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## Low Power Architectures Thrive in Emerging Markets



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## Introduction – Trends Driving a Need for Low Power

It's no secret that the semiconductor industry has been marching steadily towards power-efficient solutions. In 2020, 28 billion microcontrollers were shipped, 9 billion of which were ultra-low power (ULP)<sup>1</sup>. The growth rate for ULP microcontrollers between 2021 to 2027 is expected to be 23.3% CAGR<sup>2</sup>. This growth is attributed primarily to power consumption being a major concern across markets and applications such as automotive, networking, datacenters, AI, medical devices, wearables, and the Internet of Things (IoT). The rapidly growing mobile-device market is just one example where extending the product's battery life is essential to their success. This white paper dives into the different fundamental market challenges and multiple ways the market is shifting towards lower power, such as MCU vendors shrinking their die, the lowering of IO voltages, optimizing power management schemes, and improving battery technologies to maximize battery life.



## Market Segments and Applications Trending to Low Power

Numerous market segments and applications need to move towards lower power. This can be seen by the 23.3% expected CAGR for ULP microcontrollers compared to the expected overall microcontroller CAGR of 10.1%<sup>2</sup>. The increased demand and market shift towards lower power is attributed to multiple reasons. Primary among them is the growth in adoption and integration of IoT-enabled smart devices such as ECG monitors and continuous glucose monitors (CGMs). Additionally, the growth in sensor usage such as temperature sensors, smart meters, and smart grids. These devices gather signals in real-time, such as speed, acceleration, pressure, temperature, blood glucose, and heart rate. The data is then stored and transferred securely for further processing. Due to the vast implementation possibilities these sensors and IoT devices service, it makes sense that lower power is becoming more important across industries and applications, such as artificial intelligence, wearables, consumer electronics, medical, automotive, and communications.

Diving deeper into medical applications, the overall market is expected to experience a 5% annual CAGR between 2021-2026<sup>3</sup>, while the medical electronics market is expected to see approximately 8% annual CAGR between 2018-2024<sup>4</sup>. Within the medical electronics market, the wearables segment is expected to experience 24% annual CAGR between 2021-2025<sup>5</sup>. Therefore, it can be observed that the majority of the growth will take place in the wearables market. With the increase in remote care, an aging population and healthcare becoming more accessible globally, the industry is trending towards wearable electronic devices on individuals. These devices will require more sensors to continuously read, monitor, and process data sets as well as be able to transmit data to remote secure cloud storage facilities. Due to the extra components necessary to provide such functionality, it is imperative that these solutions consume minimum power to conserve battery life.

While the medical market is a powerful example of sensors' importance, it is by no means the only one. Look no further than the automotive market. Advanced Driving Assistance Systems (ADAS) that deliver such safety and convenience features lane-change guidance, parking assistance and blind-spot detection require IoT devices such as cameras. The expected growth in ADAS up to 2025 is 17%<sup>6</sup>. Another is the industrial market, in which IoT devices are expected to reach nearly 31 billion by 2025, doubling the 2021 figure<sup>7</sup>. This should come as no surprise considering the trends towards industrial automation and smart manufacturing, both ushering in what's come to be known as Industry 4.0. In networking, the expected growth for IoT solutions is 21.6% into 2022<sup>8</sup>, and in the communications sector, the CAGR for 5G IoT is expected to be 73%<sup>9</sup>.

The above examples and figures point to an incontrovertible shift towards lower power. The next sections of this whitepaper will discuss factors driving lower power, benefits of transitioning to low power, what is being done on the software side to support low power, and developments in battery technology for making systems more energy-efficient. Lastly, this whitepaper will highlight how Macronix is committed to supporting low power through a comparison of the impacts to overall power consumption between a 3V system, 1.8V system and 1.2V system.



## Microcontrollers Shrinking Technology Nodes

Microcontrollers — the heart of IC devices — are key components in electronic products. As with microprocessors, microcontroller technology follows “Moore’s law,” increasing in power while decreasing in size. Process nodes continue to shrink, even after decades, from micrometers to single-digit nanometer levels. The driving factors behind this continued shrinkage are an increase in logic, SRAM and analog density, as well as improvements in speed – all while maintaining the same power, if not a *reduction* in the power to maintain the same speed. In other words, chips are getting smaller, using less power, and getting faster. In order to achieve these market goals, semiconductor vendors invest in new technologies such as MOSFET (1xx nm~2x nm) change to FinFET (1x nm~x nm). For example, this kind of change enables an MCU with 100mm<sup>2</sup> in 45nm have the ability to shrink to less than 20mm<sup>2</sup> in 14nm. With this change, the performance also improves.

Additionally, the core voltage and I/O supply voltage is also decreasing from 1.2V/1.8V (4x nm) to 0.8V/1.2V (1x nm). This voltage change significantly decreases power consumption since  $P(t)=I(t)*V(t)$ .

The decrease in core voltage and I/O supply voltage is a trend that appeals to multiple and varying markets, including:

- Wearables (smart bands, motion sensors, headsets)
- Smart Home (smart lighting, thermostats, smart locks)
- Smart City (smart meters, electronic shelf labels, surveillance, smart parking)
- Industrial (machine to machine, drone gimbals)

The wearable space is particularly concerned with power consumption because batteries for portable devices are space and capacity constrained and are the sole power source between charges. The main MCU process node in wearable is predicted to be 4x nm~1x nm, which can provide a ULP solution. As a result, the I/O supply voltage will decrease from 1.8V to 1.2V, based on the MCU technology node. In order to better capitalize on the potential power savings, external IC components also need to align with this supply voltage.

As discussed above, microcontroller process nodes are shrinking, enabling them to use less power while still increasing performance. In order to best support the shift to 1.2V-based technology nodes and maximize the power savings, Macronix, has developed the MX25S series, which meets various markets’ needs for low power by featuring 1.2V(1.14V~1.6V) for ULP consumption (1.65mA ICC\_active, 0.05uA ICC\_dpd). The MX25S effectively extends devices’ battery life due to lower voltage operation and current consumption.

## Lower IO Voltage and its impact on Peripheral Components

With the rising development of applications requiring ULP, MCU vendors must meet market demand by moving to lower core and IO voltages, which in-turn encourages peripheral components to shift to lower operating voltages like 1.2V.

When MCUs transition to a 1.2V supply, other peripherals such as RAM, Flash devices, EEPROM are encouraged to make this shift as well in order to reduce the power consumption of the overall system and increase the battery life. The system is able to conserve power when the peripheral components' input voltages match the MCU because the system no longer requires additional components such as low-dropout regulators (LDOs), voltage regulators or other forms of boost circuitry, which by design are impossible to be 100% efficient. Eliminating these additional components leads to several advantages, such as a reduction in complexity in the overall design, more room in the power budget, a simpler circuit board layout, and a lower bill of materials. The image below illustrates these advantages. Not only would a system architect's design become easier to maintain, but by eliminating those components, the device would last longer in the field, shrink in overall size and ultimately cost less to produce.

Using 3.3V /1.8V MCUs in battery operated designs may lead to a larger battery size & might require higher rated batteries. However, shifting towards a 1.2V architecture, will enable the portable solutions to have the flexibility to reduce the battery size and/or increase the rating to therefore be able shrink the size of the application, and increase the time in the field.

When shifting to a 1.2V system, from a 3V or 1.8V system, the benefits, again, are simpler design, simpler pcb layout, less components, smaller battery and/or longer battery life, and reduced BOM. With respect to lower BOM, Macronix's external Flash solutions are an attractive option because embedded Flash is not able to cost-effectively shrink below 40nm. Therefore, as the rest of the system continues to be reduced in size, this inevitably makes embedded Flash too expensive, rendering it not viable as an option in advanced process nodes for many cost-sensitive applications.

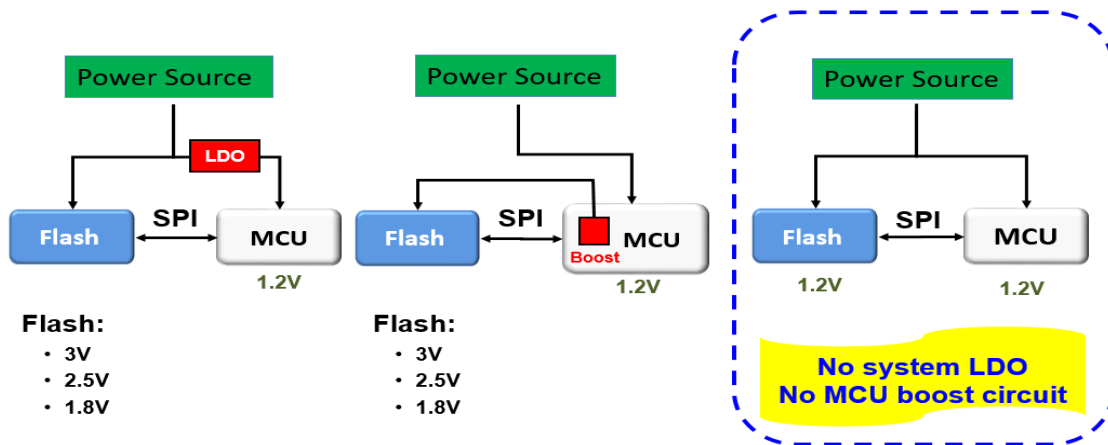


Figure 1: Image showing system with and without boost voltage circuitry



## Software Efforts Toward Optimizing Power Management

### Responsibility of Low Power

The continued growth in IoT is driving microcontrollers to an ULP design, which not only reduces dynamic run power but also offers a variety of power modes. In some implementations, a sub- $\mu$ A current consumption is possible. It is not only the MCU with the potential for creating a low-power system, especially for portable and IoT devices. Typically, these types of systems also consist of power management integrated circuits (PMICs), memory, a battery, and many other components, all of which have room for power-saving improvements.

### Power Manageable Flash

In response to the demand for better power efficiency, nonvolatile Flash has evolved to incorporate power-management features. This trend is reflected in Macronix having developed the most advanced, low-power nonvolatile Serial NOR Flash series on the market today. The MX25R, for example, is designed to support wider input voltage range applications between 1.65V and 3.6V, while the MX25S supports input voltages as low as 1.2V. Several features are designed into these solutions enabling users with optimal power management and performance. The following sections highlight a few of these features.

### Ultra-Low Power Mode and High-Performance Mode

By optimizing their architecture for power efficiency, the MX25R and MX25S Flash memories are geared toward low power applications without sacrificing performance. A mode selection is provided and applications can switch back and forth between the ULP and high-performance modes on demand to save power and handle critical tasks dynamically. In the ULP mode, both the standby current and deep-power-down leakage are reduced dramatically. The standby current is only single-digit  $\mu$ A, while the leakage of deep-power-down is 1% of that. Still, users can quickly revert to high-performance mode within microseconds to handle mission-critical scenarios by leveraging more than 50MB/sec throughput. The active currents of different operations in the ULP mode are also largely reduced to only about 50% of those in the high-performance mode.

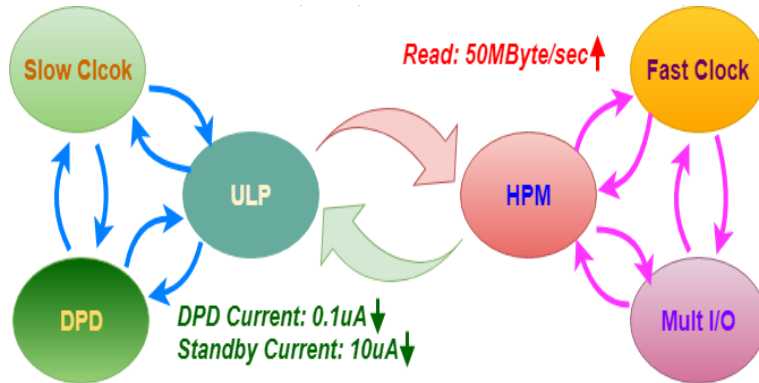


Figure 2: Image showing the tradeoffs between HPM and ULP modes

## Multi-I/O MXSMIO

Thanks to multi-I/O technology, the serial Flash performance has been significantly boosted while maintaining the backward compatibility with the conventional SPI protocol. This backward compatibility provides a scalable performance enabling users, when necessary, to revert to a single I/O protocol to reduce both peak and average drain current. It then effectively pushes off the cell voltage drop if powered by a battery. A set of different command codes are included, simplifying I/O scaling through a software implementation that employs different commands accordingly (see Table 1).

### Command Sets for Serial Flash Family

	Action	Command
READ Command	READ	03 Hex
	FAST READ	QB Hex
	Dual I/O READ	BB Hex
	Quad I/O READ	EB Hex
	Quad I/O DTR READ	ED Hex
PROGRAM Command	Quad I/O PAGE PROGRAM	38 Hex

Table 1: Command Sets for Serial Flash Family

## Frequency Scaling

Another useful scheme to control current consumption is frequency scaling. It is well known that dynamic power is proportional to the operating frequency and the current. So with the ability to adjust the frequency, users can operate at different rates to mitigate current consumption when accessing Flash through the SPI interface. Additionally, when switching to ULP mode, both the peak and average current are further reduced because the embedded operation flows and clock management are specially handled.





## Saving Power on Demand

The three major hardware features listed above make up manageable Flash and excel in power-sensitive applications. In addition, a hardware abstraction layer (HAL) with an application programming interface (API) is usually provided to accompany the hardware, allowing for maximum power optimization. Users can develop their applications embedding power states and making API calls to manage power precisely. Macronix has developed a reference Flash driver for its customers to support applications employing different modes for power management according to their requirements. For example, the MxChangeMode command can be used for applications switching among various modes, including SPI, dual SPI, Quad SPI, and DDR. MxDeepPowerDown and MxRealseDeepPowerDown API calls are used when an application needs to enter or exit deep-power-down mode, which is the most power-saving state, using only tenths of a microampere of current consumption.

## Power-Efficient Flash Management Layer

The average energy consumed for a byte read operation is approximately tenths of nanojoules, while for program/erase operations, the energy consumed is approximately tens of nanojoules in a typical Flash device. It costs around a hundred times more in energy to modify the content of Flash for each byte in general. Moreover, Flash does not offer write in place like RAM or EEPROM. In order to better mitigate the energy budget in the system when using Flash, a software-management layer such as Flash translation layer (FTL) or EEPROM emulation can be deployed to reduce the program or erase operations and therefore save energy accordingly. The FTL will map a logic address to another physical address of the Flash memory. It realizes write-in-place operation in logic address space through physically out-of-place modification to avoid energy spent on erase and the accompanied data movement operations. There are several mature file systems with built-in FTL available in the public domain, such as the comically named Yet Another Flash File System (YAFFS) and Unsorted Block Image File System (UBIFS/UBI), which integrate the FTL into the file systems oriented to Flash applications. Some standalone FTLs are also available. But it is recommended to use proprietary solutions or seasoned open-source alternatives when considering data integrity and safety.

EEPROM emulation is another kind of management software that can be used with Macronix Flash devices to provide typical read and write operations like EEPROM. Users and applications can modify the content as easy and conveniently as RAM without handling detailed program and erase operations. This emulation layer has hidden these sophisticated operations from the application layer and utilizes a buffer to cache and collect data for a complete program. Only a write back event happens when it conducts a program operation. It then largely reduces the program operations and saves power accordingly.

In short, reducing overall power consumption can also be achieved on the software side of the system. Macronix employs a wide range of features to support low-power applications such as providing different operation modes, multi-I/O backward compatibility, and frequency scaling.



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## Battery Technologies

Recently, battery technology has not only progressed from Pb-Acid/Ni-Cd/NiMH, to Lithium Anode/Li-Ion/Li-Polymer/Ag-Zn, but is now moving toward Metal-Air/Energy Harvesting/No Batteries. This trend is driven by the battery technology itself, of course, but also due to demand for more portable IoT devices, such as smart watches, smart sunglasses, true wireless stereo, and health monitoring devices.

To best understand the trends in battery technology, particularly with respect to the electrical characteristics and form factor, it is helpful to look at the portable IoT device market. Opportunities in this sector are heavily constrained by how much power the device consumes, as well as the overall dimensions of the design – critical drivers in making battery technology smaller and more efficient.

Let's begin with the electrical characteristics. There are four key areas that help us to recognize the differences of each battery technology: nominal voltage, energy density, cut-off voltage, and self-discharge rate. Table 2 (below) provides a comparison of each battery technology with those four characteristics and their approximate values from now to into the future:



	Now			Future				
	Li-Ion	Li-Polymer	Ag-Zn	Zn-Air	Li-Air	Energy Harvesting		
						Solar	Vibration	Thermal
Nominal Voltage (V)	≈ 3.7	≈ 3.6	≈ 1.55	≈ 1.65	≈ 2.91	≈ 0.6	≈ 0.1~0.4	≈ 0.02~1
Energy Density (Wh/L)	≈ 250~730	≈ 250~730	≈ 210	≈ 1,673	≈ 2,300	≈ Unlimited		
Cut-off Voltage (V)	≈ 3.3	≈ 3.0	≈ 1.2	≈ 0.9	≈ 2	≈ 0.5	≈ 0.1	≈ 0.02
Self-discharge rate (% / Month)	≈ 8	≈ 5	≈ 0.7	≈ 0.17	Very low	≈ 0		

Table 2: Electrical Characteristics of different battery technologies

To summarize Table 2, nominal voltage, cut-off voltage and self-discharge rates are moving lower, and energy density appears to be unlimited. This showcases the trend for longer battery life, and the opportunity of enhancing the portability features of IoT devices in the future.

Regarding battery form factor in portable IoT devices, small, thin, and even flexible batteries help designers develop portable IoT devices with promising market possibilities, such as in implantable medical devices and wearables.

In order to effectively shift to low power, device designers will need to employ battery features discussed above. As battery technology continues to advance by reducing the nominal, cut-off and self-discharge rates, as well as new possibilities with energy harvesting, system designers will be able to pack more energy into smaller form factors.



## Comparing Different Systems at 3V, 1.8V and 1.2V to Show Impact of Power Consumption and Battery Life

In a real-world application environment, it is difficult to describe subtle nuances that contribute to the power consumption, as there are too many factors that will make the system work differently, such as temperature, humidity, output loading, and wire bonding between the components. All those factors can bring out different results in the real world. Therefore, in order to discuss the power consumption difference in various systems, the following discussion will be based on the assumption that the system is working in an “ideal situation.” The system’s temperature, humidity, output loading, and bonding are the same -- the only variables being that the I/O voltage is 3V, 1.8V or 1.2V. The goal of this exercise is to outline the impact to the system under a lower I/O voltage and what that looks like to its overall power consumption.

We follow the physical formula “ $P=I*V*t$ ” to calculate the power consumption difference where  $P(t)$  is the instantaneous power, measured in watts (joules per second),  $V(t)$  is the potential difference (or voltage drop) across the component, measured in volts and  $I(t)$  is the current through it, measured in amperes.

If we assume  $I(t)$  is the same, then the power consumption will only be affected by  $V(t)$ . In other words, voltage is the only factor to impact the power consumption. So the power consumption in system can be simplified to:

- $P=3*I$  (voltage=3V)
- $P=1.8*I$  (voltage=1.8V)
- $P=1.2*I$  (voltage=1.2V)

Since  $I$ (current) is the same, if the time period is also the same, the power consumption( $P$ ) in each system will become: 3V, 1.8V or 1.2V. Therefore, keeping these assumptions in mind, comparing a 1.2V system to a 3V system, a designer can expect approximately a 60% savings in overall power consumption, and when compared to a 1.8V system, approximately a 33% power savings. This is a significant improvement, especially for battery-powered designs requiring a portable, finite source of power such as a wearable device.

Although there are several factors that contribute to power consumption, let us attempt to create a “simulated environment” so we can see the effects of what the power savings will look like from a battery-longevity perspective. For this experiment we use a CR2016 3V 90mAh battery as the power source, and assume a use case where the system programs 100-pages of data(2.5KB) (ex. date and hour of measurement, temperature, and log data) to the external nonvolatile Flash memory device, then goes into deep power-down mode for 30 minutes until the next page of data is written and read from external nonvolatile Flash memory every 8 hours. After which, the data is then erased. This cycle is repeated until end of battery life (see Figure 3 and 4).

With these critical assumptions in place, comparing a 1.2V system to a 3V system, a designer can expect approximately a 63% savings in overall power consumption, and when compared



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to a 1.8V system, approximately a 19% power savings. This is a significant improvement, especially for battery-powered designs requiring a portable, finite source of power such as a wearable device.

There are several factors that help explain why the above hypothetical application results between a 3V system, 1.8V system, and 1.2V system don't match the theoretical results presented earlier. These factors are operational behavior, operation period, and device specifications. Operational behavior is the amount of times the test is repeated, ie the number of times the MCU sends a specified set of tasks to the Flash device. Operation period is the number of times individual operations run such as read or program/erase. Device specification is critical in that in a real-life design, it is nearly impossible to improve a solution linearly. For example, the difference between Deep power down current between MX25L, MX25R, and MX25S is 3 $\mu$ A, 0.1 $\mu$ A, and 0.05 $\mu$ A respectively. As can be observed, initially, the design could be improved 30x, while as in the next iteration, only 2x. Another example is timing. As previously mentioned,  $P(t) = V(t) \cdot I(t)$ . Therefore, although the solution is operating at a lower voltage, it takes longer to perform the same operation, thereby impacting the ideal case improvements. It is essential to understand the application requirements to determine the best solution as there are many factors that can be optimized to provide the best balance between power and performance.

As seen in the data above, 1.2V is the key to achieving a low-power solution. Knowing this, Macronix is meeting the market needs with its Serial NOR Flash products, such as the MX25S (1.14V-1.6V) series that offers ultra-low voltage range and the competitive AC/DC characteristics to support stringent power requirements, but also the small size to fit in space constrained designs. Additionally, for customers who are still transitioning to lower power and need a solution that provides a wide range input voltage, Macronix that need as well – with the MX25R(1.65V-3.6V) series.

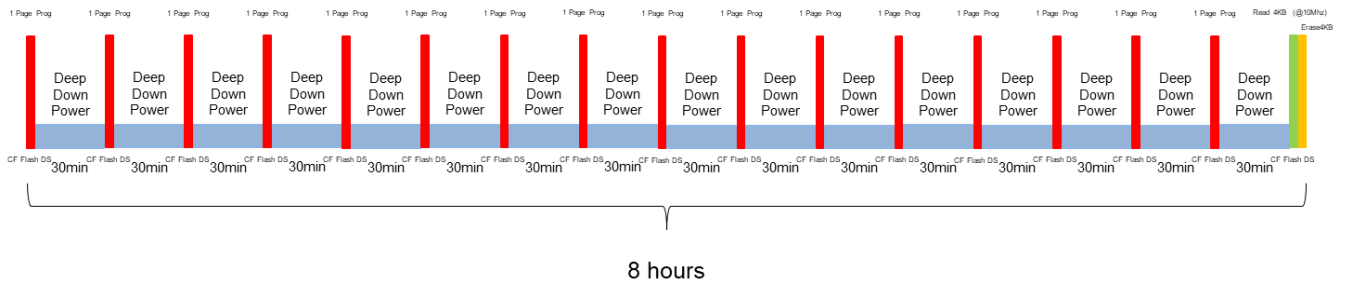
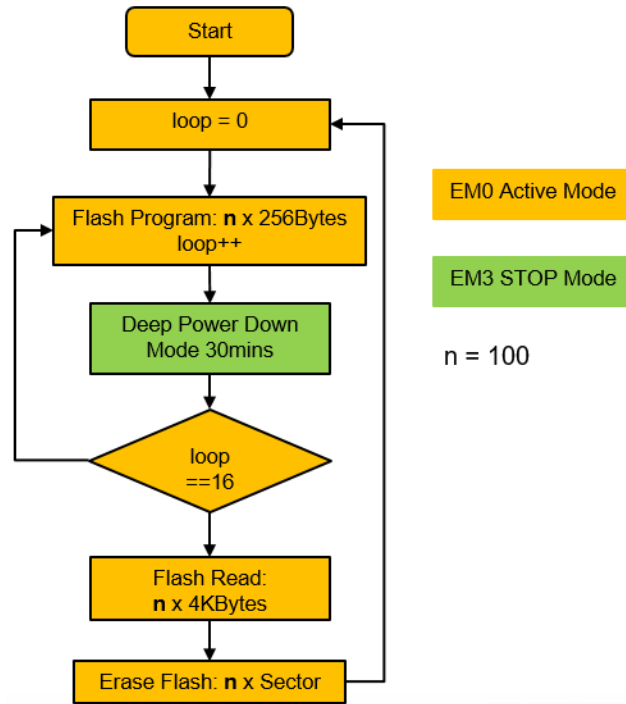


Figure 3 and 4: Diagrams showcasing real life example



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## Conclusion

This white paper confirms that as multiple markets continue to grow and evolve to adapt to market needs, lower power will be one of the critical objectives across industries. Solutions for key markets, such as industrial, automotive, consumer, communications, networking, and medical, will all require more IoT solutions to provide key functionality enhancements in their respective applications. Furthermore, many of these industries are moving towards mobile solutions, which will have a finite power source: batteries.

MCU vendors are pushing the envelope to smaller technology nodes, which in turn is lowering IO voltages. As markets trend towards lower power, it is necessary for peripheral components to lower their operating voltages in order to match MCU vendors. This will enable a faster time to market, while maintaining lower power. In addition to MCUs and peripheral components, system designers will need to take into consideration software, as well as developments in battery technologies to truly employ a low-power system. With so many elements playing a role in system designs, this transition will certainly pose a range of challenges for designers. However, but as explained above, their efforts to leverage power efficiency will enable solutions to realize approximately 33% in power savings.

Macronix understands the challenges system architects face in creating such solutions, which is why we developed the MX25R series. It's designed to support wider input voltage range applications between 1.65V and 3.6V, while the MX25S series supports input voltages as low as 1.2V.

Lower power will be a key focus area into the future to keep technology advancing and Macronix is as well positioned as any company in the industry to meet the market demands for the next generation of low-power solutions.



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