How the Choice of Battery Power affects a Design's Total Cost of Ownership

Designers of new products that use energy storage devices, such as batteries or supercapacitors, should find this paper useful. Infinite Power Solutions, Inc. (IPS) offers a line of THINERGY® Micro-Energy Cells, a type of rechargeable solid-state battery (SSB), as an innovative new technology that provides a capable and cost-effective alternative to lithium, alkaline, thin-film and other traditional batteries, as well as supercapacitors. This white paper provides an overview of this unique power source's characteristics, and how its high performance and long service life combine to result in a significantly lower total cost of ownership in many applications compared to traditional energy storage solutions.

General Design Considerations

In systems where a battery is needed, either as a primary or secondary (backup) source of power, the first consideration is the availability of AC power. In applications where AC is readily available, a traditional rechargeable battery is normally the best choice. Devices like smartphones and laptop computers have such a battery as the primary power source for normal operation, which is recharged with energy converted from utility-provided AC power. A much smaller battery is generally used as a backup power source to maintain a real-time clock (RTC) or volatile memory for periods when the main battery or external AC power source are not available. These are the easy cases.

The somewhat more challenging situations involve applications where there is no AC power source available. Here there are two equally important considerations: the expected service life of the battery; and the degree of difficulty (which affects the cost) to replace it. If the service life is relatively short and the battery is inexpensive and easy to change, a primary (non-rechargeable) battery may suffice. Many products meet these criteria, such as flashlights and remote controls.

The most difficult design considerations involve applications where there is no AC power, the product has an extended service life (sometimes measured in decades), and the battery is very difficult and/or expensive to replace. Batteries may be difficult to replace for a variety of reasons, such as when they are sealed, the device is embedded within another system, or it is deployed in a location that is difficult to access, such as within an air duct, a pipeline or a manufacturing line, requiring a service technician.

In these situations, there are three additional design considerations: the amount of power required; the amount of energy required; and the availability of ambient energy for recharging the battery (harvesting ambient energy is covered in greater detail below). The choices here range from primary batteries with very long shelf and service lives (usually when the amount of current required is very low) to rechargeable power sources, including traditional and thin-film batteries, and unique devices like the THINERGY Micro-Energy Cell (MEC).

The choice of power source in these situations will have a dramatic effect on the total cost of ownership (TCO) of the product for the end user, and design engineers sometimes fail to take this into account. To help engineers include this important consideration in their designs, Infinite Power Solutions has created a detailed TCO analysis tool in the form of an Excel spreadsheet to compare the lifetime battery cost of a traditional primary cell to a THINERGY MEC.

The IPS Total Cost of Ownership Spreadsheet

Before covering use of the spreadsheet, it is fundamentally important to understand that TCO is best considered from the perspective of the end user. When evaluating available solutions, users divide TCO into two components: the capital expenditure (CapEx) to purchase the product; and the ongoing operational expenditures (OpEx). All too often, design engineers believe that minimizing CapEx results in a lower TCO, or that prospective customers will compare alternatives based mostly or exclusively on their purchase price. While this may be true for some consumers, businesses invariably place much more emphasis on the ongoing OpEx.

Consider this interesting fact: It now costs more to power a data server over its useful life (typically three years) than it does to acquire one. The steady advances in price/performance based on Moore's Law have made servers very fast—and very inexpensive. Server vendors understand this phenomenon, and have invested in making their power supplies far more efficient to reduce OpEx. End users who purchase these servers realize that paying a higher initial cost for a more efficient server will provide significant savings over the server's useful life.

The IPS TCO analysis spreadsheet gives designers the ability to change a wide variety of parameters, as shown in the example below in ***Figure 1***, to achieve accurate and meaningful estimates of the TCO for various battery power configurations. The spreadsheet is rather intuitive, making it easy to use after a fairly short learning curve. There are additional pages (not shown here) that contain useful reference information on two popular battery types: lithium manganese dioxide and lithium thionyl chloride. A reference table is also provided showing the capacity of different models of THINERGY MECs.

Although the spreadsheet places equal emphasis on CapEx and OpEx, it is the latter that has the more profound effect on TCO if even a single battery change is required. Note the lack of any operational expenditure for the Micro-Energy Cell, giving products powered by an MEC a distinct competitive advantage in total cost of ownership. With a useful life of 15 or more years, the MEC requires no maintenance or replacement in the vast majority of applications. For this reason, the MEC can be deeply embedded and/or permanently sealed in devices (even in those that must operate in harsh and hot environments) because they never need to be replaced. Thus, MEC-powered devices can be deployed in inaccessible locations, including within other systems.

In the example results, shown in ***Figure 2***, note that the cost to replace a failed primary battery even once makes the TCO for a coin cell far exceed the TCO of the MEC and energy harvester over the useful life of the application.

User Inputs in Blue Cells	Inputs	
Lifetime of Application	10	years
	87,600	hrs
Quantity of Units to be Installed	10,000	

Average Current Calc Based on Application Duty Cycle			
	Current (mA)	Time(secs	%
1. High Current	30.000	0.01	0.02%
2. Mid Current	10.000	0.02	0.04%
3. Low Current	0.020	5	9.09%
4. Standby Current	0.005	50	90.86%
Averaged Current Over Time (mA)	0.01545	55.03	100%

Battery Type	Coin Cell CR2032	
OEM Battery Cost (In volume)	$0.50	each
Qty of Batteries per System	1	
Initial Battery Cost	$0.50	
Battery Holder Cost	$0.10	
Total Initial Battery Cost per System	$0.60	
Capacity of Selected Battery	220	mAh
Nominal Voltage of Selected Battery	3.0	V
Total Available Lifetime Energy	660	mWh
Cell Life at Average Current:	14,243	h
	1.6	years
Number of replacements required	6	
Labor Cost per Hour	$30.00	per hr
Battery Change Time	5	min
Travel Time to Battery Location	20	min
Total Replacement Time	25	min
	0.417	h
Labor Cost per Replacement	$12.50	
Battery Replacement Cost	$1.25	each
Qty of Batteries per System	1	
Total Replacement Material Cost	$1.25	
Total Cost per Battery Replacement	$13.75	
Lifetime Material Cost	$8.10	
Lifetime Labor Cost	$75.00	
Total Lifetime Cost of Power	$83.10	
THINERGY MEC Type (Select From Pull-Down)	MEC201-7	
Capacity of MEC	0.7	mAh
Nominal Voltage of MEC	4.0	V
Available Energy per Cycle	2.8	mWh
Available Lifetime Charge Cyles (deep cycles)	10,000	cycles
Total Lifetime Capacity of MEC (per Spec)*	7,000	mAh
Total Lifetime Energy of MEC (per Spec)*	28,000	mWh
Lifetime of MEC (Spec is 15yrs typical)	15	years
Price of MEC (Type, Qty & Time Dependent)**	$7.00	each
Qty of MECs per System	1	
Total MEC Cost per System	$7.00	
Cost of Energy Harvesting Components	$3.00	
Cost of Power Management IC (PMIC)	$3.00	
Total MEC Cost with EH	$13.00	

*MECs continue to provide energy well beyond the specified 10,000 cycle life in most applications

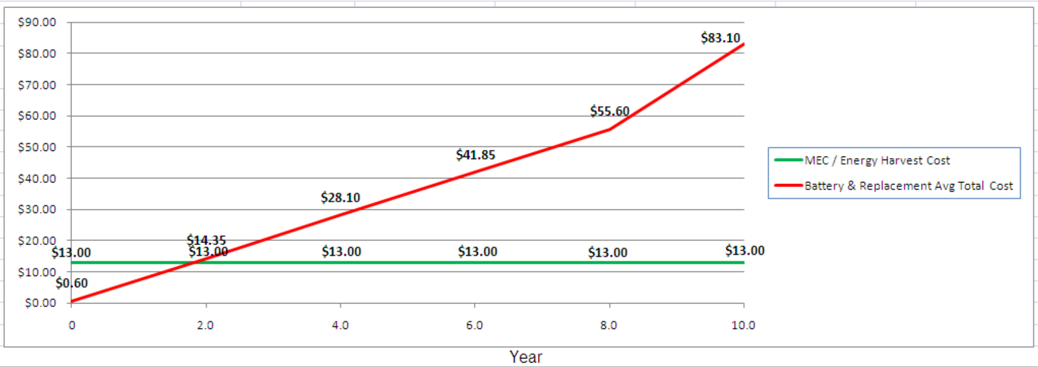
**Make sure manual price input is appropriate with MEC type selected

Figure 1 – TCO Spreadsheet Input Variables

RESULTS DATA & GRAPH OVER APPLICATION LIFE:

	Initial	Periodic Savings with THINERGY MEC & EH vs Battery Replacement				App Life
Through Year	0	2.0	4.0	6.0	8.0	10.0
MEC / Energy Harvest Cost	$13.00	$13.00	$13.00	$13.00	$13.00	$13.00
Qty of Battery Replacements	na	1	2	3	4	6
Battery & Replacement Avg Total (	$0.60	$14.35	$28.10	$41.85	$55.60	$83.10
MEC Savings	$12.40	$1.35	$15.10	$28.85	$42.60	$70.10

Unit Breakeven Analysis: THINERGY MEC + Energy Harvesting (EH) vs. Primary Battery



System Lifetime Total Cost of Ownership Comparison	Coin Cell CR2032 Battery	MEC201-7 Battery	MEC SAVINGS
Lifetime of Application (Yrs):	10	10	10
Qty Battery Replacements	6	0	
Initial Cost:	$0.60	$13.00	-$12.40
Batteries or MECs	$0.60	$7.00	
Power Management IC (PMIC)	$0.00	$3.00	
Energy Harvestor	$0.00	$3.00	
Replacement Costs:	$82.50	$0.00	$82.50
Batteries	$7.50	$0.00	
Labor	$75.00	$0.00	
Total Lifetime Cost per Unit	$83.10	$13.00	$70.10
Qty Units Installed	10,000	10,000	10,000
Total Lifetime Cost of All Units	$831,000	$130,000	$701,000

Battery Energy & Cost Comparisons Per Unit		Coin Cell CR2032 Battery	MEC201-7 Battery	MEC X-Factor
Total Available Lifetime Capacity	mAh	220	7,000	32
Total Available Lifetime Energy	mWh	660	28,000	42
Cost per Cell	$	$0.60	$7.00	12
Cost of Capacity	$/mAh	$0.0027	$0.0010	0.37
Cost of Energy	$/mWh	$0.0009	$0.0003	0.28

Figure 2 – TCO Spreadsheet Results

A Primer on the THINERGY Micro-Energy Cell Technology

A Micro-Energy Cell is an innovative and unique solid-state, rechargeable thin-film battery. MECs are manufactured by Infinite Power Solutions using wide area thin-film deposition techniques similar to those used to manufacture semiconductors. The basic technology was developed at Oak Ridge National Laboratories in the late 1990's, and IPS has since developed its own device architecture and manufacturing process to provide industry-leading performance. The use of an inorganic solid-state electrolyte affords many advantages, including an extraordinarily low leakage current and no degradation from contaminants leaking into the electrolyte from the constituent materials. These special properties of solid-state MECs account for their extraordinarily long service lives.

Micro energy cells enjoy many advantages, especially in those applications that harvest ambient energy to operate unattended over extended lifetimes. These advantages include:

- Rapid recharge and charge acceptance at currents below 1µA
- More than 100,000 recharge cycles
- A high rate of discharge, whether in pulses or for continuous draw
- Peak power delivery suffers from no pulse width limitations and requires no external capacitors for most micro power applications
- The low internal resistance enables the MEC to deliver the relatively high current needed to transmit radio frequency signals in small wireless systems
- Useful voltage maintains a flat profile, even at high currents
- Stackable to achieve higher energy and current
- Available in deeply-embeddable form factors (generally very thin and flexible) that facilitate smaller, lighter maintenance-free designs

These characteristics make MECs suitable for a wide range of applications. Here are just a few examples:

- Low power wireless sensors
- Smart Meters
- Smart Home/Smart Building controls
- Small handheld remotes
- Powered cards with displays, radios and biometrics (fingerprint sensors)
- Security and temperature sensors
- Real-time locating systems (RTLS)
- Memory and real-time clock (RTC) backup power
- Theft prevention tags

Comparing MECs to Other Power Storage Technologies

Although the initial cost of an MEC (including the energy harvesting and power management components) can be higher than some traditional energy storage devices, the substantially longer service life normally affords a much lower total cost of ownership over time. But MECs offer many other advantages beyond a low TCO.

In addition to containing no organic liquid electrolytes, as noted above, MECs contain no caustic chemicals or heavy metals, and none are used in the manufacturing process either. Most conventional battery technologies, by contrast, have liquid-impregnated separator materials, where the liquid serves as the electrolyte. Some of the chemicals used can be quite toxic, precluding their use in some applications, and requiring mitigating measures in others. Nickel metal hydride batteries, for example, contain aqueous potassium hydroxide. Most lithium ion batteries contain lithium salts suspended in organic solvents like dimethyl carbonate. Safety concerns may exist for other reasons. Lithium thionyl chloride batteries, for example, can experience an increase in internal pressure during a high, sustained discharge rate.

There are some performance issues caused by the use of conventional liquid electrolytes, as well. One is a limited shelf life owing to a relatively high self-discharge current. Over time, the acids and the bases used can attack the other materials inside the battery, causing dissolution of various contaminants into the electrolyte, resulting in accelerated degradation, or the formation of internal short circuits. High heat accelerates this degradation significantly, often limiting batteries with liquid electrolyte to applications operating at less than 60°C. Another potential problem is the initial voltage drop caused by the passivation layer that builds up on some battery cells. The depth of discharge on certain battery chemistries can also affect performance. And some batteries (e.g. NiCad) suffer from "memory effects" where the useable capacity becomes limited by shallow cycling, or from capacity degradation effects like sulfation (e.g. lead acid), which occurs during long standing periods and is accelerated by higher temperatures. MECs suffer from none of these limitations and can operate continuously up to 85^{0}C.

Finally, owing to its extraordinarily low self-discharge current (< 2 nA at 25°C), an MEC can efficiently accept and store very small amounts of recharge current from a variety of ambient energy sources and store it for decades. In challenging applications, this enables extremely low power energy harvesting sources to become viable power supplies for autonomous wireless nodes.

Harvesting Ambient Energy

For an energy storage device of reasonable size to be permanent (at least for all practical purposes) it must be rechargeable. And when a device is inaccessible or cannot be connected to a suitable source of AC or DC power, the power needed to replenish that source must be harvested from available ambient energy. The ability to accept harvested ambient energy effectively and efficiently is, therefore, of paramount importance in selecting a power storage source.

Different applications will have access to different sources of ambient energy. Listed below are the approximate ranges of power available from four such sources (in decreasing order of available energy):

- Thermal: 25 µW/cm2 human to 1000-10,000 µW/cm2 industrial
- Photovoltaic: 10 µW/cm2 indoors to 10,000 µW/cm2 outdoors
- Vibration/Motion: 4 µW/cm2 human to 100 µW/cm2 industrial
- Radio Frequency: 0.1 µW/cm2 at 900 MHz (GSM) to 0.01 µW/cm2 at 2.4 GHz (Wi-Fi)

Three different technologies capable of being recharged by these sources of ambient energy include traditional rechargeable batteries, electric double-layer capacitors (EDLC) or supercapacitors, and Micro-Energy Cells or other solid-state thin-film batteries. The table below presents a summary comparison of all three; the discussion that follows assesses each in greater detail.

	Rechargeable Coin Cell Batteries	Supercapacitors	THINERGY MECs
Capacity	1 – 100 mAh	0.1 – 1500 F	100µAh – 2.5 mAh
Maximum Continuous Current	5 µA – 40mA	10 µA – 200 A	7.5mA – 100 mA
Operating Temperature Range (°C)	-20 to 60	-40 to 70	-40 to 85
Size (mm)	4-30 (D) x 1.6–7.7 (H)	10 x 20 x 2	13x13 to 25x51
Recharge Cycles (to 80% Original Capacity at 80% DOD)	500 – 1000	> 100,000	> 10,000
Price Each (High Volume)	~ $1	~ $2 – $10	~ $3 – $10
Self Discharge Rate (Room Temperature)	10%/Year	>90% in 6-7 Days	1%/Year
Minimum Current for Accepting Charge	> 10µA	> 35 µA	< 100 nA

The primary advantage of secondary (rechargeable) batteries is their ability to provide power without wires to remote or portable applications. But because traditional rechargeable battery technologies have relatively short useful service lives, any need to ever replace one increases the total cost of ownership. This can be particularly problematic in those applications where the device is not readily accessible and/or is hermetically sealed, which can make their replacement prohibitively expensive. The useful service life of batteries is shortened even further in those applications requiring frequent deep discharges. These disadvantages, combined with a high rate of self-discharge and a low charge acceptance efficiency at low currents, can make rechargeable batteries unsuitable for applications that must harvest ambient energy.

Supercapacitors are suitable for applications requiring high pulse currents greater than 100 mA. Another advantage is that their high peak operating current is consistent over a fairly wide operating temperature range (-40 to 70°C). At sustained higher temperatures (50 to 70°C), however, the internal leakage current, capacitance, equivalent series resistance (ESR) and useful service life all begin to degrade rapidly. Also, for applications that operate above 2.5V, two or more supercapacitors must be used in series. A balancing circuit is then required to protect the individual supercapacitors from an over-voltage condition. This forces designers into making a choice between passive balancing, which increases leakage current (sometimes higher than the supercapacitors themselves), and active balancing, which adds considerable complexity. Another disadvantage is the relatively high minimum threshold charge current (often > 35 µA) that is required before supercapacitors are able to accept a charge.

Unlike both rechargeable batteries and supercapacitors, THINERGY Micro-Energy Cells are able to accept microwatts of recharge energy, and then store the harvested energy with only negligible leakage. Consider, for example, an industrial application that harvests ambient vibrational energy at a mere 100 µW/cm2. For the MEC, this is a sufficient amount of energy to create a maintenance-free, cost-effective design for sensors that must transmit regular radio frequency signals, such as sensor data from heavy equipment or moving vehicles.

Hybrid Designs

The choice of power source need not be mutually exclusive; that is, there are some applications where it may be beneficial to include multiple sources. In these "hybrid" designs, the potential limitations of one power source can be overcome with a complementary technology. Here are two examples.

In applications where there is a need for high pulse currents, but where the available ambient energy is relatively low, supercapacitors can be paired with MECs to provide long-term storage and consistent high power delivery over a wide temperature range. The MEC overcomes the relatively high minimum threshold charge current required before supercapacitors are able to accept a charge, and also provides "instant-on" capability following long periods between recharge energy availability, while the supercapacitor overcomes the MEC's inability to deliver a high pulse current at low temperatures. Indeed, this cost-effective combination is unique in its ability to take in very low levels of ambient energy, store it for extended periods of time, and then deliver that energy at very high currents.

In mission-critical applications that depend on energy harvesting, there may be periods where the available ambient energy is insufficient. Solar power, for example, is sufficient to charge virtually any type of battery—provided, of course, that the sun shines some every day. To provide reliable operation during extended periods of inclement weather, an MEC can be paired with a battery. The MEC will be able to harvest at least some energy from the solar cell on cloudy days during an Alaskan winter, and get the remainder from the battery. In this design, the battery's life can be greatly extended by limiting both its use and depth of discharge.

Conclusion

In many applications, the need to replace the power source even once can drive up a system's total cost of ownership. The end users of such systems understand this very well. When making purchasing decisions they consider both the capital expenditure and the ongoing operational expenditures, knowing that the latter usually eclipses the former.

Infinite Power Solutions created a spreadsheet to make it easy for design engineers to estimate the total cost of ownership by comparing traditional energy storage solutions, such as coin cells, against permanently- or perpetually-powered systems utilizing energy harvesting devices combined with THINERGY Micro-Energy Cells.

In all such comparisons, expect the solution powered by a THINERGY Micro-Energy Cell to prevail. The MEC is, for all practical purposes, a permanent power source. An MEC-powered solution requires no maintenance and will continue to operate for decades with little or no degradation in performance, resulting in the lowest total cost of ownership for the end user.

For more information on THINERGY Micro-Energy Cells, please visit IPS on the Web at www.infinitepowersolutions.com, call (303)749-4800, or send an email to info@infinitepowersolutions.com.

About the Author

Joe Keating, Director of Applications Engineering, has been instrumental in the development of THINERGY Micro-Energy Cell application solutions, product evaluation kits and customer technical support at Infinite Power Solutions in Littleton, Colorado.