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Energy Harvesting for Increased Safeguards Equipment Battery Life

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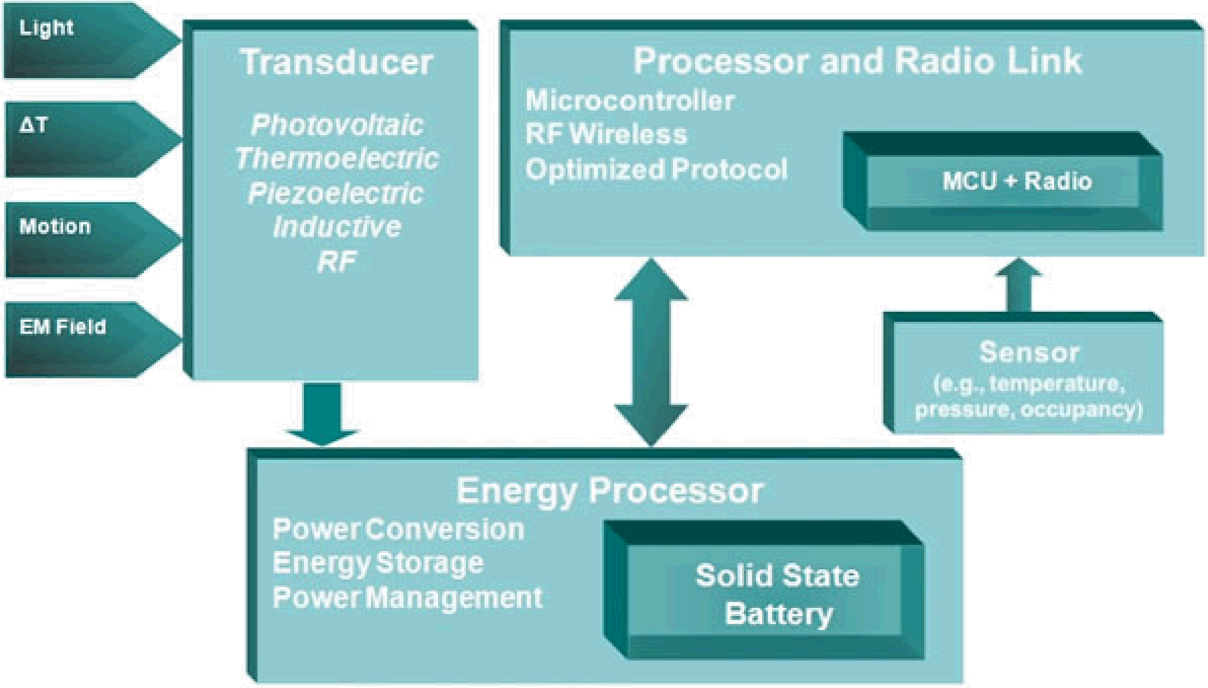
Problem Statement

- Modern unattended safeguards equipment requires battery power
  - Lithium batteries are expensive (~$10 per AA)
  - And toxic
    - ****DANGER**** INTERNAL CONTENTS ARE EXTREMELY HAZARDOUS. LEAKING FLUID IS CORROSIVE. BATTERY MAY BE EXPLOSIVE AT HIGHER TEMPERATURES.
    - $2SOCl_2 + 4Li \Rightarrow SO_2 + S + 4LiCl$
    - $SOCl_2 + H_2O \Rightarrow SO_2 + 2HCl$

- Must be replaced before total battery discharge occur to avoid loss of continuity of knowledge
  - Effective battery capacity is less than actual usable capacity
- Such maintenance is a radiological hazard to personnel

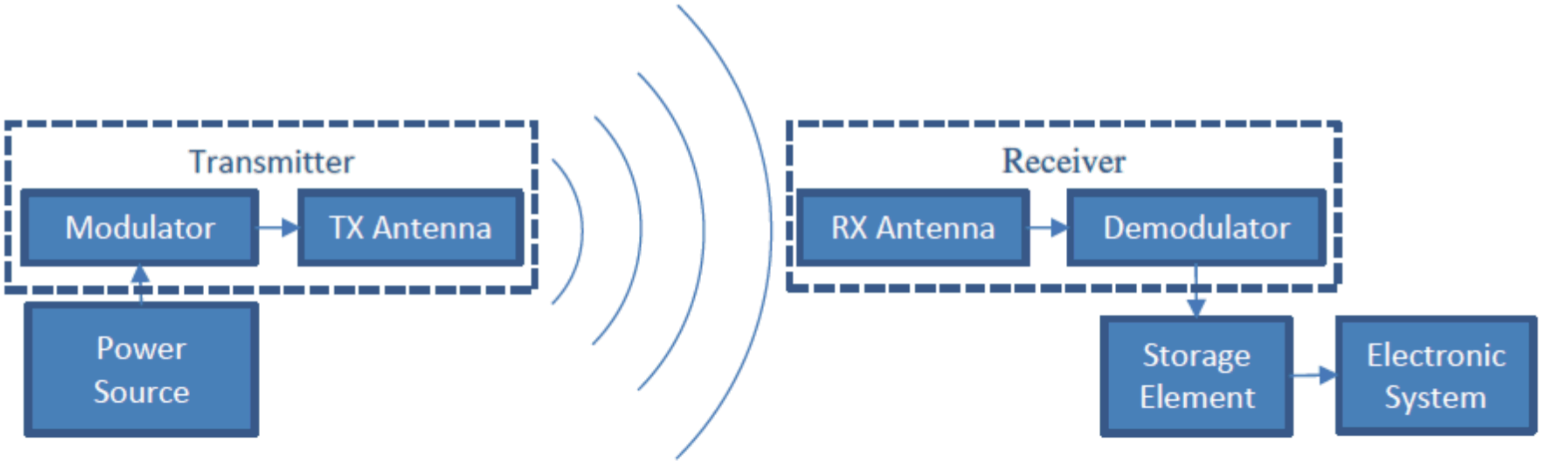
Solution?

- Energy harvesting
  - Commercially available
  - Consistent
  - Predictable
  - Un-tethered

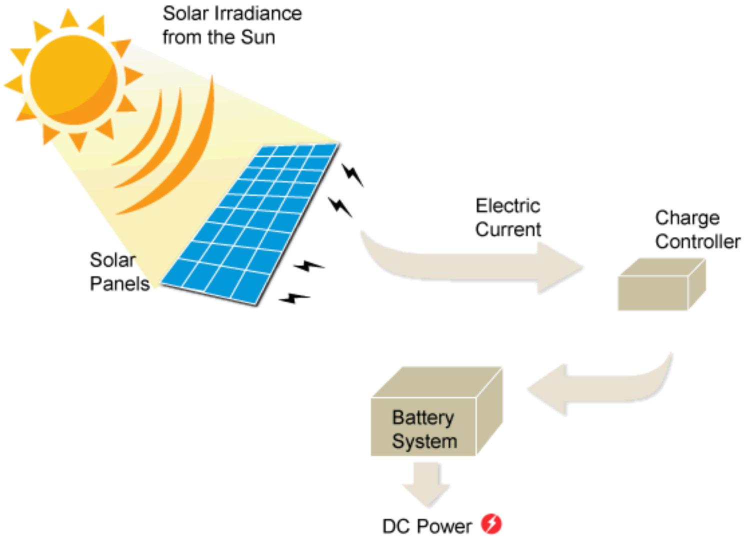


Previous work

- Far-Field Wireless Energy Harvesting For Increased Safeguards Equipment Battery Life
  - Proceedings of the 2016 Institute for Nuclear Material Management Annual Conference



Energy Harvesting Overview



- Harvest photonic energy from indoor or outdoor sources
- Convert to regulated DC electrical power
- Store for use during unlit periods
- Controllable design parameters
  - Cell construction
  - Number of cells
  - Cell bias point
  - Storage medium
  - Charge controller

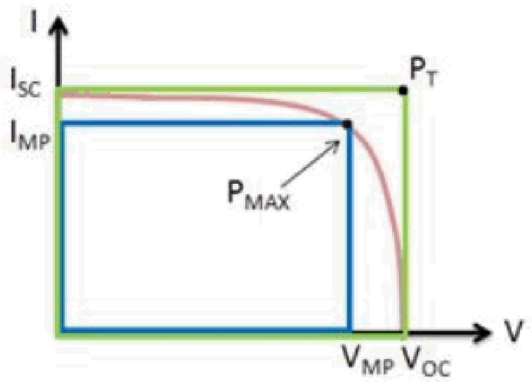
PV Cell Evaluation

- Different types available
  - Amorphous
  - Polycrystalline
  - Monocrystalline
- Usage scenario
  - Indoors
  - Outdoors
- Spectral response
- Efficiency
- Cost
- Size

PV Cell Evaluation (cont)

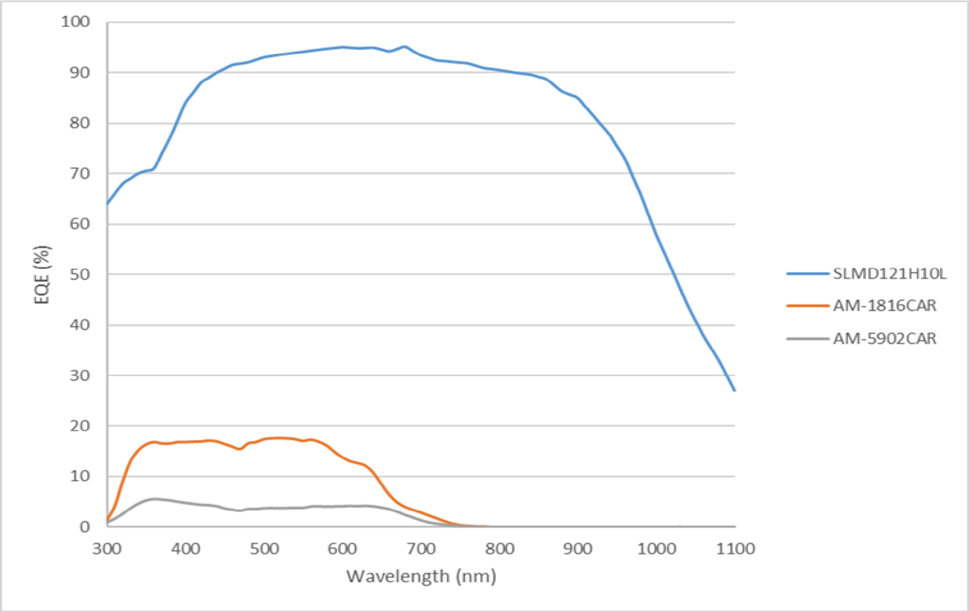
	AM-5902CAR	AM-1816CAR	SLMD121H10L
Crystal Type	Amorphous	Amorphous	Monocrystalline
Intended Use	Outdoor	Indoor	Dual
I_{SC} (1000 W/m²)	58.6 mA	3.55 mA	35.7 mA
V_{OC}	7.86 V	6.24 V	6.64 V
P_{MAX}	254 mW	5.26 mW	173 mW
Fill Factor (FF)	0.550	0.00526	0.728
I_{SC} (10 W/m²)	202 μA	227 μA	132 μA
V_{OC}	5.1 V	5.2 V	3.46 V
P_{MAX}	600 μW	770 μW	264 μW
Fill Factor (FF)	0.582	0.653	0.577
Size	8.72 in²	8.50 in²	2.28 in²
Unit Cost (quantity 10)	$23.06	$9.56	$11.81

- I_{SC}: current through the cell when short circuited
- V_{OC}: Voltage across the cell when open circuited
- P_{MAX}: maximum power a cell can deliver
- FF: Ratio of P_T to P_{MAX}



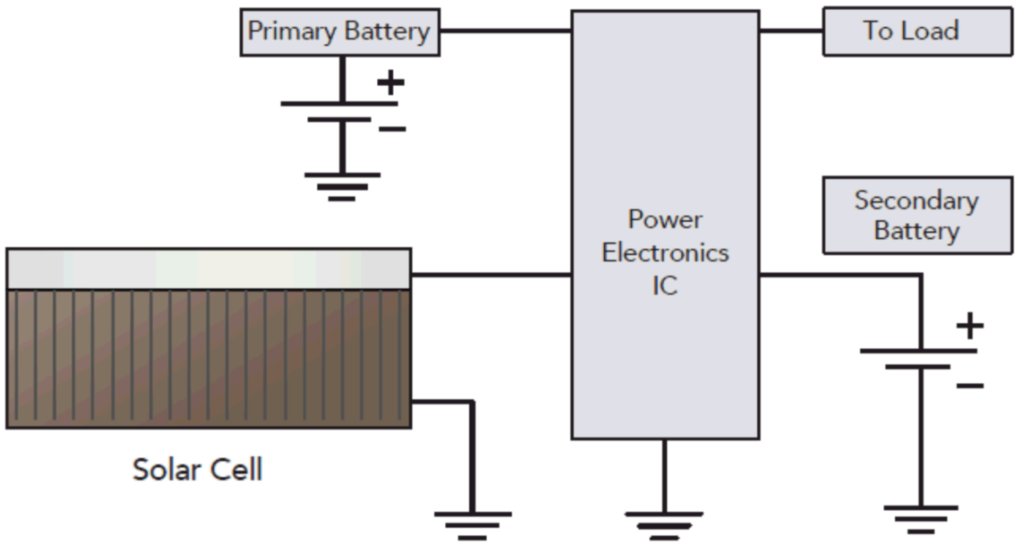
Quantum Efficiency

- Light is not evenly distributed across all wavelengths
- Cell response measurable - External Quantum Efficiency
  - Ratio of the number of charge carriers collected by the cell versus the number of photons incident
  - Varies over wavelength



System architecture

- Tiered power delivery design
  - Non-rechargeable primary batteries
    - Initial power-on, periods of no light
  - Rechargeable secondary “battery”
    - Switched to once sufficient charge has been deposited
- Extend the lifetime of the primary battery (not replace!)



Energy Storage Element

- Power buffer for the system
  - Smooths dynamic power draw of the system to maximize harvesting efficiency
- Low leakage current critical
  - Average current draw of a sensor system can be as low as 20 µA
- Required storage capacity is system-dependent

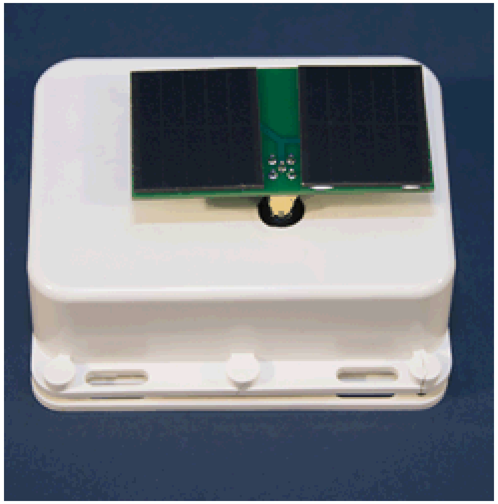
System Requirement \ Storage Type	Ceramic Capacitor[1]	Aluminum Capacitor[2]	Electric Double Layer Capacitor[3]	Thin Film Battery[4]
Physical Size	20 mm^3	250 mm^3	1000 mm^3	250 mm^3
Unit Cost (quantity 10)	$1.35	$0.80	$8.60	$33
Availability	Excellent	Poor	Excellent	Poor
Leakage	1 µA	6 µA	5 µA	1%/year
Storage Capacity	725 µC	1500 µC	165,000 µC	2.5 C

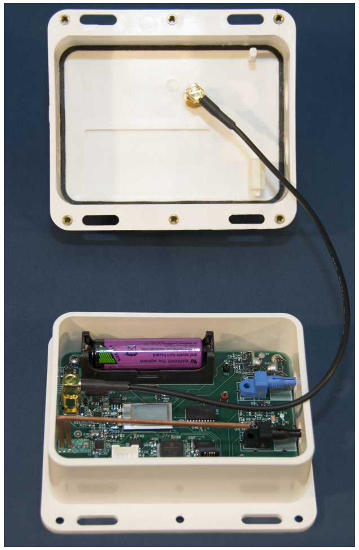
Red: Clear inability to meet requirement — Yellow: Difficult to meet requirement — Green: Clear advantage

[1] Samsung CL http://www.samsungsem.com/kr/support/product-search/mlcc/CL32A227MQVNNNE.jsp
[2] Vishay 013 RLC http://www.vishay.com/docs/28313/013rlc.pdf
[3] AVX BestCap http://datasheets.avx.com/BestCap.pdf
[4] STM EnFilm http://www.st.com/web/en/resource/technical/document/datasheet/CD00270103.pdf

Safeguards Equipment Integration

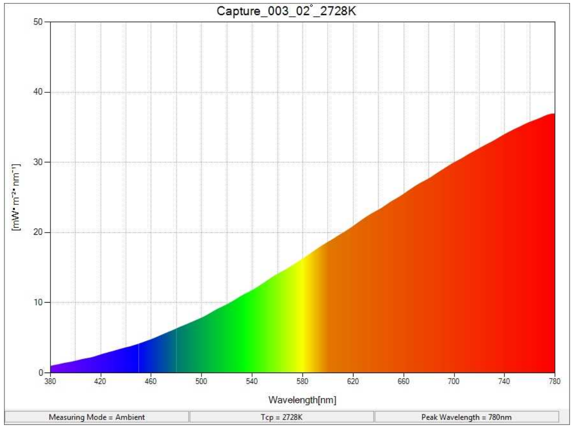
- Base testing platform is the Remotely Monitored Sealing Array (RMSA)
  - Wireless fiber optic loop seal
- Harvesting sensor mounts to external antenna port
  - No case tooling required
- Batteries still required!
  - Can be cheaper and less toxic chemistry if desired



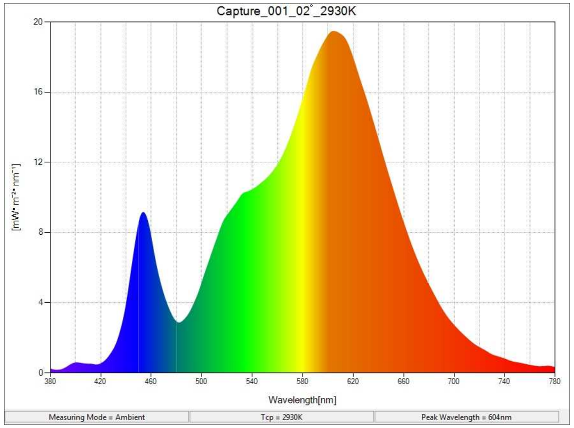


Performance

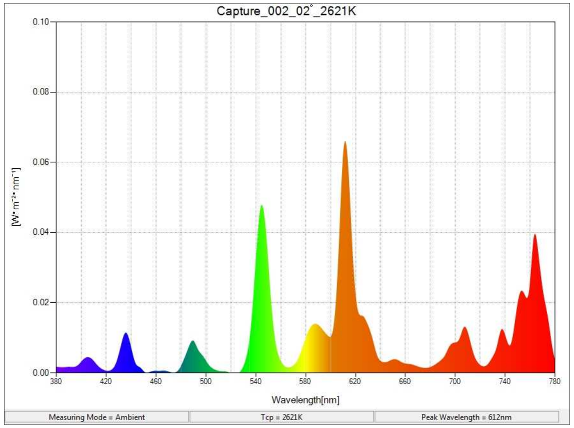
- RMSA tested with different lighting sources
  - LED
  - CFL
  - Tungsten incandescent
- Illumination and color measured using spectrometer
- Illuminance varied and current delivered to load (@ + 3.3 V) recorded



Incandescent



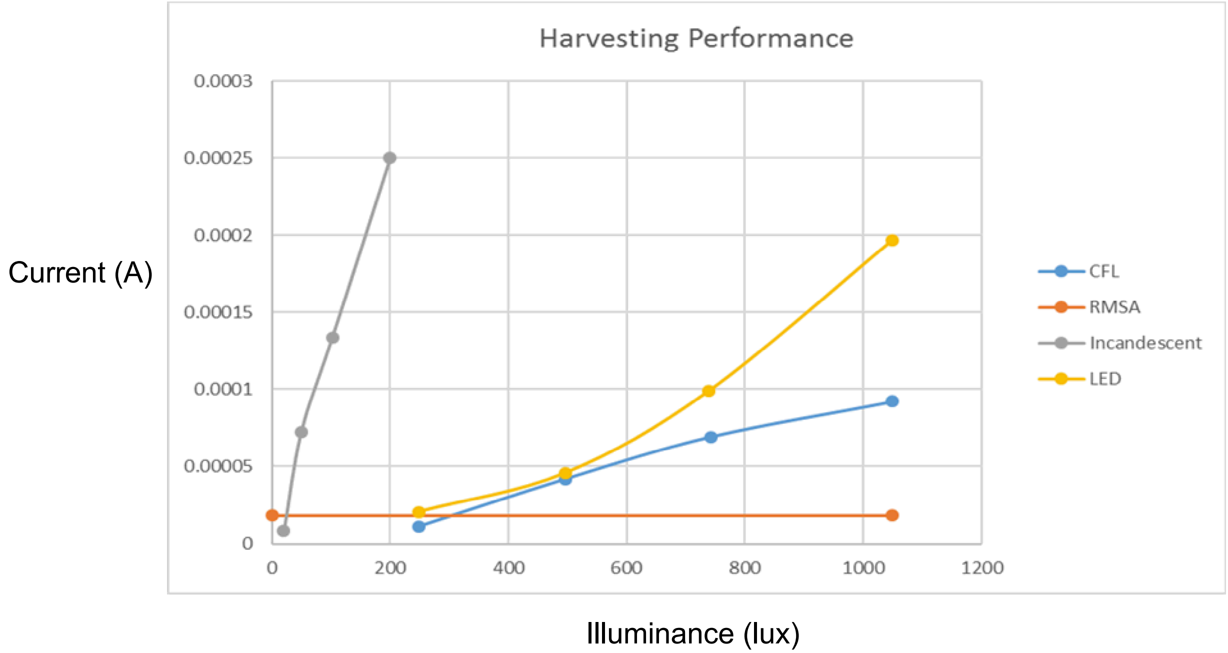
LED



CFL

Dynamic Performance (cont.)

- ~30 lux required for incandescent source to power RMSA (~20 µA)
- ~250 lux for fluorescent/LED



Illuminance (lux)	Surface illuminated
0.05–0.36	Full moon clear night
50	Family living room
100	Very dark overcast day
320–500	Office lighting
1000	Overcast day
10,000–25,000	Full daylight

Conclusion

- Photonic energy harvesting extremely can significantly extend operational deployment long-lifetime for electronic systems
  - Can provide 100% of the power needs of an RMSA under dimly lit conditions
  - ~$35 per unit ($25 PV cells, $10 PCB/cabling)
- System architecture with built-in storage permits 9 hours of downtime within the lighting cycle
- Risks:
  - Dirt/dust
  - Additional external case penetration
  - Additional components - reliability