



Energy Storage

Supercapacitors in Power System Design

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Supercapacitors, or ultracapacitors, are energy storage and delivery devices with extremely high capacitance—millions of times greater than traditional capacitors. They are an asset in modern power management because they're designed for reliable, rapid responses across hundreds of thousands to millions of duty cycles, even under demanding environmental conditions.

With an array of sizes, supercapacitor modules, comprising cells arranged in series or parallel, offer scalable solutions that deliver real-time backup power for mission-critical systems. In the right configuration, they can respond instantly to power surges or outages, bridging the gap between failure and recovery.

As energy demands grow and system requirements become more dynamic, supercapacitors are gaining widespread attention for their performance advantages over conventional batteries. This ebook explores the principles behind supercapacitor operation, compares their characteristics with traditional energy storage technologies, and highlights the specific challenges they solve in high-performance electronic systems. From electric drives and fail-safe controls to advanced medical imaging and smart logistics, supercapacitors are reshaping how engineers design for reliability, efficiency, and resilience in power delivery.

Fundamentals of Supercapacitor Performance

Supercapacitors are engineered to deliver rapid energy bursts, long operational lifespans, and high reliability in demanding environments. This section explores the underlying principles that drive their performance, including energy and power density and how their construction impacts efficiency and application suitability.

Understanding Energy and Power Density in Capacitor Applications

Energy density describes the amount of energy stored in a mass (Wh/kg or J/kg) or volume (Wh/L). High energy density implies the system can store a lot of energy in space- and weight-constrained spaces. This is particularly useful in applications like mobile devices and electric vehicles where board space is a luxury and long-term energy storage is critical for operational efficiency.

While frequently mentioned together in energy storage discussions, energy density and power density represent distinct performance characteristics. Power density describes how quickly energy can be delivered or absorbed into a system in W/kg or W/m³. High power density tells us a system can release or accept energy at a fast pace. This characteristic is ideal for applications that require quick bursts of energy like camera flashes or industrial lasers.

In short, energy density focuses on storage capacity while power density measures the rate of energy transfer, and systems designers are expected to balance the two. For example, batteries with high energy density may not be able to deliver energy as quickly as supercapacitors, which are known for their high power density.

Supercapacitors excel in power density, but they have lower energy density compared to batteries (Figure 1). They can't store as much energy for long-term use, so traditional batteries are more suitable for applications where energy delivery occurs over longer durations. The balance between power density and energy density depends on the application requirements.

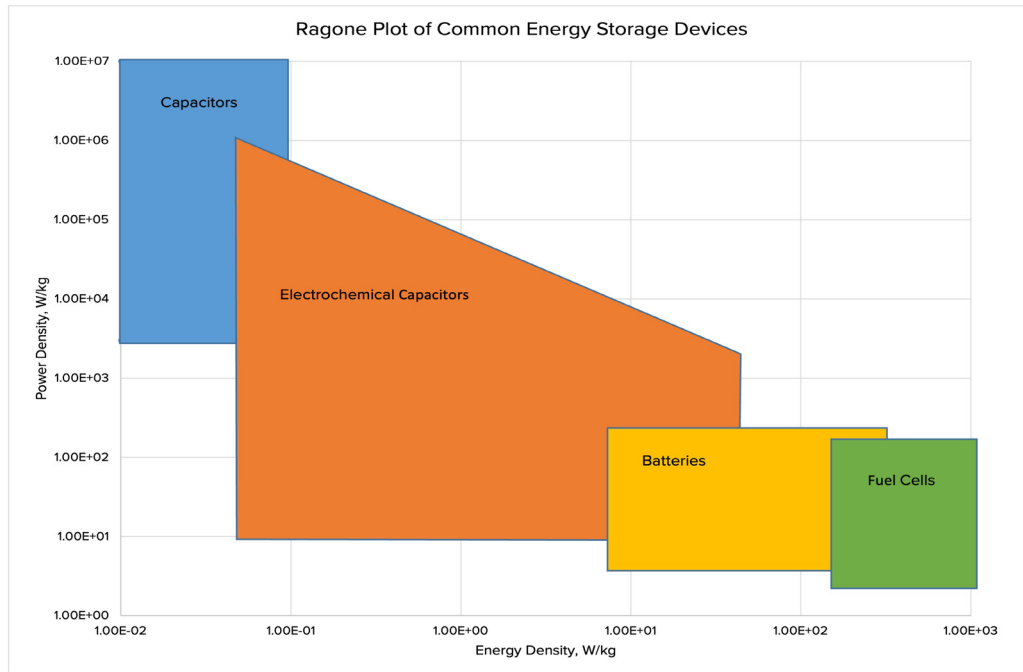


Figure 1. Ragone plot comparing the performance of several common energy storage devices, including supercapacitors and batteries. Adapted from: [Source](#).

Quantifying Energy and Power Density

To better understand how these performance metrics apply to real-world systems, we can look at how energy and power density can be quantified mathematically.

Calculate the energy stored in a capacitor using:

$$E_r = \frac{1}{2} C V_r^2$$

where C is capacitance and V_r is the voltage rating of the capacitor.

To find the volumetric energy density of a capacitor, divide E_r by volume:

$$\gamma_v = \frac{E_r}{Vol}$$

The power rating of a capacitor can be estimated from the rated voltage and current as:

$$P_r = V_r I_r$$

Power density is P_r divided by volume:

$$\rho_v = \frac{P_r}{Vol}$$

Alternatively, another approach to determining power density is to examine the impedance-matched condition, where the load matches the source impedance (i.e., the capacitor's [equivalent series resistance](#) (ESR)). Under these conditions, we find:

$$P_{im} = \frac{V_r^2}{4 \times ESR}$$

Then, power density is calculated as:

$$\rho_{Vim} = \frac{P_{im}}{Vol}$$

This method reveals that capacitors with high power density require a low ESR to maximize the rate of energy transfer.

With a foundation in how energy and power density are measured, we can better evaluate how different storage technologies, particularly supercapacitors and batteries, compare in delivering these capabilities.

Where Supercapacitors Outperform Traditional Batteries

Supercapacitors feature unique characteristics that set them apart from traditional batteries in energy storage applications. Unlike batteries, which store energy through chemical reactions, supercapacitors store energy electrostatically, enabling rapid charge/discharge cycles. In certain applications, this gives them a significant advantage in terms of power density, lifespan, efficiency, operating temperature range, and sustainability.

The growing adoption of supercapacitors in modern energy applications is driven by their:

High Power Density

As mentioned, supercapacitors store energy electrostatically, so their power density ranges from 10 to 100 times higher than batteries, and they can fully charge in a matter of seconds. Battery chemistry reactions occur at slower speeds, which impacts charge and discharge rates (typically measured in hours).

Long Life Expectancy

Due to mechanical and chemical degradation, rechargeable batteries wear out after a few thousand charge/discharge cycles maximum. Excluding those with polymer electrodes, supercapacitors have a much longer lifespan than batteries. The lifecycle of electric double layer capacitors (EDLCs) is nearly unlimited because electrostatic energy storage causes less wear and tear on components.

Wide Operating Temperature Range

Supercapacitors can function without significant degradation in environments ranging from -40°C to 70°C. Batteries, particularly lithium-ion batteries, can't operate across that wide of a temperature range without overheating.

Sustainability

Supercapacitors mostly consist of carbon and its compounds, so they biodegrade, and waste materials are easy to dispose of. Further, packaging is designed to minimize negative environmental impacts.

High Efficiency

In renewable power generation, energy efficiency is paramount. During charging cycles, supercapacitors only experience about 1 percent energy loss, compared to up to 30 percent for lead-acid batteries.

These performance traits, summarized in Table 1, directly influence where supercapacitors are deployed. Let's take a closer look at how they're constructed.

Parameter	Lead-Acid Battery	Lithium-Ion Battery	Supercapacitor
Specific energy density (Wh/kg)	10-100	150-200	1-10
Specific power density (Wh/kg)	<1000	<2000	<10,000
Cycle life	1000	5000	>50,000
Charge and discharge efficiency	70-85%	99%	85-98%
Fast charge duration	1-5h	0.5-3h	0.3-30s
Fast discharge duration	0.3-3h	0.3-3h	0.3-30s
Shelf life (years)	5-15	10-20	20
Operating temperature (°C)	-5 to 40	-30 to 60	-40 to 75

Table 1. Comparison of key specification differences between lead-acid batteries, lithium-ion batteries and supercapacitors. Abbreviated from: [Source](#).

Supercapacitor Construction

The main difference between supercapacitors and other capacitor types is the electrodes. Supercapacitors are based on a carbon technology that creates a very large surface area with an extremely small separation distance.

In supercapacitors, there's a positive electrode, negative electrode, separator, and electrolytes filling the void space in between (Figure 2). The surface area of the activated carbon layer is extremely large, yielding several thousands of square meters per gram. This large surface area allows for high ion absorption. Charging/discharging occurs in the ion absorption layer formed on the electrodes of activated carbon.

The activated carbon fiber electrodes are saturated with electrolytes, enabling the formation of positive and negative charges at the electrode-electrolyte interface. These opposing charges create an electric double layer, which initially acts as an insulator. When the applied voltage exceeds the decomposition voltage, the electrolytes begin to break down, and current starts to flow.

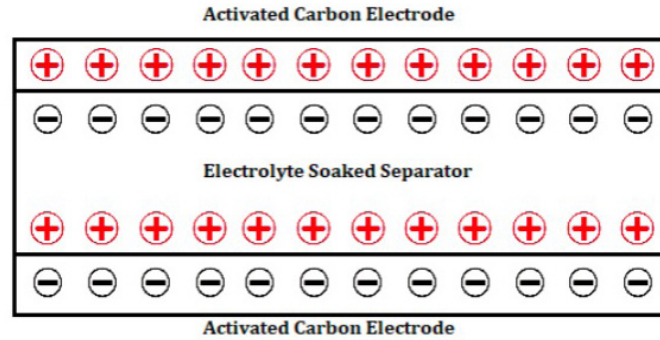


Figure 2. The configuration of carbon technology within a supercapacitor sets it apart from other capacitor types.

The double layers formed on the activated carbon surfaces can be illustrated as a series of parallel RC circuits.

As shown in Figure 3, the supercapacitor is made up of a series of RC circuits where R1, R2 ...Rn are the internal resistances and C1, C2..., Cn are the electrostatic capacitances of the activated carbons.

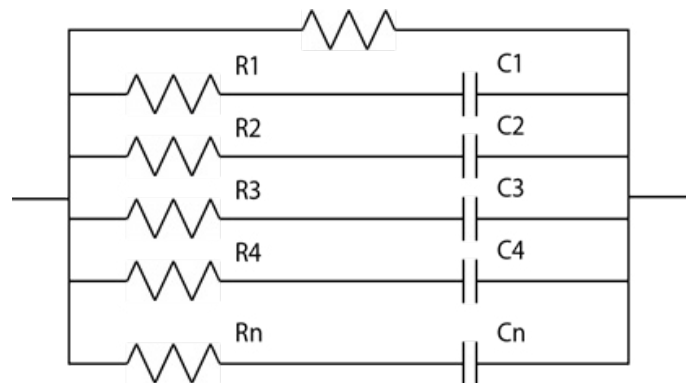


Figure 3. Supercapacitors are made up of a series of RC circuits where R is internal resistance and C is electrostatic capacitance.

When voltage is applied, current flows through each RC circuit. The time it takes to charge the capacitor depends on the product of the capacitance and resistance, known as the RC time constant, τ . The larger the RC time constant, the longer the capacitor takes to charge. The amount of current needed to charge the capacitor is determined by the following equation:

$$I = \frac{V}{R} e^{-t/RC}$$

By understanding the unique structure and performance characteristics of supercapacitors, engineers can begin to evaluate how these devices address real-world energy challenges across applications.

Meeting System-Level Energy Challenges

Supercapacitors excel in applications where traditional energy storage falls short in delivering power quickly, reliably, and repeatedly. This section highlights how these devices meet specific design and operational challenges in real-world systems, from backup power to hybrid energy storage.

Supercapacitors in Electronic Circuits

Supercapacitors play two main functions in electronic circuits. In battery-powered devices, they provide backup power in the event of disconnection (Figure 4a). They also provide alternating current (AC) voltage for devices with heavy switching currents (Figure 4b). In that case, supercapacitors protect the device's memory, for example, from large voltage drops.

The following examples demonstrate how supercapacitors assume these functions in real-time clock backups, power failure backups, high load assist systems, and hybrid energy storage systems to enhance efficiency and reliability.

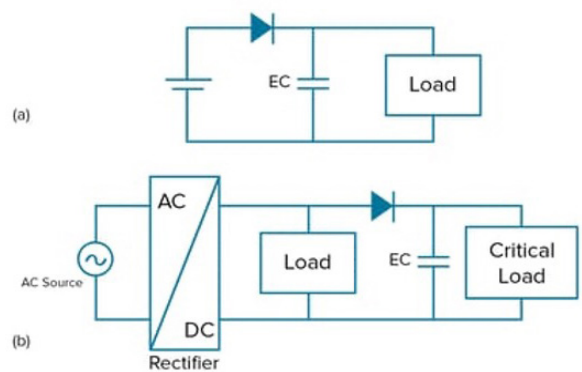
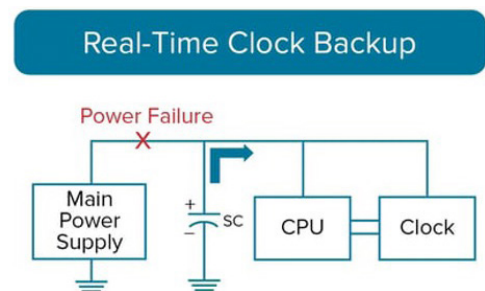


Figure 4. Common supercapacitor roles in electronic circuits, including backup power (a) and protection against voltage drops (b).

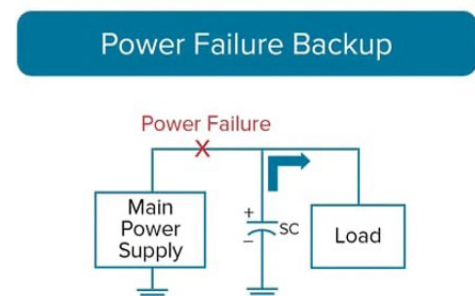
Real-Time Clock Backup

In real-time clock backup, also known as memory backup, solid-state drives have many advantages over hard-disk drives, including low power consumption and high reliability. By design, write speed is their main weakness, and that's remedied using protected cache memory (SDRAM). SDRAMs need backup power, and supercapacitors are an excellent choice because of their fast response time, high power density, and low maintenance requirements.



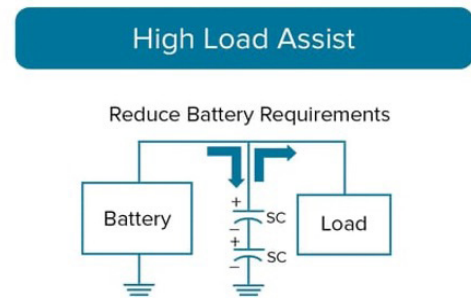
Power Failure Backup

Power supply backups, otherwise known as uninterruptible power supplies (UPS), offer emergency power when a system's primary power source fails. In these cases, telecommunications, industrial and other electrical equipment can be subject to malfunction or data loss. To successfully provide uninterrupted power, the backup supply must be able to start up reliably and instantaneously.



High Load Assist

Supplementary systems help maintain a system's primary energy storage system (ESS). In some cases, like the camera flash on a smartphone, peak lower load is significantly higher for a short period of time. Supercapacitors are ideal secondary sources to handle those power bursts while leveraging a low-power, more cost-effective battery as the primary energy source.



Hybrid Energy Storage Systems

Some energy storage systems combine supercapacitors with batteries to form hybrid energy storage systems (HESS). These are common in applications like the photovoltaic (PV) microgrids found in homes and neighborhoods (Figure 5). Microgrids are weak electrical grids, so they're sensitive to load generation changes. A HESS decreases the impact of variations in load.

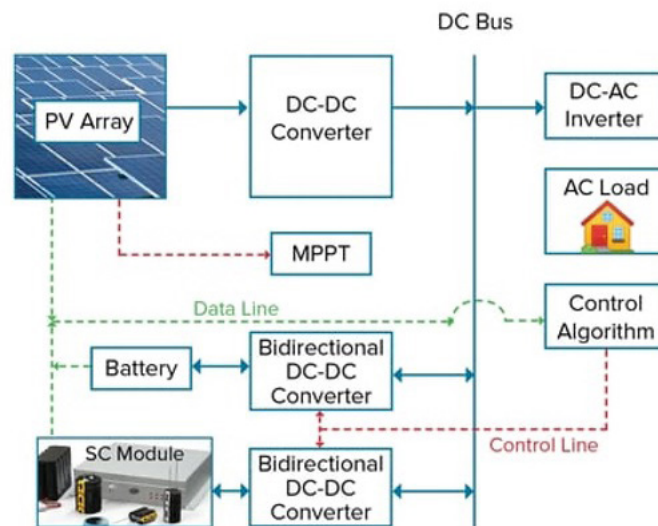


Figure 5. Photovoltaic microgrids are hybrid energy storage systems featuring both batteries and supercapacitors.

By solving critical energy delivery challenges across a range of systems, supercapacitors have proven their versatility.

High-Impact Energy Storage Solutions

With more and more mission-critical systems relying on electrical power, consistent and reliable backup power is essential to ensure uninterrupted operation. Facilities like data centers and hospitals leverage backup power to manage the short, but potentially catastrophic, delay between grid power failure and the start of long-term back up (e.g., local generation via diesel generators).

Short-term and long-term backup power sources are critical layers of protection. While batteries are useful in some backup functions, they present disadvantages in others. With

limited runtime, capacity degradation concerns and limited power surge capabilities, they're not designed to provide those quick bursts of energy needed to bridge the gap between failure and local power generation.

Common Supercapacitor Applications

While supercapacitors are used in many different application areas, they thrive under two key conditions.

High Power: With their built-in high-power characteristics, supercapacitors are critical in power electronics, where engineers are looking for short-time power peaks.

Long Life Cycle: In low-power applications, like security installations, batteries present maintenance issues or insufficient performance over time. Supercapacitors can efficiently handle quick bursts of energy when needed and can endure many more charge/discharge cycles over time.

Supercapacitors for Recloser Back-Up Power

To protect electrical grids from overloads and faults, utility companies can incorporate reclosers. When a fault occurs, this high-voltage circuit breaker automatically closes to isolate the faulty sections of the grid, allowing other areas of the grid to continue to operate safely. The recloser can then automatically test the electrical lines to determine if the issue has been resolved and reset itself, restoring power more quickly once a fault is cleared. Reclosers are also designed to perform remote switching, enabling utilities to manage their networks more efficiently.

Batteries are commonly used as the backup power source for reclosers because the battery power enables the device to rapidly switch in and out, preventing damage to equipment and ensuring public safety. However, batteries have a limited number of charge/discharge cycles and will degrade over time, reducing overall performance and reliability. This is especially true when batteries are repeatedly exposed to extreme cold or heat. As a result, most recloser manufacturers recommend replacing batteries every five years, which can be costly and logistically challenging. Supercapacitors are now an option for an alternative power storage solution that addresses these shortcomings by design.

Supercapacitors for Fail-Safe Control

Unplanned power interruptions and shutdowns pose serious risks for industrial facilities. Even a few seconds of lost control can result in equipment damage, safety hazards, or production losses.

Engineers are turning to supercapacitors for reliable and precise energy delivery in automated valve control systems. Especially in applications where traditional batteries or spring-return mechanisms are less practical, they can achieve greater resilience and safety with supercapacitors.

In the context of a valve control system, supercapacitors continuously charge from the main power supply during normal operation. If a power failure occurs, stored energy drives the

actuator motor to move valves to a predefined, safe position (e.g., closing steam valves or opening ventilation dampers). Advanced energy management systems leverage algorithms to optimize charging patterns and prevent deep discharge, which causes accelerated wear, reduced efficiency, and potential failures.

Electronic valve control systems have historically used traditional battery or spring-based fail-safe mechanisms; however, supercapacitors offer a more reliable, maintenance-free alternative and a longer lifespan compared to lithium batteries. They also maintain efficient operation in extreme temperatures, charge fully in seconds vs. hours, and don't experience degradation from partial charging.

Switching to supercapacitors from mechanical springs eliminates opportunities for mechanical wear and allows for smaller actuator design. Supercapacitors are better for consistency too. It's possible to program fail-safe positions and actions (e.g., torque) are more consistent. For this reason, supercapacitors are uniquely beneficial for remote or hard-to-access installs.

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What are the potential drawbacks? Cost is a concern if your budget is tight. Further, the team will need to dedicate time and attention to precise energy calculations in mission-critical industrial applications. For quickly reaching a safe position, supercapacitors excel. For sustained operation during long outages, traditional batteries may be necessary.

Supercapacitors for Precision Medical Imaging

Magnetic resonance imaging (MRI) technology relies heavily on precise RF systems to generate and detect signals essential for imaging. The interplay between magnetic field strength, coil design, and amplifier performance is crucial for achieving high-resolution images.

MRI machines leverage large superconducting magnets to establish the magnetic field and partially polarize protons. Gradient coils make it possible to fine tune the magnetic field in the x, y, and z directions.

Field strength and the particle strength determine the frequencies the system can detect. Adjusting the magnetic field locally enables the system to use signal processing to determine where in the tissue sample a signal came from and build images accordingly.

For high precision, gradient coil current amplifiers must supply the coils with very consistent electrical signals. To maintain that consistency, it's useful to have supercapacitor modules for backup energy.

Supercapacitors for Smart Warehousing

Smart warehousing involves the strategic deployment of robotics and automation to optimize the day-to-day operations and management of warehouses. Implementations traditionally include a combination of automation, Internet of Things (IoT), artificial intelligence (AI), warehouse management systems (WMS), advanced robotics, augmented and virtual reality (AR/VR), and cloud computing.

Smart logistics leverages robotic arms, automated guided vehicles (AGVs), automated mobile robots (AMRs), goods-to-person systems and drones for common tasks like order picking, replenishment and goods transportation. AGV/AMR power systems typically include a combination of motors, wheels, breaks, sensors and lead-acid or lithium batteries. However, batteries aren't the most effective option when it comes to instant power availability, rapid charging, or energy efficiency. Shortcomings in these areas contribute to the growing popularity of supercapacitors, or supercapacitor modules (SCAP).

Choosing the Right Supercapacitor

When determining the right supercapacitors for your application, in type and number, consider:

- Average current or power
- Peak current or power
- Required runtime
- Maximum and minimum operating voltage
- Temperature of the operating environment
- Required lifespan

Since supercapacitors are low voltage devices, their rated voltage is generally less than the application voltage required. Using the expression below, the maximum application voltage ($V_{\max}$) tells you how many capacitor cells should be connected in series:

$$\frac{V_{\max}}{V_R}$$

Next, you can calculate an approximate system capacitance using average current (I) in amps, the required run time (dt) in seconds, and the minimum working voltage ($V_{\min}$):

$$C_{sys} = I \cdot \frac{dt}{dV} = I \cdot \frac{dt}{(V_{\max} - V_{\min})}$$

The total system capacitance consists of the capacitance of all series connected capacitors used for achieving Vmax. When capacitors are connected in series, the capacitance of the individual cells is calculated using:

$$\frac{1}{C_{sys}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$$

To meet the required energy in a parallel capacitor configuration, the total capacitance is calculated using:

$$C = C_1 + C_2 + \dots + C_n$$

Additional factors such as internal resistance, ambient temperature, and end-of-life performance requirements should also be considered to ensure accurate system sizing and long-term reliability.

Whether you're looking for a custom or off-the-shelf option, here are some questions you'll need to answer before selecting the supercapacitor technology, cell arrangement, and balancing approach for your module:

- What's the minimum voltage level the system needs to maintain?
- How much time do you need to maintain that minimum voltage before long-term backup power kicks in?
- What voltage level is available for module charging during normal system operation?
- What current and power levels must your system be able to support?
- What are your anticipated lifetime requirements?
- What are your most stringent mechanical constraints (e.g., size)?
- What environmental or thermal conditions will the system operate under?

Still unsure of which path to take? Our team can help translate your system needs into the right supercapacitor solution. Contact Knowles for expert guidance.

Contact Us

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Peter Matthews is the Director of Technical Marketing at Knowles Precision Devices. As a division of Knowles Corporation, Knowles Precision Devices (KPD) focuses on production of a wide variety of highly engineered capacitors and microwave to millimeter-wave components for use in critical applications in military, medical, electric vehicle, and 5G market segments. Peter has over 20 years of experience in technology sales, marketing, and product management.

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