating RE power in their energy mix. As microgrids are enabled in ports, the need for peak load shaving and to balance frequency and voltage fluctuations is leading to a need for alternative power sources. Replacing batteries will increase penetration of ultracapacitors in power tools, which can benefit from lower maintenance and higher power density.

The case for ultracapacitors

Ultracapacitors serve as an energy storage and supply device for industrial machines such as cranes and elevators. Energy can be recovered from cranes during lowering and braking operations. It is stored in ultracapacitors and can be used for lifting operations. This helps in reducing diesel engine size as peak power requirements are taken over by the ultracapacitors. For example, the use of Skeleton Technologies' graphene-based ultracapacitor has reduced power consumption by 34% in a crane in the Baltic region. Expanding RE power and microgrids in ports are creating demand for balancing grid and voltage fluctuations where heavy cranes are deployed for loading and unloading of goods. Ultracapacitors provide quick bursts of power, which enable the rapid starting of cranes without the need for power from the grid or batteries. They also provide peak shaving, which can balance loads and lead to the deployment of RE power. This can lower loads on the primary source of power to extend its life. With their long life and low maintenance, ultracapacitors enable lower operating costs for crane operators.

Elevators also are ideal candidates for ultracapacitors to capture and store energy for their operations. Elevators are capable of generating their own energy upon descent or braking using a kinetic energy recovery system (KERS), which stores the generated kinetic energy in ultracapacitors for later use in lift operations. The energy generated due to elevator movement is less than the total power demands of elevators, so they depend on grid power or batteries as their prime source of power. Ultracapacitors can be used in parallel with the prime power sources, reducing their load and extending their service life. Several ultracapacitors can be installed in parallel if there is an increase in stored energy, and because they are lightweight, they do not add much weight to the elevator.

The increasing use of hybrid power management in power tools has led to ultracapacitors taking over several of the battery power functions. The absence of any chemical substances leads to high charge and discharge currents, higher safety due to lower incidences of fire or explosions, and simpler power control circuits for ultracapacitors compared to batteries. As ultracapacitors have a charge/discharge cycle of a million, this leads to longer life and a lower replacement rate in power tools. This reduces costs, ensures higher reliability, and lowers maintenance and downtimes. The replacement of batteries also ensures less pollution, and ultracapacitors enable power tool operations at low temperatures of -40 degrees Celsius. Ultracapacitor manufacturer IOXUS has introduced lithium-ion ultracapacitors that can charge power tools in less than a minute.

Unlocking the value potential

Ultracapacitors provide high-power efficiency of more than 90% for use in industrial equipment. Their usage also reduces energy consumption by 70% in elevators as regenerated energy is used. Modern ultracapacitors such as graphene and lithium-ion-based ultracapacitors can ensure cost reduction of 50% for elevators. Nearly 40% of the power requirement for crane systems comes from peak power usage, and by reducing the peak power load, ultracapacitors enable significant monthly savings on the power bill for crane operators.

Ultracapacitors face drawbacks in their cost as implementation in industrial equipment leads to high initial costs and redesign of existing systems. These barriers are expected to be overcome by investments in next generation ultracapacitors, which can bring down costs equivalent to batteries by 2030.

Figure 17: Key value drivers for industrial equipment

Source: Frost & Sullivan

ELEVATORS AND CRANES VALUE DRIVERS

- Energy Efficiency – 34% efficiency in case of cranes and 70% in case of elevators
- No hazardous materials – reducing risk of fire
- High power efficiency of 90%
- Long lifetime: > 10 years
- Fuel efficiency: 5 to 10% for cranes
- Fast charging/discharging: < 10 seconds
- Start/Stop: 20% less starting time
- Enable power tool operations at very low temperatures of -40 degrees Celsius

The Final Word

Ultracapacitors have been relatively under-explored compared to other established energy storage technologies, such as batteries. Although the technology is already being implemented in some applications, there is great potential to develop it further to overcome some of its limitations.

As highlighted in this paper, some features of ultracapacitors are far superior to those of batteries; for example, they have much longer life cycles, the ability to withstand extremes, high-power discharge, etc. However, some key challenges remain, most notably the cost of the technology and its energy density. Although great strides are expected in the coming decade to address these weaknesses, which will help with adoption, these need not be deal-breakers for the technology.

As the energy transition towards cleaner and more efficient systems gains momentum, ultracapacitors have the potential to play a significant role and allow the industry to generate value in innovative ways. Indeed, in many respects, ultracapacitors cannot compete directly with batteries, e.g. lead-acid batteries in overall cost versus performance. However, this is not the argument for the increased role of ultracapacitors in this application - the 'sweet spot' of the technology lies in the value that it will unlock when combined with batteries to form hybrid systems. For example, using ultracapacitors with lead-acid batteries in vehicles significantly increases battery lifetimes and eliminates the need for additional batteries in trucks, which greatly reduces the total cost of ownership for the end user.

In this instance, ultracapacitors do the heavy lifting for batteries (e.g. engine start) and allow the batteries to be optimised and used in other increasingly important functions, such as powering an increasing number of devices due to automation and electrification.

On the other hand, ultracapacitors may compete with batteries in applications where cost is not the main value driver. For example, in pitch control systems for wind turbines, ultracapacitors are preferred, given the low requirement for maintenance and ability to operate in more extreme temperatures. This allows wind farm operators to exploit sites that may have been previously too harsh for batteries and also enables them to reduce the costs of maintenance, which can be considerable in remote sites – 25% of current downtimes associated with wind turbines have to do with failures of pitch control systems. Along similar lines, ultracapacitors also enable industries to unlock new value opportunities that would have otherwise not been possible with batteries. For example, horizontal drilling applications in Oil and Gas require constant communication between the drill head and the surface for positioning; given the extremes of high temperatures and high power requirement to transmit the communication signal, this would not be possible with batteries.

It is therefore critical that the industry does not look only at cost, but rather considers the holistic benefits the technology would bring to a use case. In this respect, the potential to unlock new value streams from ultracapacitors across industries is considerable and equipment manufacturers should investigate how they could leverage this technology to the fullest extent.

Appendix

1. Rationale for Ratings in the Matrix

The ratings provided in the tables refer to the degree of relative attractiveness of ultracapacitors for various applications. This is a qualitative assessment based on the current usage profile in the industries along with the future potential for the technology, depending on cost, reliability and the availability of competing power sources/existing technology. Interviews with key industry participants were conducted to gain external perspectives of the potential for the technology.

2. Definitions of Applications

Engine Start-up/Engine Cranking: Ultracapacitors are used to start engines in automobiles and other transport equipment such as trucks, trams, rail, buses, etc., by providing a short burst of high power. They are especially useful for starting engines at low temperatures.

Pitch Control for Wind Turbines: Pitch control systems adjust the blade of the wind turbine during high winds to ensure increased efficiency and less damage to the turbines. Ultracapacitors are used to provide power to help run pitch control systems instead of hydraulic or electric pitch control systems.

Generator Control Gradient: Ultracapacitors help generators balance the high load variations by delivering the power needed to compensate for the high load variations. This helps maintain the stability of the power generation.

Frequency Response/Synthetic Inertia: Rising RE penetration increases the load imbalance on the grid, leading to blackouts and load shedding. Ultracapacitors with high-energy discharge help stabilize the grid by providing a quick burst of high power, which compensates for the variations in grid power.

Fast Charging: Ultracapacitors can charge quickly, provided the right amount of power is available. Charging time is between 10 seconds to 10 minutes, compared to 2-12 hours for batteries.

Hybrid/Electrification: Ultracapacitors offer short bursts of high-power applications and can be used along with batteries in hybrid and electric vehicles, helping automakers increase the electrification of automobiles to improve fuel efficiency and reduce emissions in electric vehicles.

Energy Storage/Back-up Power Bridging: Ultracapacitors are used to store excess energy generated from various sources, which can then be released when needed. Ultracapacitors act as energy storage devices that can provide backup power.

Catenary-free Operation: Applicable for urban rail and tram networks, ultracapacitors reduce the need for overhead power lines in urban areas because they absorb the power generated while braking quickly and also in power lines located only at stations, which is then used to power the rail from station to station.

Peak Load Shaving: Ultracapacitors are enabled to handle peak load situations in which they act as a secondary power source, supplementing prime power applications. This reduces the need to scale down operations as well as reduces the load on electrical equipment.

Power Steering: Ultracapacitors provide a large amount of power to steering systems for short periods, thereby reducing the load on batteries.

Ebrake/Kinetic Energy Recovery System (KERS): Braking systems in vehicles, rails, trams, etc., release energy that can be stored by ultracapacitors due to their fast-charging nature to be used for further applications, such as engine starting or vehicle acceleration.

Lead-acid Battery Hybridisation: With higher efficiency and lower charging times, ultracapacitors are being considered for use in parallel with batteries. They last for more than 10 years and require low maintenance compared to lead-acid batteries.

Autonomous Driving: Autonomous vehicles require high power and lower load on batteries. Ultracapacitors tied to batteries are increasingly adopted in such vehicles as they provide a secondary source of power, reducing the load on batteries while increasing fuel efficiency and reducing emissions.

Electric Catalyst Heating: Ultracapacitors can operate in temperatures between -40 degrees Celsius and +65 degrees Celsius. They can be used to heat automobile catalysts to purify exhaust gases.

Start/Stop: Automobile engines are automatically switched off when the vehicle comes to a stop and restarted when the brake is removed. This system requires restarting the engine several times in heavy traffic conditions, which drains batteries. The use of ultracapacitors enables adequate power for start/stop systems without putting a burden on batteries.

Heave Compensation: Heave compensation systems are used in the marine industry to lift equipment. Ultracapacitors are used to store energy during heave-up movements, which is then discharged when needed. This helps reduce the peak energy load on ships' main power systems and increase efficiency of the system.

VSD Backup: Voltage drops affect the operation of variable speed drives (VSDs) of electrical motors, leading to production shutdowns. Ultracapacitors are used as backup power for short-term outages and voltage drops, thereby ensuring power quality.

Prime Power in IoT Devices & Tools: Smaller devices such as sensors, which require constant discharging of power without frequent replacement of the power source, employ ultracapacitors to power their operations, including sending data in periodic high-power bursts. Power tools can also use ultracapacitors for their key power requirements.

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