Trameto
Smarter Energy Harvesting PMICs

White Paper

Understanding the role of storage in energy harvesting systems

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1 Understanding the role of storage in energy harvesting systems

There's renewed intensive interest in energy harvesting technologies, driven by the explosive growth in internet-of-things (IoT) devices, notably sensor modules. Many such modules have integrated short-range or cellular radios because they operate at some distance from wired networks. This necessitates powering them with batteries.

The requirement to replace the batteries over the operating life of the application adds significant cost and may introduce periods of inactivity during which the devices they power are unable to function. Energy harvesting can eliminate, or at least mitigate these issues, reducing costs, reducing waste (much of which may be toxic), and improving system efficiency.

Deploying self-sustaining sensors, where no battery or grid power is needed, is the ultimate aim for many IoT network designers. But where this is not technically feasible, the ability to use harvested energy to reduce or eliminate battery changes during the life of devices brings substantial financial and environmental benefits. This article looks at the fundamentals of micro-energy harvesting (microwatts to milliwatts), explores the energy storage options available to system designers, and explains how to calculate the requirements for specific applications.

1.1 Energy harvesting fundamentals

Energy harvesting is concerned with the accumulation of low-grade energy into a storage component from where it can then be delivered in short bursts of higher power to an active load. By low-grade energy, we mean an intermittent supply that is dependent upon varying environmental conditions. The load will typically be an MCU or FPGA, typically found at the heart of IoT sensors.

The device responsible for managing energy derived from a harvester (such as a photovoltaic panel or piezoelectric element) is a power management integrated circuit, or PMIC. Recent developments in this technology at Trameto include what we call smarter energy harvesting PMIC. Our OptiJoule devices collect low-grade energy from a variety of harvesters - thermal, light, vibration, and temperature gradient – optimizing the delivery of the harvested energy to the storage component. OptiJoule devices typically works with up to four inputs, each of which adapts independently and autonomously to the type of harvester connected to it. It then detects when the storage device has adequate stored energy to support the power requirements of the load and delivers the energy at that time, or when demanded by the load.

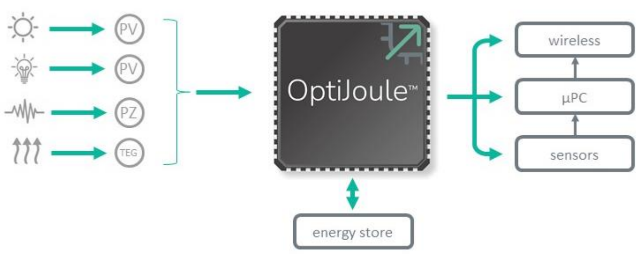

Figure 1: A multi-source energy harvesting system

1.2 Options for energy storage: batteries or capacitors

Energy in the form of electric charge is accumulated into an electrostatic and/or electrochemical storage device. There are numerous types of electrostatic and electrochemical redox (reduction-oxidation) energy storage components. The most appropriate choice depends on the specific application, but it comes down to using batteries or capacitors.

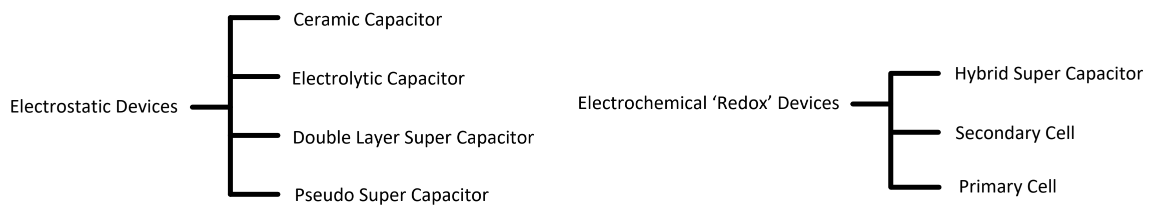

Figure 2: Storage device types

1.2.1 Primary battery cells

Primary cells are not rechargeable, at least with any reliability, so cannot be used to accumulate charge within an energy harvesting system. However, an energy harvester may be used to extend the serviceable life of a primary cell. Primary cells such as alkaline display low self-leakage and have an energy density that can rival the best Li-Ion secondary cells.

1.2.2 Secondary battery cells

Lithium-Ion (Li-Ion) cells now dominate the secondary, rechargeable battery market due to their high energy density and low self-discharge rate However, other technologies are sometimes deployed, including cells based on nickel-cadmium (NiCd) and nickel-metal hydride (NiMh) chemistries. Here's a brief overview of the most significant features of each:

- NiCd
  - Banned from many markets due to the toxicity of Cd
  - Tolerates abuse
  - Relatively high leakage 10%-20% per month
  - Limited operating voltage window
  - Memory effect with micro-cycles
- NiMh
  - Tolerates moderate abuse – cell chemistry can be damaged through overcharging
  - Limited operating voltage window
  - Relatively high leakage 0.4% to 4% per month (10% to 20% first day) – Low self-discharge cells are available (0.25% per month)
- Li-Ion
  - High capacity
  - Highest Volumetric and gravimetric energy density of any commercially available secondary cell
  - Highest cell voltage
  - Relatively low leakage 1% to 2% per month
  - Long calendar life – up to 10 years
  - Does not tolerate abuse

- Requires strict constant-current, constant voltage (CCCV) charge regime
- Higher internal impedance than supercapacitors – prone to self-heating and thermal runaway

1.3 Storage device considerations

The type of storage device best suited to an application depends on three main factors:

1. Time between the availability of ambient energy
2. Periodicity of the load
3. Load power requirement

Extended time between the availability of harvested energy coupled with a high-power, high-periodicity load requires a low-leakage, high-capacity storage device.

In an energy-rich environment, lower capacity storage with a less stringent leakage requirement can be implemented.

For loads that require to be active independent of the status of available ambient energy, moderate to high-capacity storage is required.

Short event loads whose activity is linked to the availability of ambient energy can implement low values of storage capacity with moderate leakage.

Table 1 extends our technologies comparison to the various types of capacitors suitable for micro-energy storage. The figures shown represent the typical performance of the device technology, the parameters of specific components may differ.

Parameter	Ceramic Capacitor	Aluminium Electrolytic Capacitor	Super Capacitors			Lithium Cells					
			Double-Layer	Pseudocapacitor	Hybrid (Li-Ion)	LCO	LCA	NMC	LFP	LTO	SSB
Capacitance	1µF to >100µF	≤2.7F	0.1 to 470F	100F to 1kF	300 to 3.3kF	mAhr to kAhr	mAhr to kAhr	mAhr to kAhr	mAhr to kAhr	mAhr to kAhr	mAhr+
Thermal Stability	High	Good	Good	Good	Moderate	Poor[2]	Poor[2]	Fair[2]	Good[2]	Very Good	High
Operational Temperature Discharge	-55°C to 125°C	-40°C to 125°C	-40°C to 70°C	-20°C to 70°C	-20°C to 70°C	-20°C to 60°C	-20°C to 60°C	-20°C to 60°C	-20°C to 60°C	-40°C to 75°C	-20°C to 100°C+
Operational Temperature Charge	-55°C to 125°C	-40°C to 125°C	-40°C to 70°C	-20°C to 70°C	-20°C to 70°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	0°C to 45°C	-40°C to 50°C	
Operational Voltage range	0V to 25V	0V to 630V	0V to 3.3V	0V to 12V[1]	2.2V to 3.3V	3.0V to 4.2V	3.0V to 4.2V	3.0V to 4.2V	2.5V to 3.65V	1.8V to 2.85V typ.	
Specific Energy	0.005 to 0.02 Wh/kg	0.01 to 0.3 Wh/kg	1.5 to 3.9 Wh/kg	4 to 9 Wh/kg	10 to 15 Wh/kg	150 to 200 Wh/kg	150 to 200 Wh/kg	150 to 220 Wh/kg	90 to 100 Wh/kg	50 to 110 Wh/kg	
Internal Impedance	Low	Low to High	Low	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate to High	Moderate to High
Recharge Cycle Life	<Unlimited	<Unlimited	100k to 1M	100k to 1M	20K to 100K	500	1k	1k to 2k	>2k	6k to 30k	>10k
Calendar Life	>20 Years	>20 Years	5 to 10 years	5 to 10 years	5 to 10 years	3 to 5 years	5 to 10 years	5 to 10 years	5 to 10 years	>10 years	>10 years
Self-Discharge	1% to 3% per minute	0.5% to 1% per second	1% to 2% per hour	3% to 4% per hour	0.35% per hour	1% to 2% per month	1% to 2% per month	1% to 2% per month	1% to 3% per month	1% to 3% per month	

Table 1 Performance comparison of storage devices

The specifications shown above are largely self-explanatory but there are few important points worth noting.

Some capacitor types have significant limitations in energy harvesting applications. For example, higher-voltage supercapacitors tend to exhibit relatively high internal impedance, which generally restricts the practical voltage selection to around 3V to 5V. The low capacity of ceramic capacitors makes them unsuitable for most energy harvesting systems, although they may be used to complement higher-capacity storage devices that have high internal impedance by connecting them in parallel with these devices. And the relatively high leakage current of aluminium electrolytic capacitors is generally unacceptable in energy harvesting.

Both Lithium Titanite (LTO) and Solid-State Batteries (SSB) show great promise for energy harvesting. However, the availability and cost of the technologies are potential barriers to implementation, and their relatively low capacities and high internal resistance will be limiting factors in some applications. There is a wide range of SSB technologies being developed, the most promising of which is based on Lithium.

Lithium-Ion secondary cells comprise a family of different chemistries, each denoted by a three-letter acronym. Each chemistry has different properties, including energy density and thermal stability. The cells are available in a wide range of useful capacities from sub mAhr to >100Ahr but wet/gel-based electrolytic Lithium-Ion cells are vulnerable to thermal runaway and are therefore a safety concern. They require additional management circuitry to prevent electrical abuse, and this may be too expensive and complex for cost-sensitive IoT devices.

1.4 Storage sizing for a periodic load

A variety of different types of harvesters can be implemented with an omni-adaptive system. Some, like solar, are periodic in behaviour and supply a variable source of energy. Others, such as thermal types may have access to a constant temperature gradient and provide a constant source of energy. The calculation below assumes a single periodic harvester.

Assuming a harvested power, P_{har}, available for a period P_e at intervals of T_e supplying a load current of I_l for a duration of T_{on} at intervals of T_{off} with a PMIC conversion efficiency of Ɛ. The storage operating voltage Is given as v.

P_e = Period of ambient energy availability
T_e = Time between available ambient energy
I_l = Load current
T_{on} = Load period
T_{off} = Time between load activation
Ɛ = Efficiency of PMIC conversion
v = Storage voltage
P_{pmic} = Operating power requirement of the PMIC device

Duty cycle of ambient energy availability, $D_e = \frac{P_e}{P_e + T_e}$

Duty cycle of load, $D_l = \frac{T_{on}}{T_{off} + T_{on}}$

Required minimum storage capacity, $Q_{stor} = \frac{I_l D_l T_e}{\varepsilon}$ A.hr

Required minimum harvested capacity, $Q_e = \frac{Q_{stor}(1 - D_e)}{\varepsilon D_e}$ A.hr

Minimum required harvested energy to support load, $E_{har} = \frac{I_l D_l T_e (1 - D_e)}{2\varepsilon^2 D_e} v$ Joules

Required minimum harvested power to sustain load, $P_{har} = \frac{E_{har}}{P_e} + \frac{P_{pmic}(1 - D_e)}{\varepsilon D_e}$ Watts

The size of the harvesters, in terms of their ability to produce power, must exceed the maximum anticipated load requirement allowing for the efficiency, energy availability, and overhead of PMIC conversion and storage.

1.5 Other storage factors

The internal impedance of a storage device can affect the operation of the PMIC. Each packet of charge delivered to the storage device raises its voltage. A voltage is developed across the internal impedance of the cell, associated with the rise in voltage. This can result in a voltage overshoot that may compromise the performance of the PMIC, so a storage device with an appropriate internal impedance should be selected.

The highest capacity storage devices are the family of Li-Ion secondary cells. These need additional cell management circuitry to ensure safe operation and to extend their operational life. For optimum integration, smallest footprint, and lowest cost, this additional circuitry should be built into the energy harvesting PMIC.

1.6 Acknowledgment

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