# Opportunities in Energy Harvesting

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**Co-chair**, *PSMA Energy Harvesting Committee*
**Co-chair**, *PSMA Reliability Committee*

*Thursday, May 10, 2018*
*Sunnyvale, CA*

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*Any vendor-specific content is provided for example purposes only.*

# PRESENTER


## Brian Zahnstecher

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San Jose, CA


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

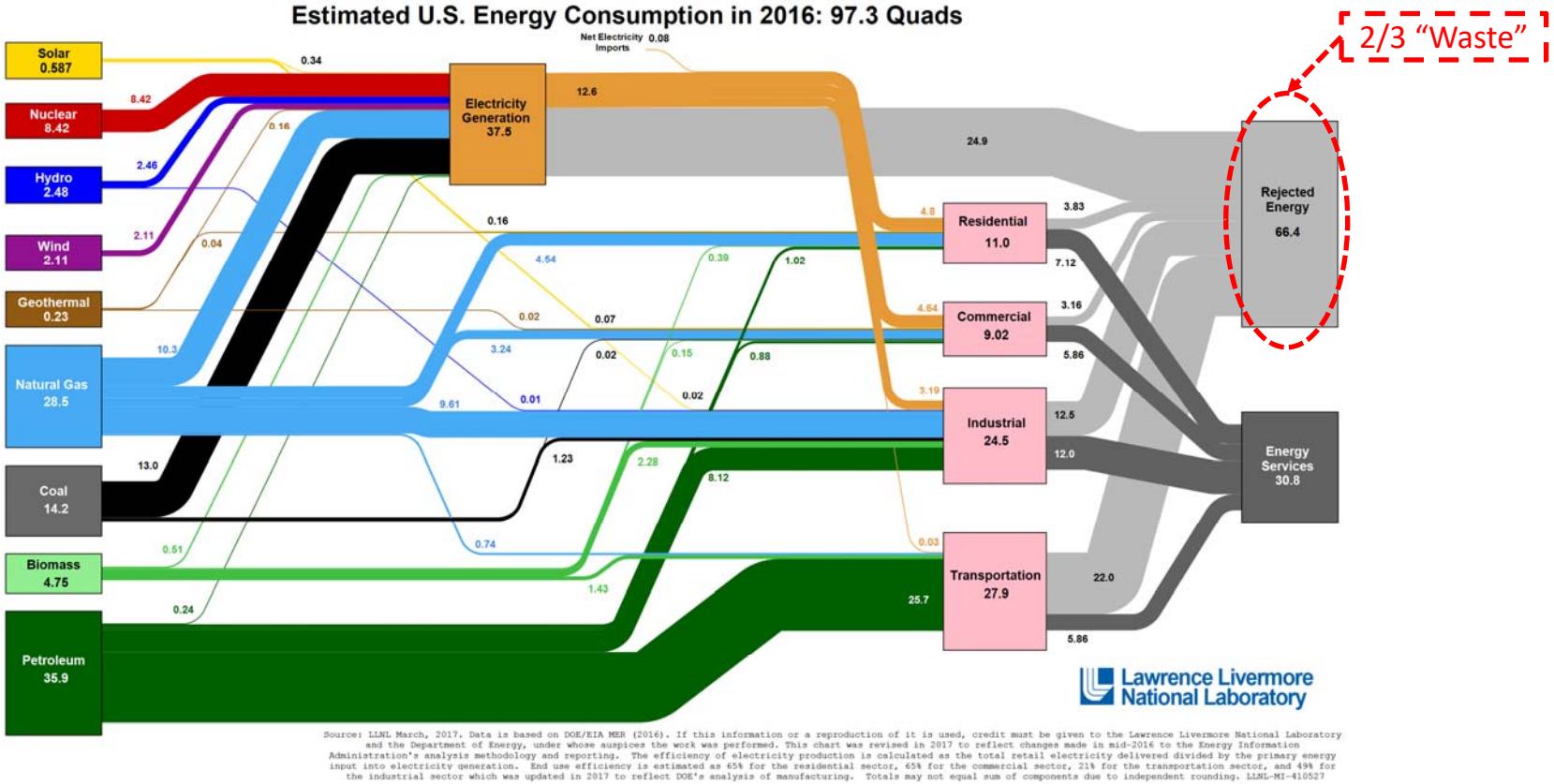
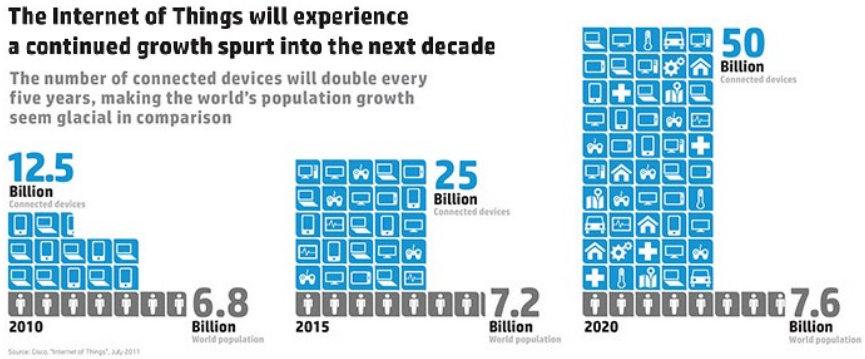
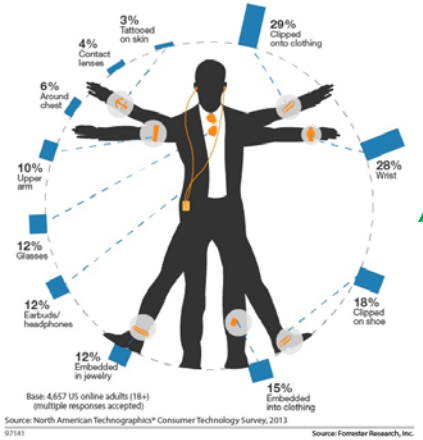



*IMAGE CREDIT: "Estimated U.S. Energy Consumption in 2016," Lawrence Livermore National Laboratory, March 2017.*

# 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???




That is a lot of stuff for a non-bionic being!

# MARKET / MOTIVATIONS

- 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

$$ENERGY_{UTILIZATION} = \frac{ENERGY_{IN}}{ENERGY_{OUT}}$$

# 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 storage 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)

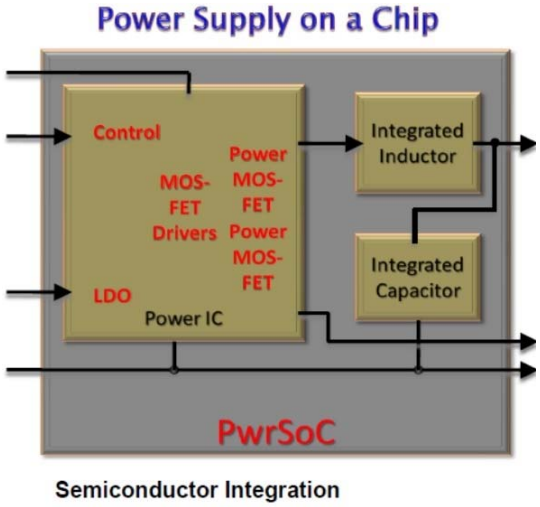



*IMAGE CREDIT: "Power Supply in a Package (PSiP) & Power Supply on a Chip (PwrSoC): Taking Stock of the Trials and Triumphs of Adoption that Lie Ahead" Arnold Alderman, Anagenesis, IEEE APEC 2014.*

# 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

*IMAGE CREDIT: https://snc1dcedarbrae.wikispaces.com/Poorva*

*IMAGE CREDIT: http://i01.i.aliimg.com/wsphoto/v0/490395881/5267-NEW-3-LED-lights-font-b-Dynamo-b-font-Hand-Pressing-Flash-Light-1135.jpg*

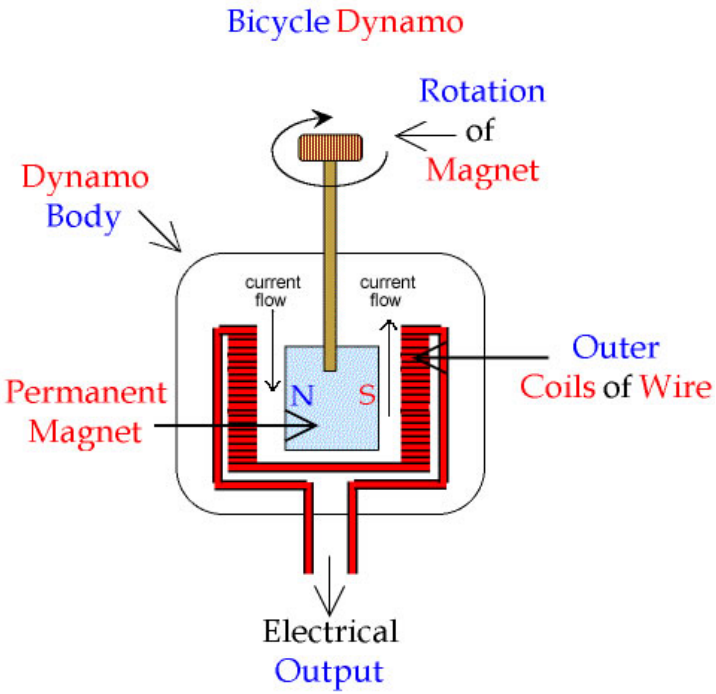



*IMAGE CREDIT: Roadmap – Motors and Generators, 6pie, 2015. [Online]. Available: http://www.6pie.com/coilsandmagneticflux.php.*

# WHAT IS EH?

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

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

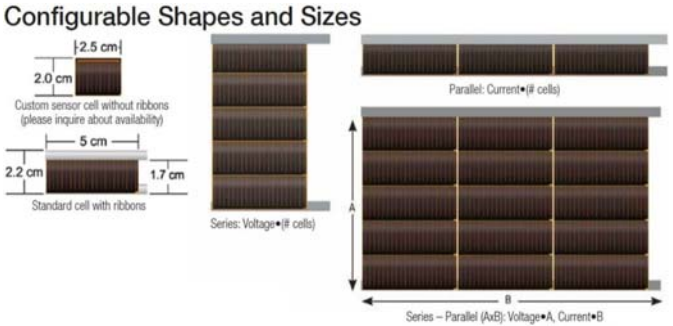



*IMAGE CREDIT: Alta Devices Technology Corporate Brochure "AnyLight Mobile Power" (2015)*


*IMAGE CREDIT: Ascent Solar EnerPlex Surfr phone charging case. http://www.goenerplex.com/products/solar-and-battery-phone-cases/surfr-for-iphone-6-6s*

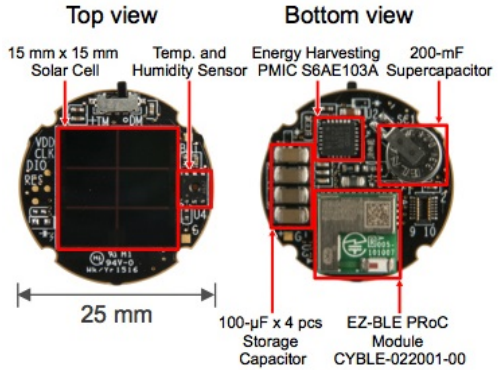



*IMAGE CREDIT: Roadmap – Cypress – Solar Powered BLE Sensor Beacon Reference Design Kit, Future Electronics, 2016. [Online]. Available: http://fcs.futureelectronics.com/2016/08/cypress-solar-powered-ble-sensor-beacon-reference-design-kit/.*

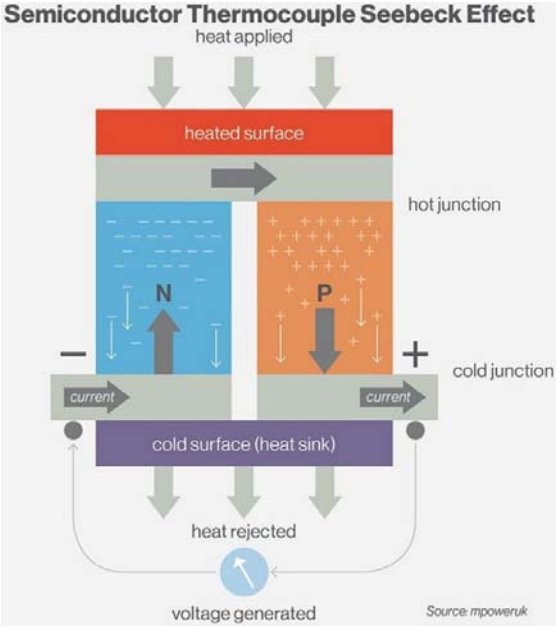
# WHAT IS EH?

- **Energy Source Overview**
  - Solar
    - Thermal

*IMAGE CREDIT: World's largest solar plant goes live, will provide power for 1.1M people, Computerworld, 2016. [Online]. Available: https://www.computerworld.com/article/3031659/sustainable-it/worlds-largest-solar-plant-goes-live-will-provide-power-for-11m-people.html.*

# WHAT IS EH?

- **Energy Source Overview**
  - Thermoelectric Generator (TEG)



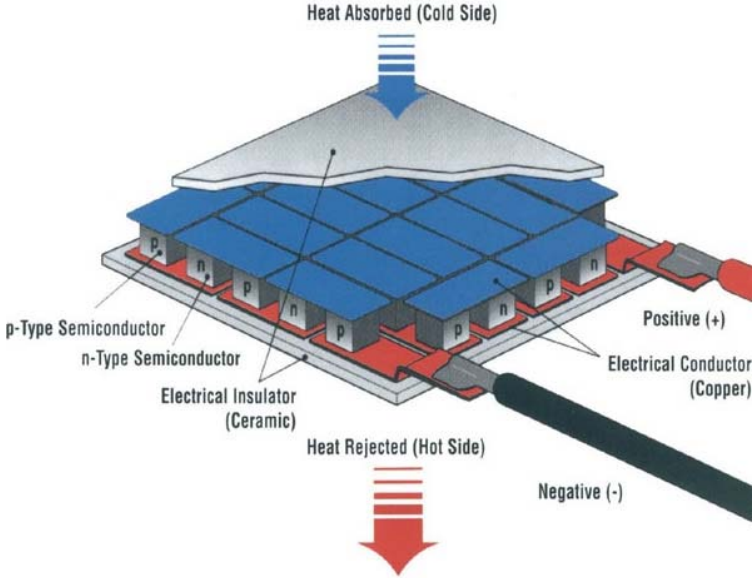
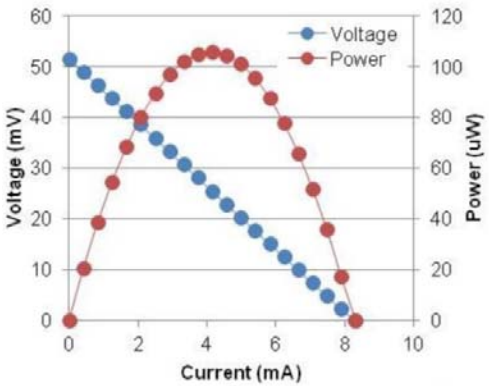




*IMAGE CREDIT: How to Build a Homemade Thermoelectric Generator, 2017. [Online]. Available: https://topmagneticgenerator.com/build-homemade-thermoelectric-generator/.*

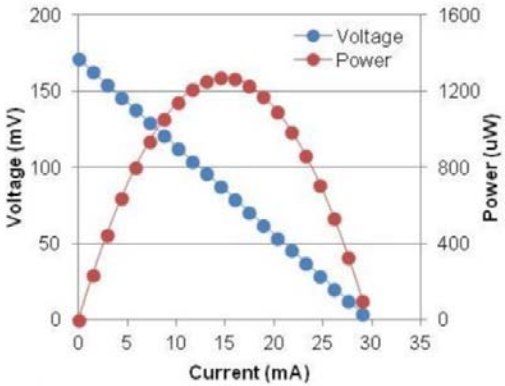
*IMAGE CREDIT: Laird*

# WHAT IS EH?

- **Energy Source Overview**
  - Thermoelectric Generator (TEG)




| ΔT=10K | Measured |
|---|---|
| No-load output voltage | 52 mV |
| Device resistance | 7.1 Ω |
| Output power | 105 μW |




| ΔT=40K | Measured |
|---|---|
| No-load output voltage | 171 mV |
| Device resistance | 7.3 Ω |
| Output power | 1252 μW |

*IMAGE CREDIT: "Self-powered wireless sensor network node using Thermoelectric Ceramics," Murata Manufacturing Company, April 7, 2016.*

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


*IMAGE CREDIT: Devil Watt Product Overview Brochure "Wood Burning Stove Water Cooled Thermoelectric Generator DW-WC-70W" (2015).*

# WHAT IS EH?

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

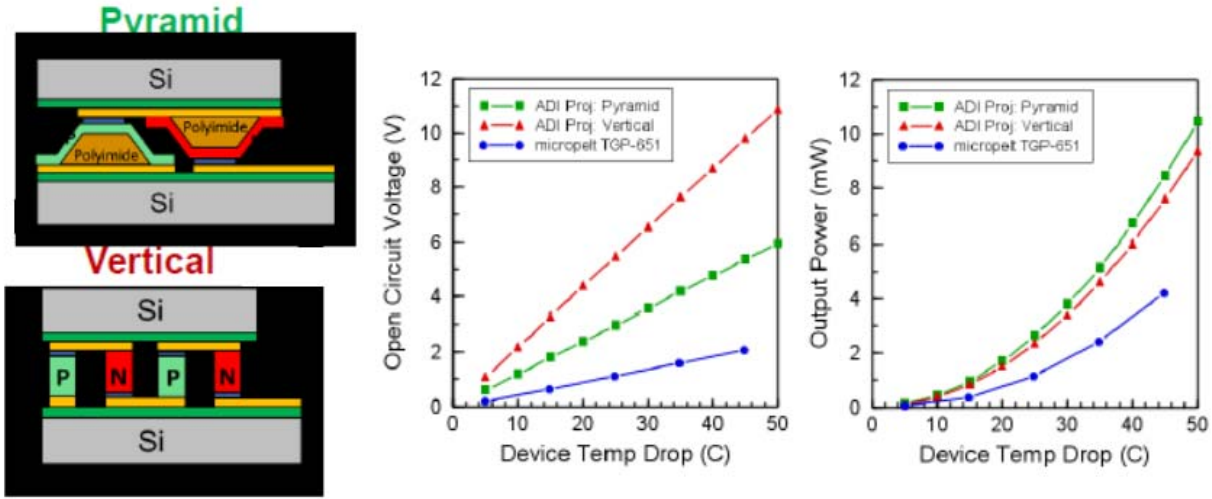



*IMAGE CREDIT: B. Chen, J. Cornett, "Chip Scale TEG and its Use for a Wireless Machine Health Monitoring System," Analog Devices, APEC 2017 Industry Session, Tampa, FL, March 30, 2017.*

# WHAT IS EH?

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


*IMAGE CREDIT: Matrix Industries - Introducing the world's first smartwatch you never have to recharge., Matrix Industries, 2017. [Online]. Available: https://www.powerwatch.com/.*

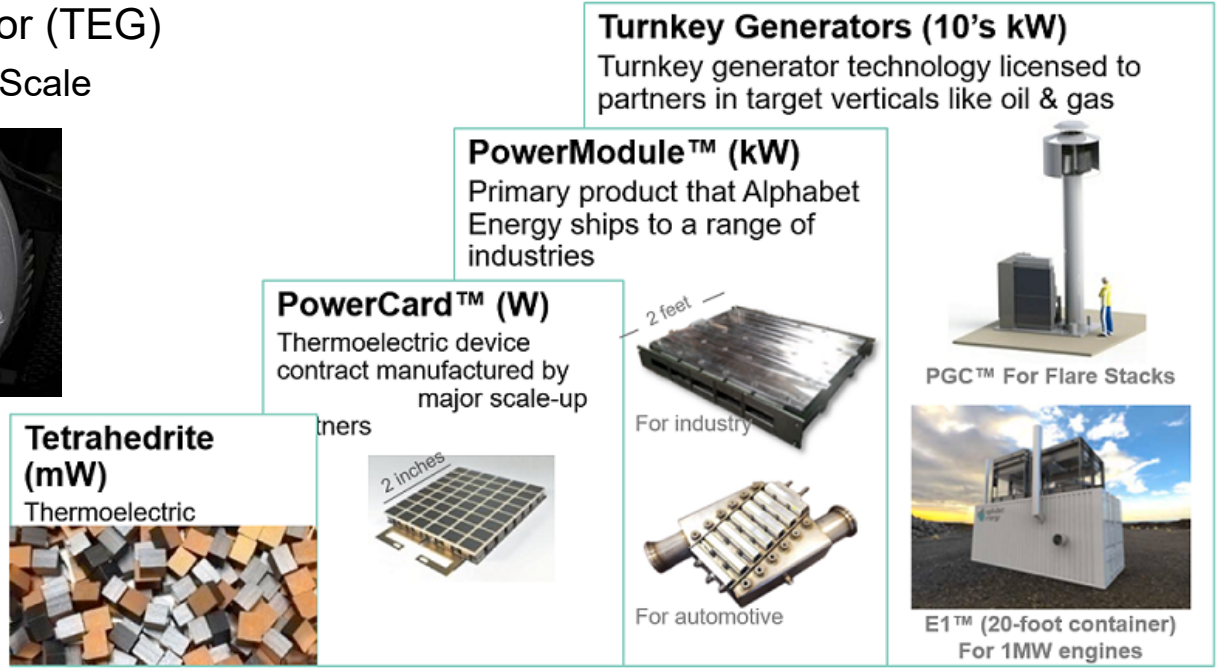



*IMAGE CREDIT: J. Reifenberg, "Application of Thermoelectric Devices for Industrial Waste Heat Recovery," Alphabet Energy, SFBAC PELS Energy Harvesting Workshop, Santa Clara, CA, April 20, 2017.*

# 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

*IMAGE CREDIT: https://www.amazon.co.uk/Spiratronics-Uncased-Piezo-Transducer/dp/B00940V1EG*

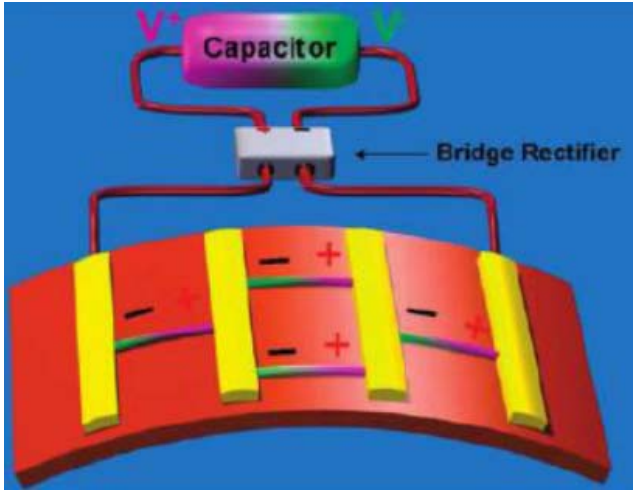



*IMAGE CREDIT: Guang Zhu, Rusen Yang, Sihong Wang, Zhong Lin Wang, "Flexible high-output nanogenerator based on lateral ZnO nanowire array", Nano Lett., 10 (2010) 3151–3155.*

# WHAT IS EH?

- **Energy Source Overview**
  - Fuel Cells (FC)

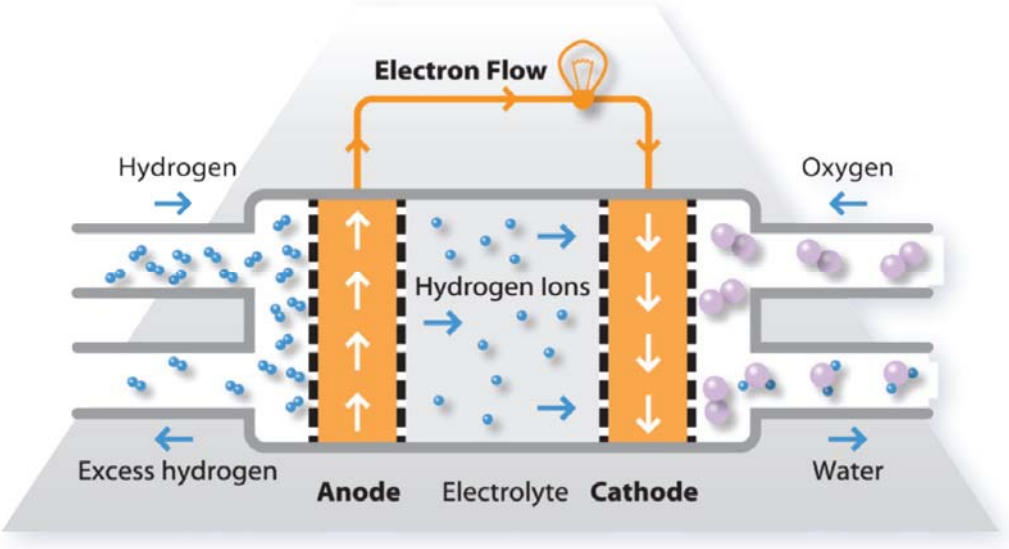



*IMAGE CREDIT: Fuel Cell Today, 2012. [Online]. Available: http://www.fuelcelltoday.com/media/1637138/fc_basics_technology_types.pdf. Accessed 11/6/17.*

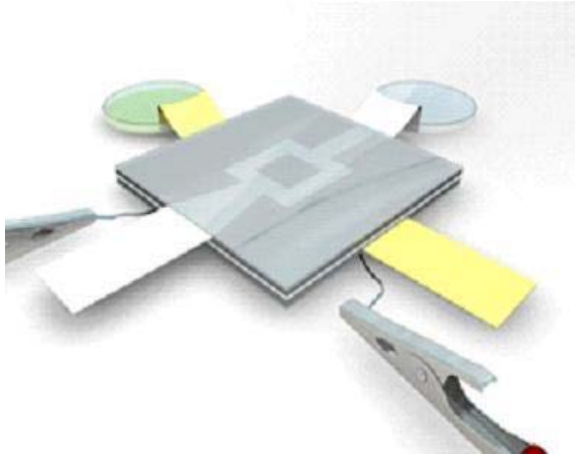


*IMAGE CREDIT: "Paper-based microbial fuel cell produces 1.3µW," EE Times, Posted 05 July 2016 = http://www.electronics-eetimes.com/news/paper-based-microbial-fuel-cell-produces-13mw*

# WHAT IS EH?

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

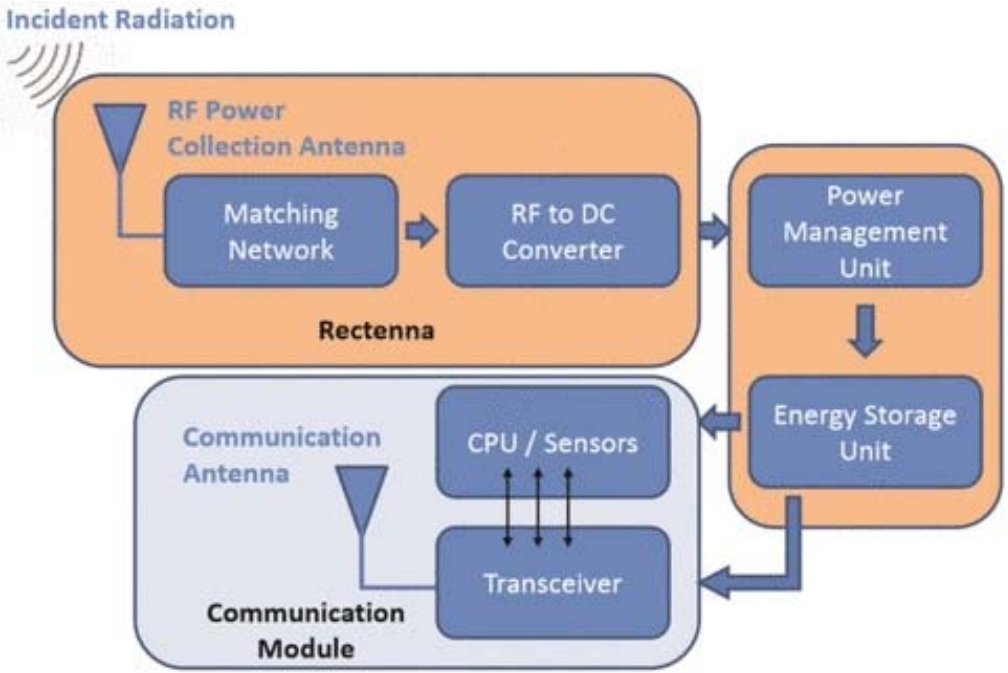



*IMAGE CREDIT: "Chair for Digital Transmission: Energy Harvesting Webpage," Institute for Digital Communications, Updated May 19, 2015.*

# 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.

*IMAGE CREDIT: "Powerharvester® Receivers," Powercast Marketing Brochure, Downloaded July 21, 2016.*

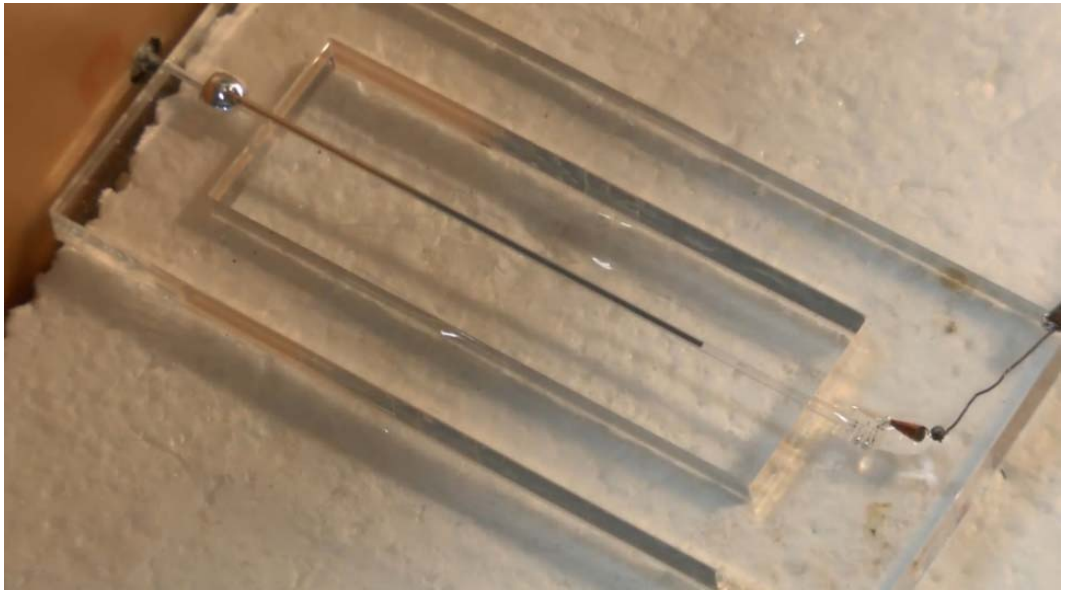


*IMAGE CREDIT:* David Schneider "Shape-shifting Liquid-Metal Antennas," IEEE Spectrum, Posted 21 Aug 2015.

# WHAT IS EH?

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

PMG perpetuum


Vibration Energy Harvester

**1. Performance**

**1.1. Power output**

| | Description | 5V Model | 8V Model |
|---|---|---|---|
| 1.1.1 | Maximum | 5.5 mA (27.5mW) | 3.0 mA (24mW) |
| 1.1.2 | Minimum @ 0.050g RMS, nominal frequency | 0.840 mA (4.2mW) | 0.525 mA (4.2mW) |
| 1.1.3 | Minimum @ 0.050g RMS, 2Hz bandwidth | 0.600 mA (3mW) | 0.375 mA (3mW) |
| 1.1.4 | Minimum @ 0.025g RMS, nominal frequency | 0.240mA (1.2mW) | 0.150mA (1.2mW) |

*IMAGE CREDIT: "Vibration Energy Harvesters," Perpetuum Datasheet, Downloaded October 10, 2017.*

# WHAT IS EH?

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

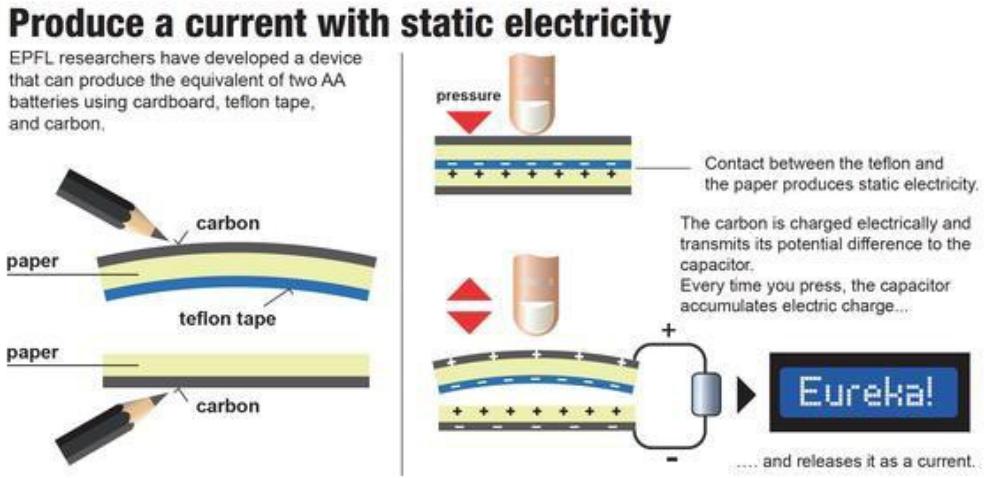



*IMAGE CREDIT: R. Colin Johnson, "Create a Cardboard Energy Harvester," EE Times, Jan 26, 2016.*

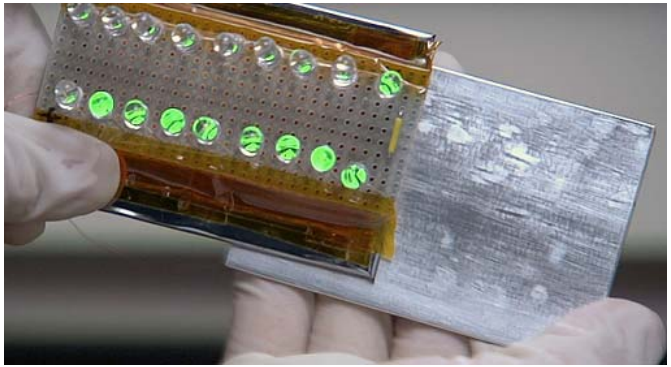


*IMAGE CREDIT: Inertia Films*

# WHAT IS EH?

- **Energy Source Overview**
  - Hybrid Solutions
    - Capture Multiple Energy Sources Concurrently

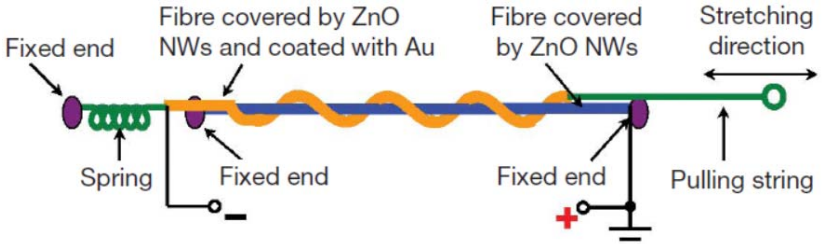



*IMAGE CREDIT: Yong Qin, Xudong Wang and Zhong Lin Wang, "Microfibre–nanowire hybrid structure for energy scavenging", Nature, 451 (2008) 809-813.*

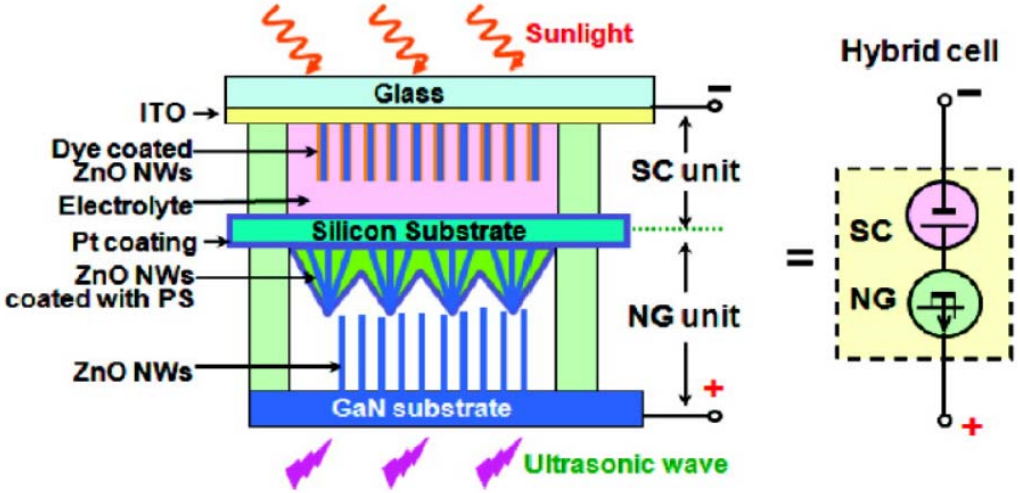



*IMAGE CREDIT: Chen Xu, Xudong Wang and Zhong Lin Wang, "Nanowire Structured Hybrid Cell for Concurrently Scavenging Solar and Mechanical Energies", J. Am. Chem. Soc., 131(2009) 5866-5872.*

# 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

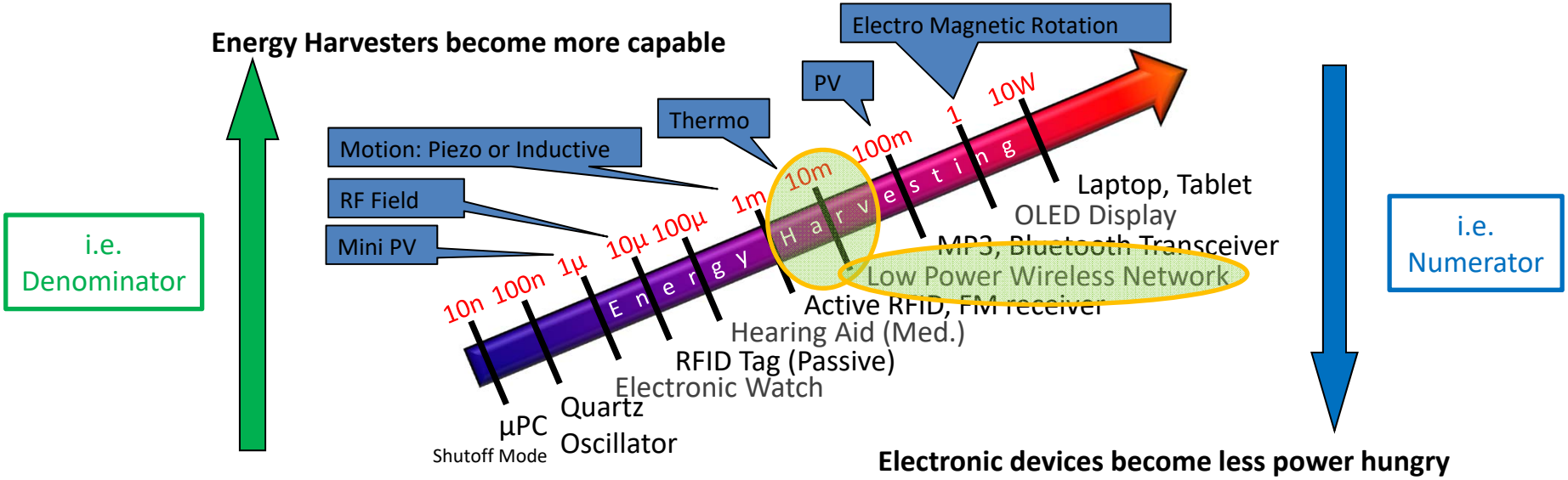



*IMAGE CREDIT: Lorandt Foelkel, "Energy Harvesting Seminar," Wurth Elektronik eiSos, 2013.*

# 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

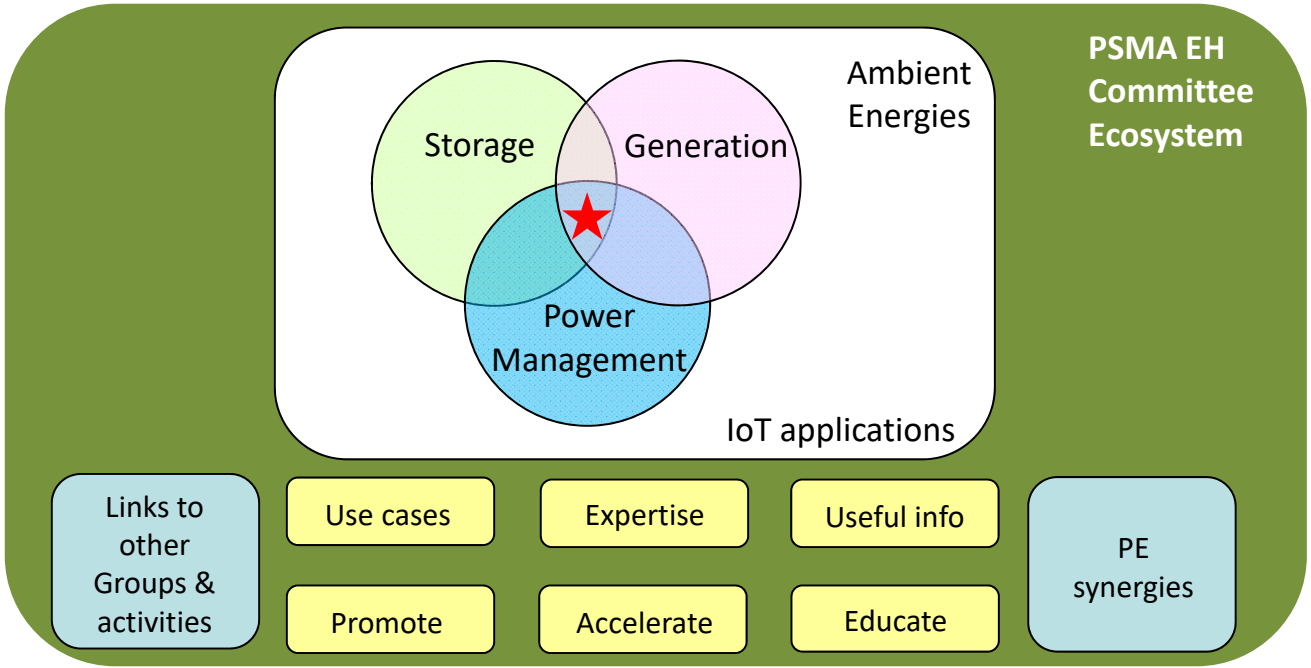



*IMAGE CREDIT: Mike Hayes, "Synergies between Energy Harvesting and Power Electronics," Tyndall National Institute, IEEE PELS Young Professionals Webinar, October 20, 2016.*

# 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*

EnerHarv 2018

# WHAT IS EH?

- **Ecosystem**
  - 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)


*IMAGE CREDIT: PowerFilm LightSaver Max. [Online]. Available: https://www.powerfilmlightsaver.com/lightsaver-max. Accessed 1/29/18.*

# 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
      - $I_Q$ = 325nA
      - Multiple EH source & storage support
      - Includes power conversion/regulation!

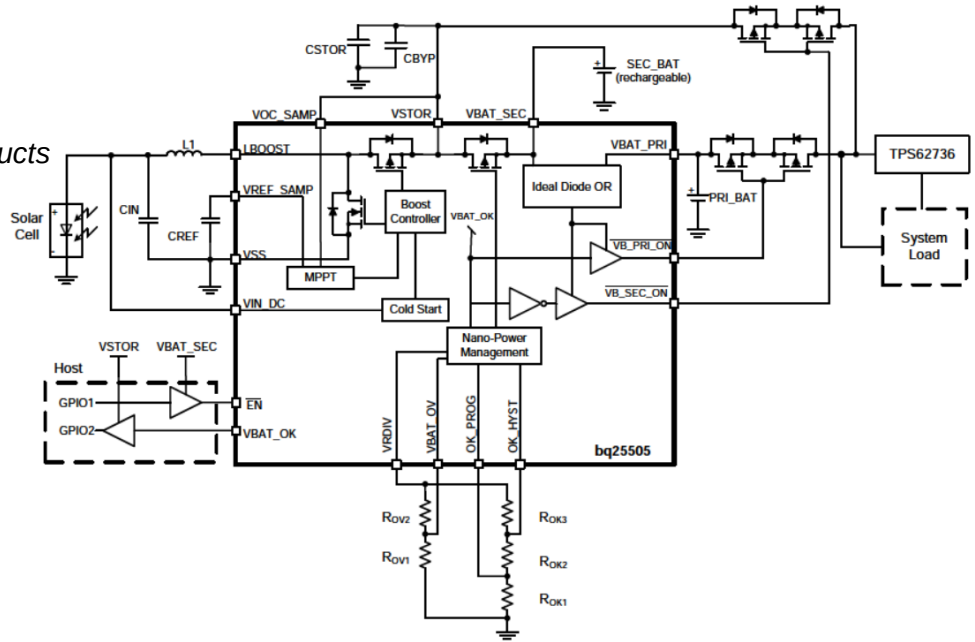



*IMAGE CREDIT: "bq25505," Texas Instruments Data Sheet, Downloaded July 20, 2016.*

# 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

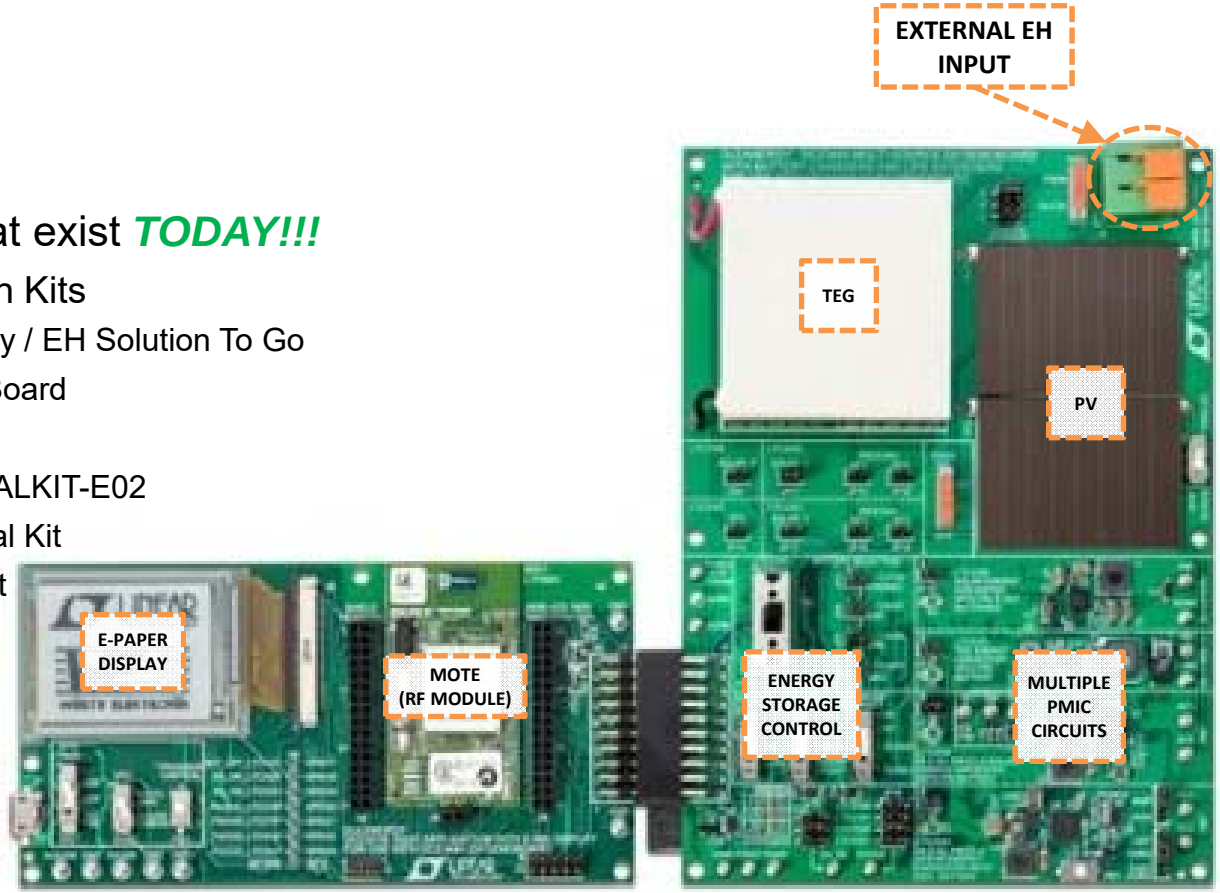



*IMAGE CREDIT: Würth Elektronik Gleanergy = http://www.we-online.com/web/en/electronic_components/produkte_pb/demoboards/gleanergy/gleanergy.php*

# WHAT IS EH?

- **Ecosystem**
  - Industry Consortiums / 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 Consortiums / 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

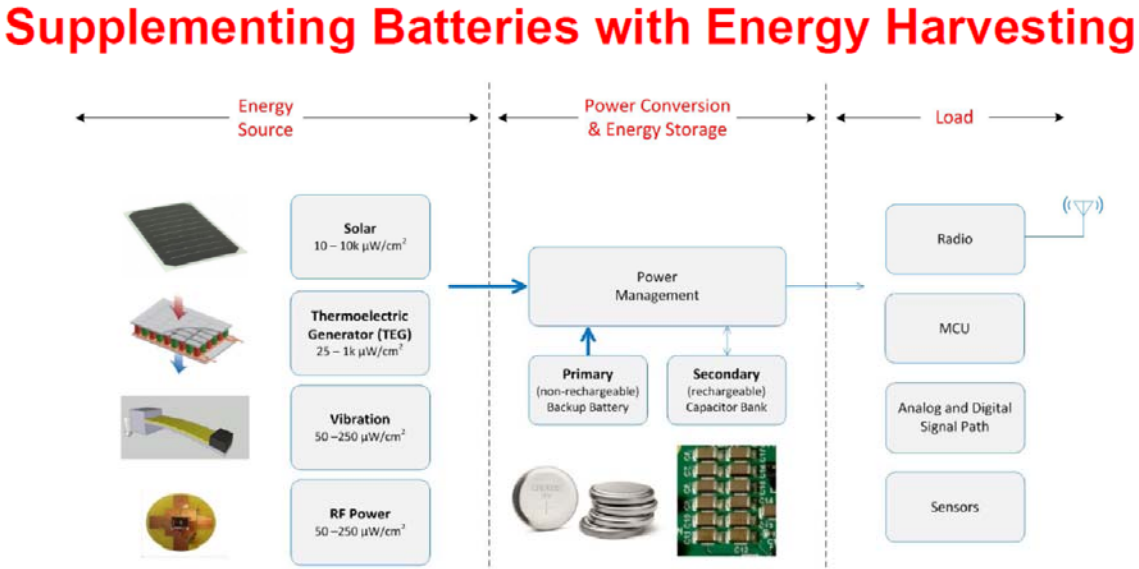



*IMAGE CREDIT: A. Singh, "IoT - Power Challenge - How low can we go?," Texas Instruments, APEC 2017 Industry Session, Tampa, FL, March 30, 2017.*

# APPLYING EH TO ULP APPLICATIONS

- **Matching the EH to the Load**

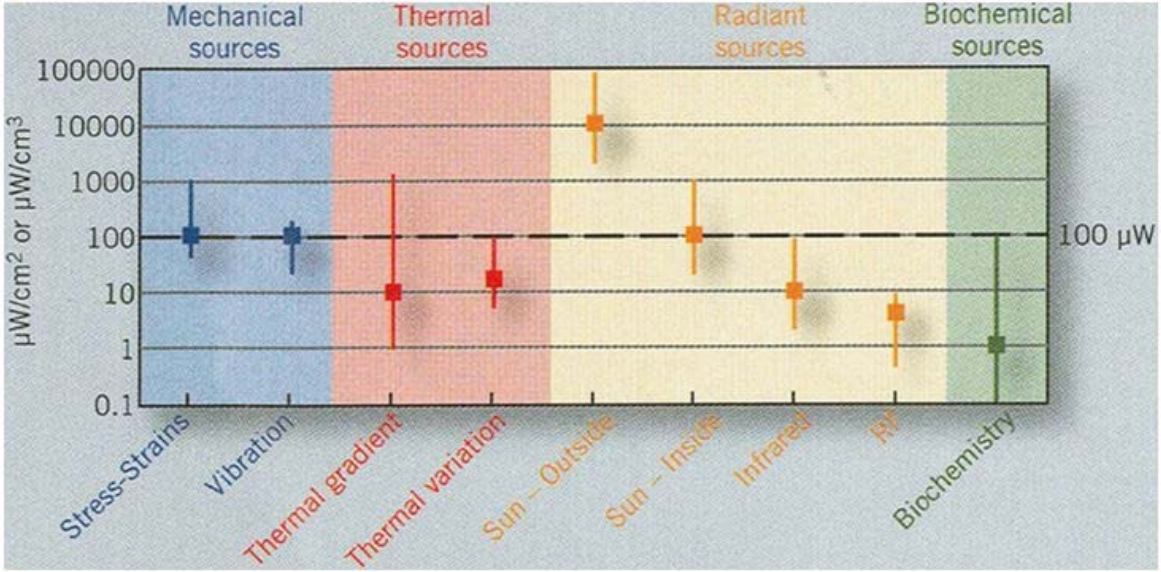



*Figure 2: A comparison of ambient energy sources (before conversion). (Data source: CEA-Leti; graphic source: Linear Technology; used by permission)*

*IMAGE CREDIT: Joshua Israelsohn, "Harvesting and scavenging ambient energy," ECN, July 14, 2015.*

# APPLYING EH TO ULP APPLICATIONS

| EH TECH | Base Station (BS) | Data Center | Smartphones | IIoT | Mobile (on-the-fly) Charging | Wireless Sensor Network (WSN) | Automotive / V2V | IoT |
|---|---|---|---|---|---|---|---|---|
| Dynamic | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| PV | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| TEG | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| PZ | ✓ | | ✓ | ✓ | | ✓ | | ✓ |
| FC | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ |
| RF | | | ✓ | ✓ | | ✓ | | ✓ |
| Vibe | | | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Tribo | | ✓ | ✓ | | | ✓ | | ✓ |

# 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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