Opportunities in Energy Harvesting

Brian Zahnstecher, Principal, PowerRox
Senior Member, IEEE
Chair, IEEE San Francisco Bay Area (SFBAC) Power Electronics Society (PELS)
Board of Directors, Power Sources Manufacturers Association (PSMA)
Co-chair, PSMA Energy Harvesting Committee
Co-chair, PSMA Reliability Committee

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There is neither any sponsored promotion nor bias toward any of the products/organizations mentioned in this tutorial.

Any vendor-specific content is provided for example purposes only.
Brian Zahnstecher is a Sr. Member of the IEEE, Chair of the IEEE SFBAC Power Electronics Society (PELS) awarded 2017 Best Chapter awards at the local/national/worldwide levels concurrently (an unprecedented achievement), sits on the Power Sources Manufacturers Association (PSMA) Board of Directors, and is the Principal of PowerRox, where he focuses on power design, integration, system applications, OEM market penetration, market research/analysis, and private seminars for power electronics.

He has successfully handled assignments in system design/architecting, AC/DC front-end power, EMC/EMI design/debug, embedded solutions, processor power, and digital power solutions for a variety of clients. He previously held positions in power electronics with industry leaders Emerson Network Power (now Artesyn), Cisco, and Hewlett-Packard, where he advised on best practices, oversaw product development, managed international teams, created/enhanced optimal workflows and test procedures, and designed and optimized voltage regulators. He has been a regular contributor to the industry as an invited speaker, author, workshop participant, session host, roundtable moderator, and volunteer. He has over 14 years of industry experience and holds Master of Engineering and Bachelor of Science degrees from Worcester Polytechnic Institute.
OVERVIEW

- Market / Motivations
- Intelligent Power Management (IPM)
- What is Energy Harvesting (EH)?
  - Energy Source Overview
  - Ecosystem
- Applying EH to Ultra-Low Power (ULP) Applications
- Conclusions
  - NOTE: LOTS OF REFERENCES AT END!
MARKET / MOTIVATIONS

Estimated U.S. Energy Consumption in 2016: 97.3 Quads

Source: LBNL March, 2017. Data is based on DOE/EIA MED (2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, unless otherwise noted. This chart was revised in 2017 to reflect changes made in mid-2016 in the Energy Information Administration’s energy accounting methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy inputs to the system. The numerator of the efficiency calculation includes the delivered energy by the consumer (see box), which was updated in 2013 to reflect more accurate estimates of manufacturing. Totals may not equal sum of components due to independent rounding. LBNL-EE-11017

MARKET / MOTIVATIONS

- **50B Devices!!!**
  - 20-50B IoT Devices, 1T IoT Devices?!?...A **REALLY** Big Number
    - Not getting into IoT semantics here, but most folks agree there will be a whole lot of devices, sensor networks, etc. connected to some form of web/cloud interface.
    - A battery is commonly the limiting factor so the more energy that can be harvested from an ambient source, the more sensor/IoT device applications are enabled. 1T too **LOW** a number???

The Internet of Things will experience a continued growth spurt into the next decade

The number of connected devices will double every five years, making the world's population growth seem glacial in comparison

- **12.5 Billion**
  - Connected devices
  - 2010
- **25 Billion**
  - Connected devices
  - 2015
- **7.2 Billion**
  - World population
  - 2020
- **7.6 Billion**
  - World population
  - 2025

That is a lot of stuff for a non-bionic being!
• Billions of smart devices + Massive Networks = Awesome!
• Devices + Consumer Interest/Application = Exponential Growth Market Estimates!!!

• Wait a sec, how are we enabling these transformative technologies and fantastic market projections?!?
  • Innovations in power electronics & energy harvesting will drive the integration and intelligent power management required for enablement.
MARKET / MOTIVATIONS

- Energy Savings
  - Waste = Opportunity
  - Many Energy Sources...much more on this later
  - Put Reclaimed Energy To Better Use
  - Reduce Infrastructure / CAPEX

“There is no such thing as waste heat...just underutilized energy recycling opportunities.”

– Brian Zahnstecher

\[
\text{ENERGY}_{\text{UTILIZATION}} = \frac{\text{ENERGY}_{\text{IN}}}{\text{ENERGY}_{\text{OUT}}}
\]
MARKET / MOTIVATIONS

- Battery Mitigation
  - Garbage / Hazardous Materials
  - Replacement Efforts
    - Push For Rechargeable Battery Applications
  - Overall Design Effort (i.e. – Redundancy, Overprovisioning, Etc.)
  - Short-, Near-, & Long-Term Strategies…much more on this later

All we need is improved battery technology so we can go a really long time without having to plug-in and recharge, right?

WRONG!!!
INTELLIGENT POWER MANAGEMENT (IPM)

- Far And Away Best Opportunity for Action
- Power Management Integrated Circuit (PMIC)
- Power Shedding / Dynamic Power Allocation
- Start with the Power Budget
  - Sum of Maxima
- Breakout Into Key Areas of Focus
  - Architecture
  - Distribution
  - Utilization
- **QUIZ:** What is the most efficient power conversion device on Earth?
INTELLIGENT POWER MANAGEMENT (IPM)

- **Battery Life**
  - From Improvement to Infinity *(and beyond!)*

- **Power Converter Efficiency**
  - How much room for improvement do you think there is here?

- **Integration**
  - Shrink it, integrate it, reduce housekeeping overhead.
    - System on Chip (SoC)
    - Power Supply on a Chip (PwrSoC)
    - Power Supply in Package (PSiP)
    - Power Management IC (PMIC)

WHAT IS EH?

- The Many Forms of Free, Ambient Energy
  - What is EH?
    - Power Capture from Free, Ambient Energy Sources
    - Any Transducer is a Potential EH Source
  - What is NOT EH?
    - Wireless Power Transfer (WPT)
      - Wireless Commutation Via Resonance = Wall Source
        » Table-Top Chargers, RFID Tags, Etc.
      - Far-Field RF from Ambient = Energy Harvesting
WHAT IS EH?

- The Many Forms of Free, Ambient Energy
  - Goals
    - **Short-Term**: Mitigate Battery Usage
    - **Long-Term**: Complete Utilization of Free Energy
  - EH is **NOT** All or Nothing
    - Extend Battery Life
    - Standby Power
    - Complimentary Technologies
    - CAPEX / OPEX Mitigation
WHAT IS EH?

- Energy Source Overview
  - Dynamo (i.e. – kinetic EH, electrodynamic)
  - Solar
    - Photovoltaic Cell (PV)
    - Thermal
  - Thermoelectric Generator (TEG)
  - Piezoelectric Transducer (PZ)
  - Fuel Cells (FC)
  - Radio Frequency (RF)
    - Near-field
    - Far-field (*not to be confused with wireless power transfer*)
  - Vibration (inc. vibroacoustic resonant membranes)
  - Triboelectric
  - Hybrid Solutions
WHAT IS EH?

- **Energy Source Overview**
  - Dynamo (i.e. – kinetic EH, electrodynamic)
    - Oldest, Most Common Form of EH on Earth

WHAT IS EH?

- Energy Source Overview
  - Solar
    - Photovoltaic Cell (PV)

IMAGE CREDIT: Ascent Solar EnerPlex Surf phone charging case. [Link](http://www.goenerplex.com/products/solar-and-battery-phone-cases/surfr-for-iphone-6-6s)

IMAGE CREDIT: Alta Devices Technology Corporate Brochure “AnyLight Mobile Power” (2015)


IMAGE CREDIT: http://wiseenergy.org/solar/

WHAT IS EH?

- Energy Source Overview
  - Solar
    - Thermal

WHAT IS EH?

- Energy Source Overview
  - Thermoelectric Generator (TEG)

[Image: Diagram of Thermoelectric Generator]

WHAT IS EH?

- Energy Source Overview
  - Thermoelectric Generator (TEG)

- Wood Burning Stove Water Cooled Thermoelectric Generator DW-WC-70W

<table>
<thead>
<tr>
<th>ΔT=10K</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-load output voltage</td>
<td>52 mV</td>
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<tr>
<td>Device resistance</td>
<td>7.1 Ω</td>
</tr>
<tr>
<td>Output power</td>
<td>105 μW</td>
</tr>
</tbody>
</table>

<table>
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<th>ΔT=40K</th>
<th>Measured</th>
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<tbody>
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<td>No-load output voltage</td>
<td>171 mV</td>
</tr>
<tr>
<td>Device resistance</td>
<td>7.3 Ω</td>
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<tr>
<td>Output power</td>
<td>1252 μW</td>
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</tbody>
</table>


WHAT IS EH?

- Energy Source Overview
  - Thermoelectric Generator (TEG)
    - IC-Level

WHAT IS EH?

- Energy Source Overview
  - Thermoelectric Generator (TEG)
    - Consumer to Industrial Scale
  


  Turnkey Generators (10’s kW)
  Turnkey generator technology licensed to partners in target verticals like oil & gas

  PowerModule™ (kW)
  Primary product that Alphabet Energy ships to a range of industries

  PowerCard™ (W)
  Thermoelectric device contract manufactured by major scale-up

  PGC™ For Flare Stacks
  E1™ (20-foot container) For 1MW engines

  For industry
  For automotive
  2 feet

  Tetrahedrite (mW)
  Thermoelectric

  2 inches
WHAT IS EH?

- Energy Source Overview
  - Piezoelectric Transducer (PZ)
    - Piezoelectric Effect
      - Apply Voltage to Material (Typically Ceramic) = Mechanical Deformation
      - Apply Mechanical Stress to Material = Voltage
        » Pushing
        » Sound Wave

![Piezoelectric Transducer Image]


![Diagram of Piezoelectric Energy Conversion]

IMAGE CREDIT: https://www.amazon.co.uk/Spiratronics-Uncased-Piezo-Transducer/dp/B00940V1E2
WHAT IS EH?

- Energy Source Overview
  - Fuel Cells (FC)


WHAT IS EH?

- **Energy Source Overview**
  - Radio Frequency (RF)
    - Near-Field
    - Far-Field

WHAT IS EH?

- Energy Source Overview
  - Radio Frequency (RF)

P1110 Powerharvester Receiver
- Designed for battery charging and direct power applications.
- Harvesting range from 850-950MHz.
- Works with standard 50-ohm antennas.
- Configurable overvoltage protection up to 4.2V.
- Connect directly to rechargeable batteries including Alkaline, Lithium Ion, and Ni-MH.


WHAT IS EH?

- Energy Source Overview
  - Vibration (inc. vibroacoustic resonant membranes)

![IMMEDIATE ENERGY HARVESTERS](image)

**1. Performance**

<table>
<thead>
<tr>
<th>Description</th>
<th>5V Model</th>
<th>8V Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.1 Maximum Maximum @ 0.050g RMS, nominal frequency</td>
<td>5.5 mA (27.5mW)</td>
<td>3.0 mA (24mW)</td>
</tr>
<tr>
<td>1.1.2 Minimum @ 0.050g RMS, nominal frequency</td>
<td>0.840 mA (4.2mW)</td>
<td>0.525 mA (4.2mW)</td>
</tr>
<tr>
<td>1.1.3 Minimum @ 0.050g RMS, 2Hz bandwidth</td>
<td>0.600 mA (3mA)</td>
<td>0.375 mA (3mA)</td>
</tr>
<tr>
<td>1.1.4 Minimum @ 0.025g RMS, nominal frequency</td>
<td>0.240mA (1.2mW)</td>
<td>0.150mA (1.2mW)</td>
</tr>
</tbody>
</table>

WHAT IS EH?

- Energy Source Overview
  - Triboelectric
    - Triboelectric Nanogenerators (TENG)

**Produce a current with static electricity**

EPFL researchers have developed a device that can produce the equivalent of two AA batteries using cardboard, teflon tape, and carbon.

- [Image](image1.png)
- [Image](image2.png)
- [Image](image3.png)

WHAT IS EH?

Energy Source Overview
  • Hybrid Solutions
    • Capture Multiple Energy Sources Concurrently
**WHAT IS EH?**

- **Typical Energy Harvester Output Power**
  - RF: 0.1µW/cm²
  - Vibration: 1nW/cm²
  - Thermal: 10mW/cm²
  - Photovoltaic: 100mW/cm²

- **Typical Energy Harvester Voltages**
  - RF: 0.01mV
  - Vibration: 0.1 ~ 0.4 V
  - Thermal: 0.02 ~ 1.0 V
  - Photovoltaic: 0.5 ~ 0.7 V typ./cell

**Energy Harvesters become more capable**

- RF Field
- Mini PV
- Motion: Piezo or Inductive
- Shutoff Mode
- Quartz Oscillator
- LED
- Electronic Watch
- RFID Tag (Passive)
- Active RFID, FM receiver
- MP3, Bluetooth Transceiver
- Low Power Wireless Network
- Hearing Aid (Med.)
- Laptop, Tablet
- OLED Display
- Hearing Aid (Med.)
- RFID Tag (Passive)
- Active RFID, FM receiver
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- Hearing Aid (Med.)
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- Electronic Watch
- RFID Tag (Passive)
- Shutoff Mode
- Quartz Oscillator
- LED
- Mini PV
- Motion: Piezo or Inductive
- RF Field

**Electronic devices become less power hungry**

- i.e. Numerator
- i.e. Denominator

WHAT IS EH?

- Challenges
  - Efficiency Dependent on Input
  - PMICs with Multiple Input Support
  - Developing Ecosystem
  - Wariness to Adoption
  - Philosophical Approach to Waste Vs. Source
WHAT IS EH?

- Ecosystem
  - The Primary Constituents of the EH Ecosystem

![Diagram](image-url)

WHAT IS EH?

- Ecosystem
  - A Production Ecosystem Exists
    - While Nascent, Exists Today
    - Lots of Production Parts
    - Many Mature PMICs from Industry Leaders
    - Tends to be Siloed

Cheap plug for EnerHarv 2018:
3-Day Workshop Week of May 28, 2018
Tyndall National Institute, Cork, Ireland
www.EnerHarv.com
WHAT IS EH?

▪ Ecosystem
  o A **short** list of things that exist **TODAY!!**
    • Transducers (**EH type**)
      – Alta Devices (**PV**)
      – Murata (**TEG**)
      – Jennova (**Electrodynamic**)
      – Powercast (**RF**)
      – ZF/Cherry Electrical Products (**Electrodynamic**)
      – Perpetuum (**Vibrational**)
      – Tyndall National Institute (IP only)
      – Fraunhofer Institute (IP only)
      – EnOcean Alliance (IP only)
WHAT IS EH?

- **Ecosystem**
  - A short list of things that exist *TODAY!!!*
    - Vendor Power Management ICs (PMICs)
      - Linear Tech (LT): 25+ EH-related products
      - Analog Devices (ADI): ADP5090/5091
      - Texas Instruments (TI): 6+ EH-related products
      - ST Micro: 3 EH-related products
      - Cypress Semi: 3 PMICs
      - Dialog Semi: BLE PMICs
      - On Semi: NCS36510 PMIC
      - Mischief Collaboration
  
  - See how little is actually required
    - **EXAMPLE:** TI BQ25505
      - $I_o = 325\text{nA}$
      - Multiple EH source & storage support
      - Includes power conversion/regulation!

*IMAGE CREDIT: "bq25505," Texas Instruments Data Sheet, Downloaded July 20, 2016.*
WHAT IS EH?

- Ecosystem
  - A short list of things that exist TODAY!!!
    - Development / Evaluation Kits
      - Würth Elektronik Gleanergy / EH Solution To Go
      - ADI ADP5090/5091 Eval Board
      - LT DC2080A Eval Board
      - Cypress Solar BLE Kit CYALKIT-E02
      - TI CC2650 SimpleLink Eval Kit
      - EnOcean EDK 350 Dev Kit

WHAT IS EH?

- Ecosystem
  - Industry Consortia / Major Contributors
    - Georgia Tech Institute for Electronics & Nanotechnology
      - Georgia Electronic Design Center
      - Georgia Tech Research Institute's Microelectronics & Nanotechnologies Laboratory
      - Flex@Tech Flexible Electronics Program
      - University Center of Excellence for Photovoltaics
      - The Center for Co-design of Chip, Package, System
      - Center for Compound Semiconductors
      - Center for MEMS and Microsystems Technologies
      - 3D Systems Packaging Research Center
    - UC Berkeley
      - Berkeley Sensor & Actuator Center (BSAC)
      - Berkeley Wireless Research Center (BWRC)
      - SWARM Lab
WHAT IS EH?

- Ecosystem
  - Industry Consortia / Major Contributors
    - Energy Harvesting Network
    - MISCHIEF = EH PMIC
      - Tyndall National Institute
      - Microelectronic Circuits Centre Ireland (MCCI)
    - Fraunhofer Institute for Integrated Circuits (IIS)
    - Power Sources Manufacturers Association (PSMA)
APPLYING EH TO ULP APPLICATIONS

- ULP Loads
  - Supplementing with EH Power

Supplementing Batteries with Energy Harvesting

APPLYING EH TO ULP APPLICATIONS

- Matching the EH to the Load

*Figure 2: A comparison of ambient energy sources (before conversion). (Data source: CEA-Leti; graphic source: Linear Technology; used by permission)*

## APPLYING EH TO ULP APPLICATIONS

<table>
<thead>
<tr>
<th><strong>EH TECH</strong></th>
<th>Base Station (BS)</th>
<th>Data Center</th>
<th>Smartphones</th>
<th>IIoT</th>
<th>Mobile (on-the-fly) Charging</th>
<th>Wireless Sensor Network (WSN)</th>
<th>Automotive / V2V</th>
<th>IoT</th>
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CONCLUSIONS

• Reducing power demand yields far more benefits than simply a bigger battery.
• EH (i.e. – scavenged energy) is very applicable to many applications TODAY, whether complimentary or comprehensive to the application.
• Power electronics & EH are critical factors in enabling IoT/WSN/Portable/5G applications.
• Device/System design (inc. SW) should be rethought with EH in-mind.
• The explosion of devices will primarily come in the form of WSNs (and their endpoints), which are ideal for EH.
• This is just the start of EH getting into the mainstream with a lot more to come.
MORE INFORMATION

- www.PowerRox.com
- EnerHarv 2018: www.EnerHarv.com
- bz@powerrox.com
- See REFERENCES section at end
Thank you!

Questions?
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- "bq25505," Texas Instruments Data Sheet, Downloaded July 20, 2016.
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