Forging Ahead: Global Commercialization of Energy Harvesting Technology

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APEC 2013 Industry Session Presented by:

PSMA Energy Harvesting Forum
Energy Harvesting Info & Resources for the Power Electronics Industry
Commercialization of EH Technologies

- Identify key trends and market forces driving the need for Energy Harvesting-based power
- The economics behind Energy Harvesting
- Diagram the system architecture of an EH-based system – networked or stand-alone
- What are the high level design considerations
- Energy Harvesting technology that enables cost effective EH-powered products.

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Key Trends Driving Innovation

- New innovative products are smarter, smaller and wireless
- Smart devices that must communicate status/control
- There will be billions of new networked smart devices
- Health, Industrial, Buildings, Appliances, Transportation
- New Powering solutions are required
Introducing Energy Harvesting:

*Life of Product Energy Generation and Storage...*

- Energy can be harvested from almost any environment:
  - Light, vibration, flow, motion, pressure, magnetic fields, RF, etc.

- Energy Harvesting applications found in every industry segment

- EH-powered systems need reliable energy generation, storage and delivery:
  - Must have energy storage as EH Transducer energy source is not always available: (Solar @night, motor vibration at rest, air-flow, etc.)
  - Longer operating times – high-efficiency minimizes charge loss
  - Self-Powered allows remote locations & lower installation costs
  - High cycle life enables extended operation – fewer service calls

- Ideal solution is a highly-efficient, eco-friendly, power generation system that can be cycled continuously for the life of the product
EH Powering The “Internet Of Things”
HP CeNSE, IBM Smarter Planet

Giving the Planet a Voice with Sensors

CeNSE

Central Nervous System for the Earth
– Awareness of planet
– Measurement of impact
– Taste/Smell/Touch/Sound/Sight
– Safety
– Sustainability
– Security

~1 trillion sensor network
Quantity of data creates quality of data

“Trillions of digital devices connected to the Internet, are producing a vast ocean of data…”

Who’s going to change 1 Trillion Batteries????!!
Energy Harvesting Market in 2012 $0.7Bn

Source: IDTechEx Energy Harvesting Report

- Consumer Electronics: 630 million/$420 million
- Mobile Phones: 0.2 million/$1.8 million
- Bicycle Dynamo: 6.3 million/$63 million
- Wristwatches: 33 million/$26 million
- Industrial - non mesh: 2 million/$16 million
- Other - including medical: 0.2 million/$2 million
- Military & Aerospace: 0.05 million/$175 million
- Wireless Mesh Networks: 0.2 million/$2 million
Energy Harvesting Market in 2017 $1.5Bn

Source: IDTechEx Energy Harvesting Report

- **Consumer Electronics**: 900 million/ $630 million
- **Military & Aerospace**: 0.07 million/ $210 million
- **Wireless Mesh Networks**: 20 million/ $200 million
- **Healthcare**: 1 million/ $9 million
- **Wristwatches**: 43 million/ $33.4 million
- **Laptops/ebooks**: 5 million/ $80 million
- **Industrial - non mesh**: 40 million/ $140 million
- **Mobile Phones**: 20 million/ $100 million
Energy Harvesting Market Forecasts

From the IDTechEx EH Study:
- 90% of envisaged use of wireless sensor networks are impractical without EH
- Many installations are inaccessible or prohibitively expensive for replacement
- Sensors such as bionics or embedded devices need life of product power
- Many standalone products need “off-the-grid” powering solutions
Total Market Value by EH Technology 2019

From the IDTechEx EH Study:
• EH from light is 60% of applications
• Electrodynamic/Electromagnetic is 27%
• Vibration and Thermal 13% but may be low by some estimates
• What new energy harvesting technologies are coming???
EH-Powered Autonomous Wireless Sensor Block Diagram

Sensor (e.g., temperature, pressure, occupancy) → MCU + Radio

Input Power

“Energy Aware” Communications and Control

Processor, Sensor and Wireless Link

Energy Harvesting Power Supply

EH Transducer
Electrical Interface
Discrete Components

IC - Energy Conversion
Battery Management
Power Management

Rechargeable
Energy Storage
Device

Light
ΔT
Motion
EM Field

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Design Considerations for EH

1. Determine energy available from your environment
   - Indoor solar is in tens to hundreds of microwatts
   - Thermoelectric in tens to hundreds of microwatts based on delta T

2. Harvest energy as efficiently and cost effectively as possible
   - Design for Maximum Peak Power Point
   - Avoid components with excessive leakage or quiescent current

3. Calculate application power requirements in all operation modes and minimize to fit available input EH power
   - Use sleep modes of components when possible
   - Write Energy-Aware code -> no polling loops, check Vcc before running

4. Size storage for times when ambient energy is not available
   Bigger battery is not always better: don’t fill the pool with a paper cup!
EH vs. Battery Business Case Realities

- Small device designs that do not have a charging source – either AC/DC, Energy Harvesting or Wireless Power – use a primary battery.
- Primary batteries have reached commodity status with billions/yr shipped.
- To compare rechargeable battery $/mAh metric you must use the Lifecycle capacity of the rechargeable battery - #charge cycles x Depth of Discharge per cycle in uAh. This gives the total lifetime energy delivery cost.
- Example using 3Volt batteries 1K Qty on Digi-Key:
  - CR2032 coin + holder: $.36/225mAh x 1 cycle = $0.0016/mAh
  - Tadiran coin: $4.82/1000mAh x 1 cycle = $0.0048/mAh
  - Alkaline 2 AAA = holder: $1.71/1000mAh x 1 cycle = $0.0017/mAh
  - IPS MEC TFB : $13.09/700uAh x 10,000 cycles= $0.0019/mAh
  - Cymbet EnerChip: $2.70/50uAh x 10,000 cycles = $0.0054/mAh
- To charge rechargeable batteries, need to add the Cost for EH power system.
- Supercapacitors can be used, but electrical characteristics are a concern.
Calculating the Cost of the Energy Harvester

- Think of the Energy Harvester as a variable capacity battery
- The output energy will depend on the ambient energy conditions
- Energy Harvester designs will have a min/max energy output range
- Calculate the EH cost based on the energy output average
- Cost is Transducer + interface components + conversion electronics (IC)

Example: Simple Solar Energy Harvester at 200Lux with 24/7 operation
  - Sanyo AM1815 4.9V solar cell $4.39 (1K pcs) output is 147uW
  - Assume simple conversion electronic components for $1.25
  - 3.3V x Current = 147uW. Current = 44.7microAmps output
  - Total capacity over 10 year 24/7 life = 3,916 mAh
  - $/mAh for Solar EH = $0.0014. Lower than AAA and Coin cell costs
  - Fewer light hours increases cost, brighter light decreases costs

➤ Energy Harvesters can be designed as cost effectively as Primary Batteries
Assigning $ Value to other Attributes

- What is the product power lifetime requirements – 200mAh, 1Ah, 5Ah?
- Life of product duration expectations – 3, 5, 10, 20 years?
- Battery Footprint and overall product size
- Battery Height and overall product size
- $cost/uAh/mm³ - how much energy for $ in how small a space?
- Assembly Issues and Costs
- Primary Battery Change-out – device access and cost of replacement
- Product Physical design – No doors or customer access
- Electrical Characteristics - flat voltage, fast recharge, low discharge
- Aging Characteristics – chemical leakage, seals drying out
- Transportation Restrictions – UN and Country Air Safety shipping laws
- Safety and End-of-Life Disposal - what are the procedures and costs
# Energy Harvesting Transducers

What Ambient Energy is Available?

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Challenge</th>
<th>Typical Impedance</th>
<th>Typical Voltage</th>
<th>Typical Power Output</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Conform to small surface area; wide input voltage range</td>
<td>Varies with light input Low kΩ to 10s of kΩ</td>
<td>DC: 0.5V to 5V [Depends on number of cells in array]</td>
<td>10µW-15mW (Outdoors: 0.15mW-15mW) (Indoors: &lt;500µW)</td>
<td>$0.50 to $10.00</td>
</tr>
<tr>
<td>Vibrational</td>
<td>Variability of vibrational frequency</td>
<td>Constant impedance 10s of kΩ to 100kΩ</td>
<td>AC: 10s of volts</td>
<td>1µW-20mW</td>
<td>$2.50 to $50.00</td>
</tr>
<tr>
<td>Thermal</td>
<td>Small thermal gradients; efficient heat sinking</td>
<td>Constant impedance 1Ω to 100s of Ω</td>
<td>DC: 10s of mV to 10V</td>
<td>0.5mW-10mW (20 C gradient)</td>
<td>$1.00 to $30.00</td>
</tr>
<tr>
<td>RF &amp; Inductive</td>
<td>Coupling &amp; rectification</td>
<td>Constant impedance Low kΩs</td>
<td>AC: Varies with distance and power 0.5V to 5V</td>
<td>Wide range</td>
<td>$0.50 to $25.00</td>
</tr>
</tbody>
</table>

Designs must deal with different: Impedance, Voltages, Output power, etc.
EH Power System Cost vs. Benefit

Processor, Sensor and Wireless Link

Sensor (e.g., temperature, pressure, occupancy) → MCU + Radio

Input Power → “Energy Aware” Communications and Control

Energy Harvesting Power Supply

Light → EH Transducer Electrical Interface Discrete Components → IC - Energy Conversion Battery Management Power Management

$ Cost vs. $ Benefit vs. Requirements

Rechargeable Energy Storage Device
Industry is Providing Cost Effective Sensor Building Blocks

- Low Power Microprocessors with nanoAmp sleep currents.
- Low Power Radio Transceivers:
  - IEEE 802.15.4 standards 2.4Gigahertz
  - MilliAmp to tens of milliAmps currents for transmitters and receivers
  - Quick startup with low sleep power
- Energy Efficient Radio Protocols:
  - Proprietary Ultra-low power protocols
  - ZigBee and ZigBee Green
  - Bluetooth LE
  - ANT+, EnOcean Alliance
  - Dust Networks IP 6LoWPAN
- Micropower Sensors with low sleep currents:
  - Passive IR, Temp, Humidity, Acceleration, Pressure, etc.
- Lower quiescent current peripheral circuits:
  - Clocks, power management chips, etc.
Example of Wireless EH-Powered Intra-Ocular Pressure Sensor

Summary

• Billions of smart devices deployed over the next 10 years need:
  • Powered autonomously and be “off-grid”
  • Have a power source that lasts the life of the device
  • Be small, integrated and cost effective
• Cost effective Energy Harvesting solutions can power products
• Success is based on the EH Ecosystem converging:
  • EH Transducers
  • High Efficiency power conversion
  • Life of Product Energy storage
  • Ultra low power Microcontrollers and Sensors
  • Low power wireless radios and protocols
  • Optimized system architecture, hardware and firmware
Session Agenda

1. Forging Ahead: EH Commercialization Drivers
   Steve Grady – Cymbet
2. Advancements in Energy Harvesting Transducers
   Brian Shaffer – Linear Technology
3. High Efficiency Designs for Energy Conversion
   Henrik Zessin – Fraunhofer Institute
4. New Technologies for ULP MCUs, Sensors and Actuators
   Mark Buccini – Texas Instruments
5. Wireless Transceivers, Protocols, SoCs and Architectures
   Roman Budek - NXP
6. Successful Commercial Energy Harvesting Deployments
   Troy Davis - EnOcean
7. Hot Topics in EH Power Designs and Table Top Demos
   Speakers Roundtable

Session Chair – Arnold Alderman – Anagenesis