Breakthrough Technologies Driving Successful Energy Harvesting-Powered Products

March 18, 2014

APEC 2014 Industry Session Presented by:

PSMA Energy Harvesting Forum

Energy Harvesting Info & Resources for the Power Electronics Industry

Breakthrough Technologies for EH Success

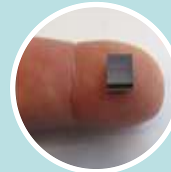
- Identify key trends and market forces driving the need for Energy Harvesting-based power
- The economics behind Energy Harvesting
- Diagram the system architecture of an EH-based system – networked or stand-alone
- What are the high level design considerations
- Energy Harvesting technologies that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

The Key Trends Driving Innovation for Internet of Everything and Wearable Tech

Ultra Low Power Processors & Electronics

Smart Devices and Sensors Everywhere

Wireless is pervasive



Integration with other components

Miniaturization

Eco-Friendly and Renewable Energy

Convergence of Trends into Products

- 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 Efficient and Cost-Effective Powering solutions needed

Introducing Energy Harvesting:

Life of Product Energy Generation and Storage…

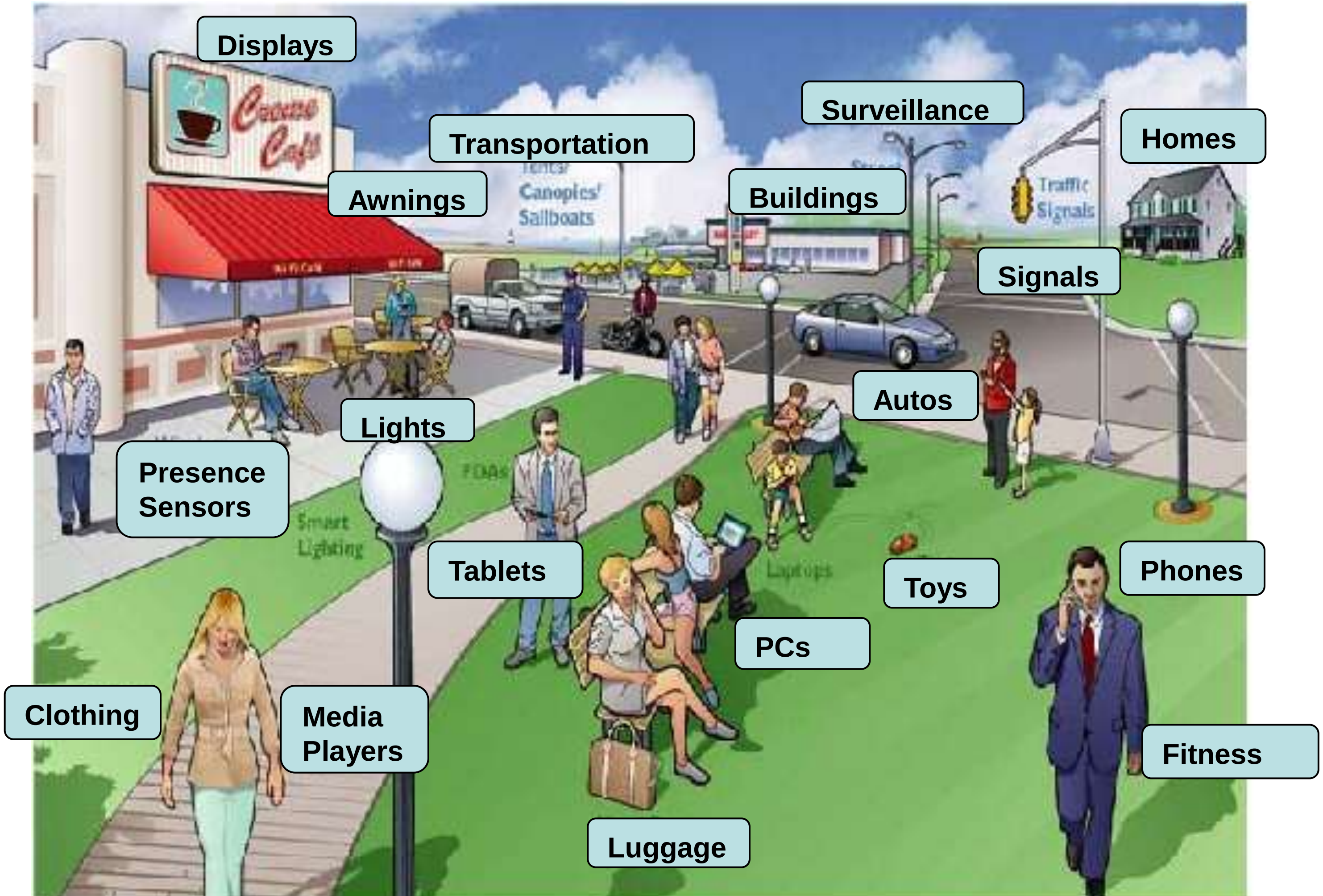
- Energy can be harvested from almost any environment:
  - Light, vibration, flow, motion, pressure, magnetic fields, RF, etc.

- 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

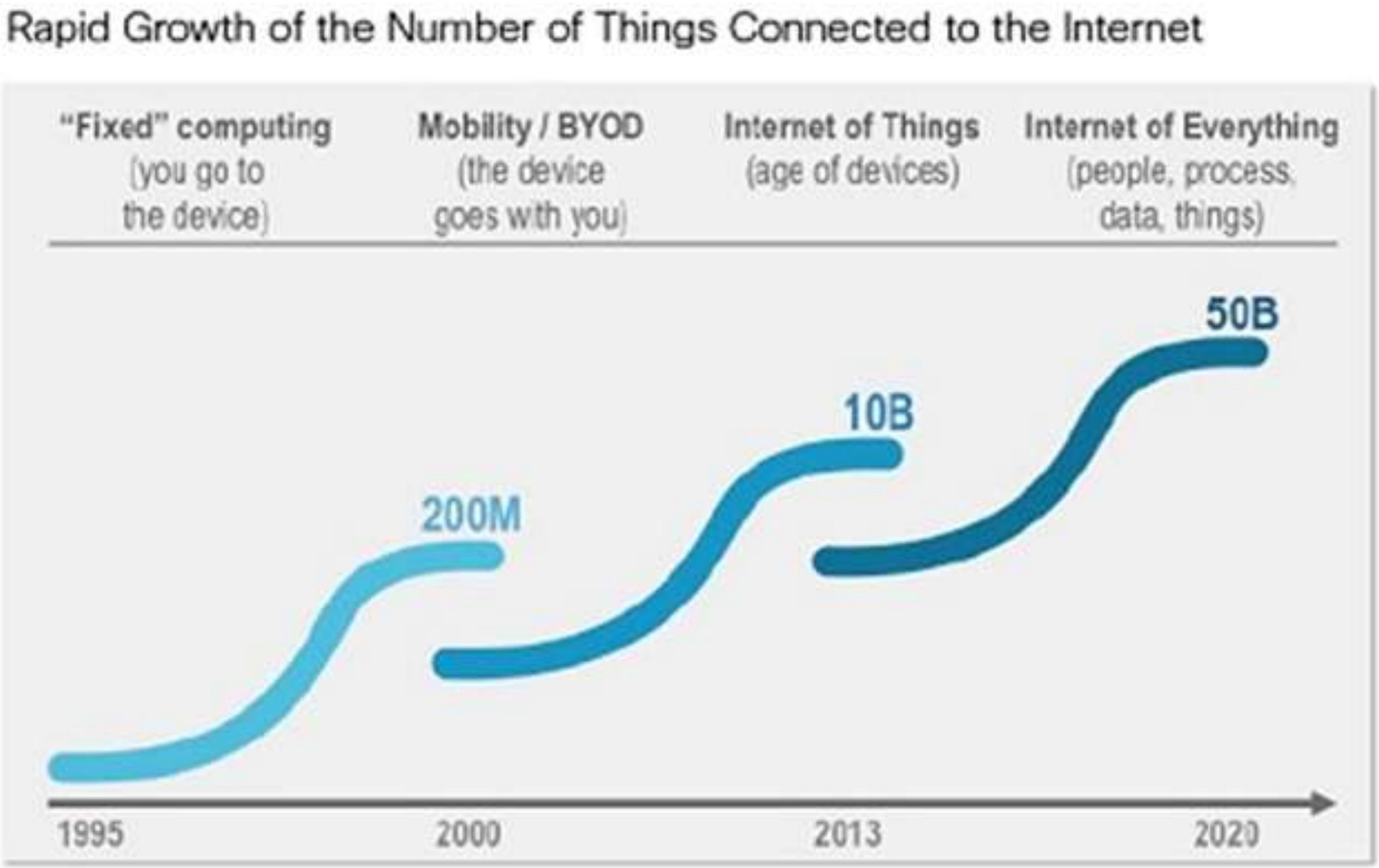
EH Powering The “Internet Of Everything”



Source Konarka

25 Years of Evolution:

Fixed Computing to Internet of Everything



Source: Cisco

Financial Benefits Drive IoE Business Case

- **Better use of assets** –Businesses track, sell and manage processes more effectively,
- **Improved employee productivity** – Smart environments drive productivity
- **More efficient supply chains and logistics** – Less waste, theft, spoilage and processes cost reductions
- **Happier customers** – By improving customer experiences companies will increase loyalty and sales
- **Accelerating profitable innovation** – Smarter, more plugged-in businesses can launch successful new products more quickly and enjoy improved returns on their investments in R&D
- Total value of IoE benefits over the next 10 years = **$ 17.7 Billion**

HP, IBM, Google, Cisco, et al…

Giving the Planet a Voice with Sensors

HP CeNSE Project

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

IBM Smarter Planet

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

"The Internet of Everything builds on the Internet of Things by adding network intelligence and security that allows convergence, orchestration and visibility across disparate systems.

Who's going to change 1 Trillion Batteries????!

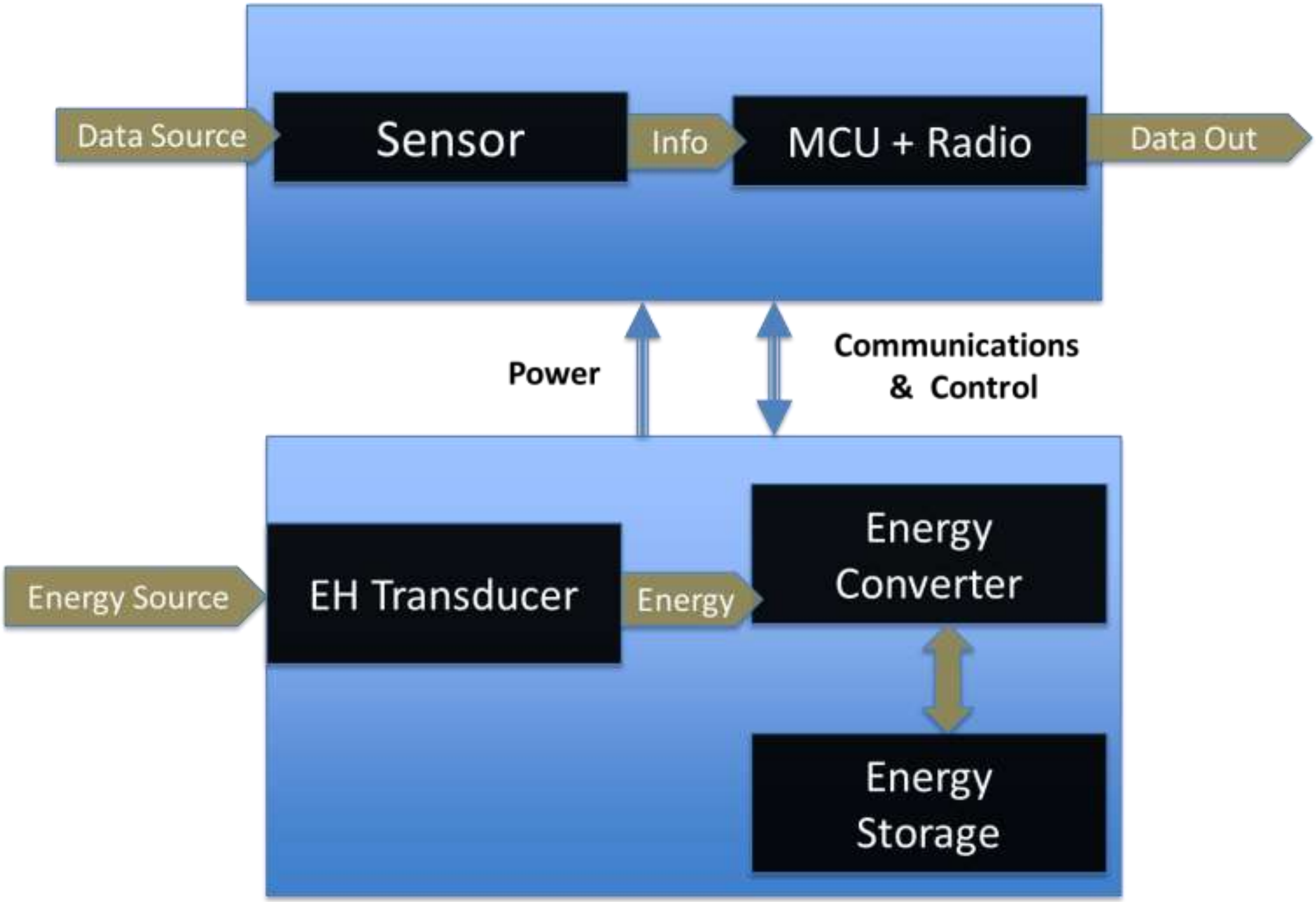
Wearable Tech Market

The Consumer is increasingly resisting electronic "gadgets" that do not add value. To be successful, wearables need to be an invisible "Part of Life"

- ***ABI Research***
  - ✓ By 2016, wearable wireless medical device sales will reach more than ***100 million devices*** annually
  - ✓ The market for wearable sports and fitness-related monitoring devices is projected to grow to **80 million device** sales by 2016
- ***IMS Research***
  - ✓ Devices worn on or close to the body are expected to produce the most ground-breaking innovations. The market for **wearable technologies in healthcare is projected to exceed $2.9** billion in 2016, accounting for at **least half of all wearable technology** sales
- ***BCC Research***
  - ✓ Micro-sensors – Micro Electro Mechanical Systems (MEMS), biochips, and nanosensors - are one of the fastest-growing technology markets due to advantages such as compact size, reduced-power consumption, lower cost, and increased reliability. Reports
  - ✓ The global micro-sensors market was valued at $8.5 billion in 2012 , $9.5 billion in 2013 and is projected to be **$15.8 billion in 2018**, (10.7% CAGR)

Energy Harvesting will be used to power highly integrated wearable systems

EH-Powered Wireless Sensor Block Diagram



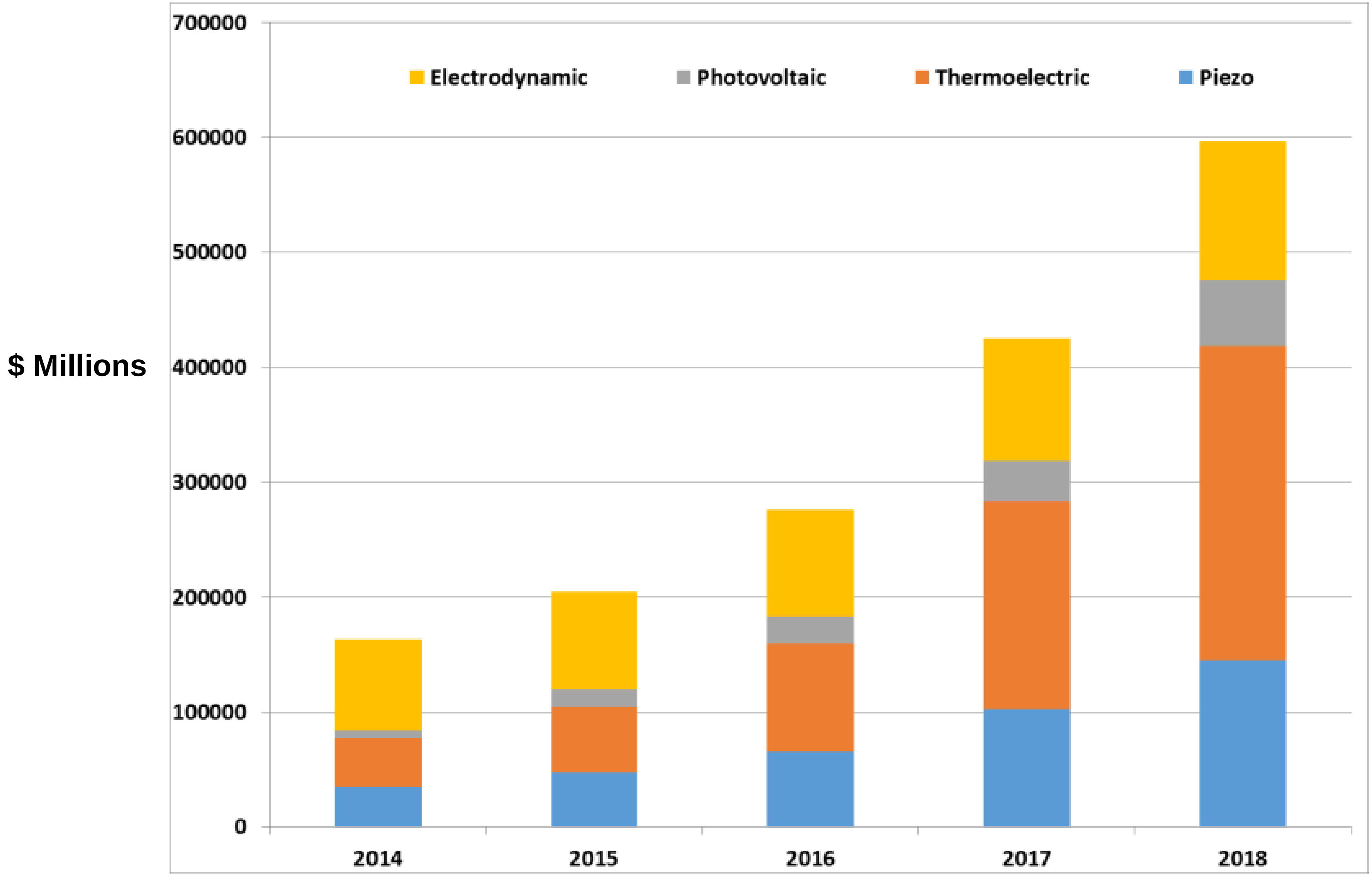
Energy Harvesting Transducers

What Ambient Energy is Available?

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

Designs must deal with different: Impedance, Voltages, Output power, etc.

Energy Harvesting Market Forecast by Transducer



Source: IDTechEx

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 Quantity from Distributors:
  - 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
  - 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)

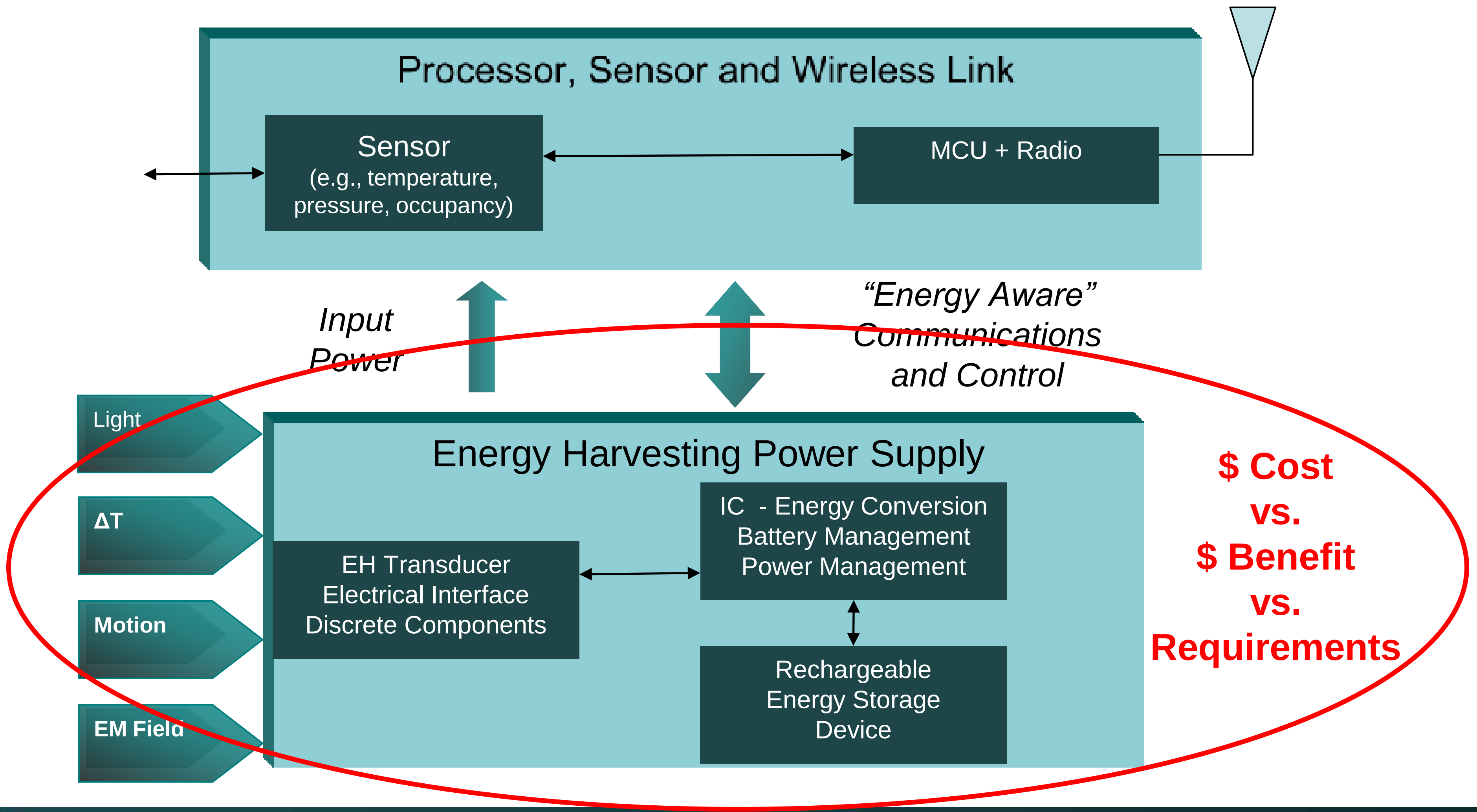
- **Example:** Simple Solar Energy Harvester at 400Lux with 24/7 operation
  - Sanyo AM1815 4.9V solar cell $4.39 (1K pcs) output is 294uW
  - Assume simple conversion electronic components for $1.25
  - 294uW/3.3V = 89microAmps output from Solar Harvester
  - Total capacity over 10 year 24/7 life = 7796 mAh
  - $/mAh for Solar EH = $0.0013/mAh. 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

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

EH Power System Cost vs. Benefit



4 Key Considerations for EH Designs

1. Determine energy available from your environment
   - Light, Temperature Gradient, Vibration, Motion, Flow, Electromagnetic
   - Must characterize the energy source – amount, variability over lifetime
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 design to fit available input EH power
   - Must use sleep modes of components whenever possible
   - Write Energy- Aware code -> Interrupts, no polling loops, check Vcc before running, understand input power and storage conditions
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!

Industry is Providing Cost Effective Sensor Building Blocks

- Low Power Microprocessors with nanoAmp sleep currents.
- Low Power Radio Transceivers:
  - IEEE 802.15.4 standards – sub-Gigahertz or 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 IEC Standard
  - IPv6 6LoWPAN
- Micropower Sensors with low sleep currents:
  - Passive IR, Temp, Humidity, Acceleration, Pressure, etc.
- Lower quiescent current peripheral circuits:
  - Clocks, power management chips, etc.

INDUSTRY TRENDS AND CURRENT SOLUTIONS ARE MISALIGNED

TREND: GROWTH OF ELECTRONIC DEVICES THAT ARE SMALLER, PORTABLE, CONNECTED

Ultra-Low Power Processors

Wireless Smart Devices & Sensors Everywhere

Component Integration and Miniaturization

Eco-Friendly and Renewable Energy

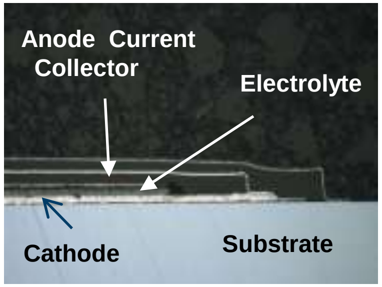
Key Trends Driving Billions of New Devices

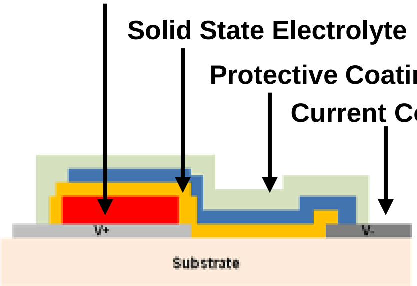
CURRENT ENERGY STORAGE SOLUTIONS ARE INADEQUATE

- LARGER PROFILE / BULKY SIZE
- LOW ENERGY FOR SPACE USED
- INTEGRATION ISSUES
- HIGH WEAR-OUT AND FAILURE ISSUES
- TOXIC CHEMICALS – SAFETY AND DISPOSAL ISSUES

Solid State Batteries

EnerChip Co-packaged
Solid State Battery & PMU

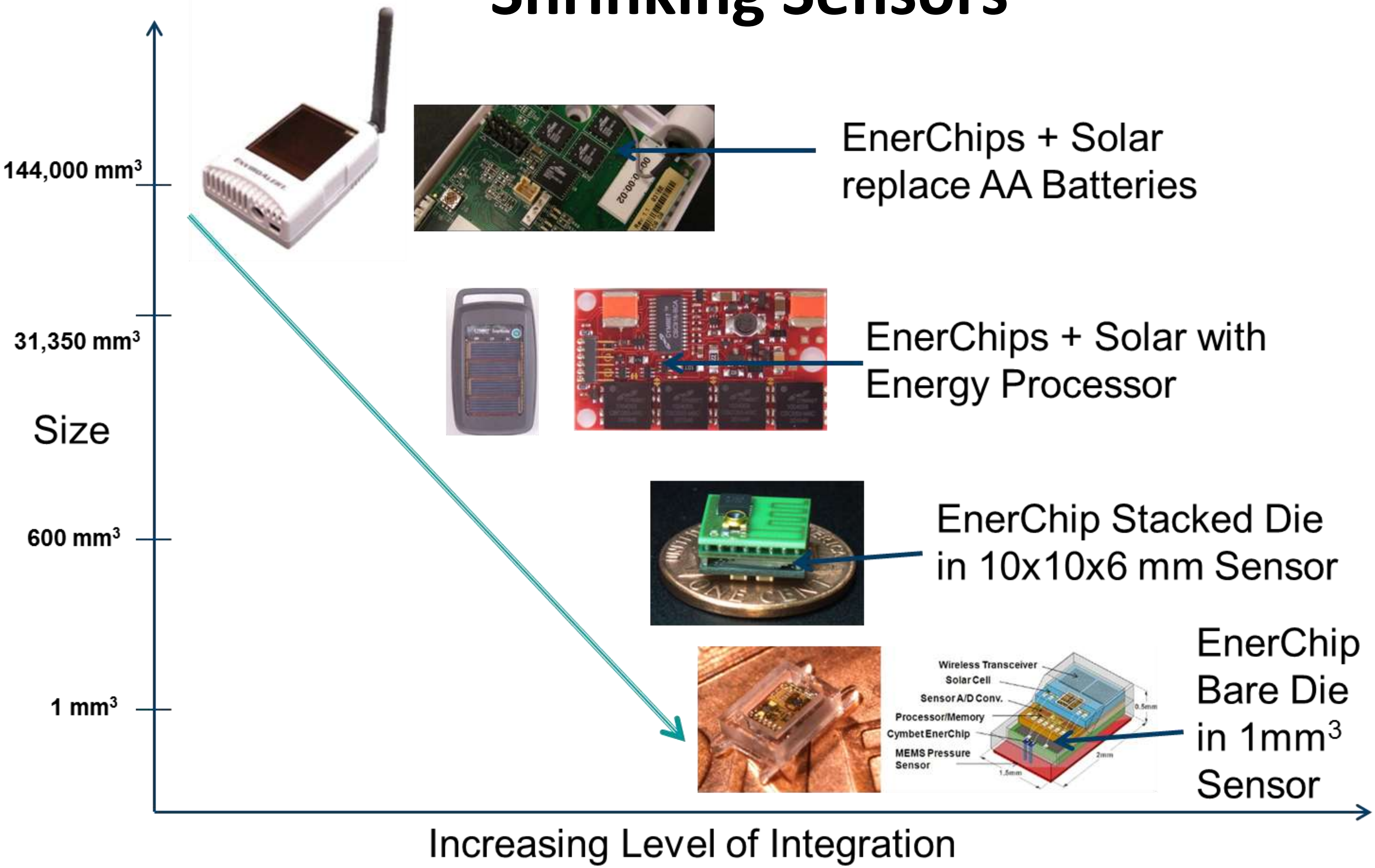




Key Features:

- **Manufactured with standard silicon CMOS-type processes.**
  - ✓ **Small Chip-scale footprint - bare die or packaged parts - 150 microns thick**
  - ✓ **Thousands of Recharge cycles – "life of product"**
  - ✓ **Fast recharge – 80% in 10 minutes**
  - ✓ **Ultra-low self-discharge + flat discharge profile - Uniquely suited to Energy Harvesting**
  - ✓ **Reflow tolerant for low cost automated assembly SMT - >360^{0}C**
  - ✓ **Completely Eco-Friendly; No heavy metals, liquids, binders, etc**
  - ✓ **As a silicon-based device, can be co-packaged or embedded with other silicon devices such as MCUs, RTC, etc – "Packaged Power" – Coin cell and caps cannot be used in these configurations**

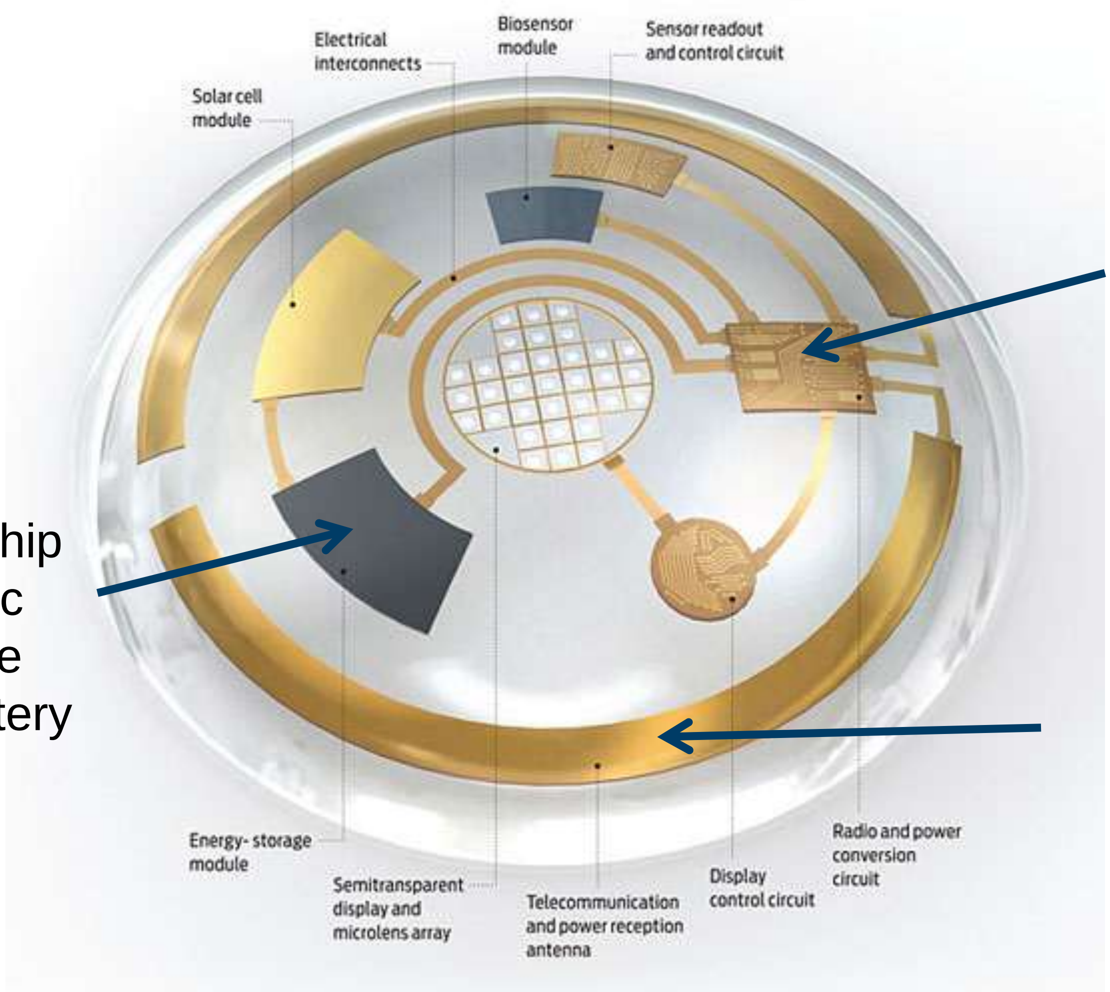
Shrinking Sensors



CYMBET™ CORPORATION

Bluetooth Smart Wearables Scale Faster

Example of Wireless EH-Powered Smart Contact Lens Concept



Ultra Low Power Management IC Designs Integrated with MCU and Radio

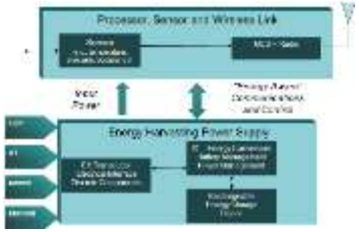
Cymbet EnerChip Non-Cytotoxic Rechargeable Solid State Battery

Wireless Communication to Smartphone and Wireless Charging

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. EH Market Requirements, Economics, Drivers
   Steve Grady – Cymbet
2. Advancements in Energy Harvesting Transducers
   Henrik Zessin – Fraunhofer Institute
3. Small Footprint High Efficiency Designs for Energy Conversion
   Brian Shaffer – Linear Technology
4. New Ultra-low Power Sensor Devices and Control Mechanisms
   Roman Budek - NXP
5. Sub-microamp MCUs and Wireless transceivers and protocols
   Mark Buccini – Texas Instruments
6. Successful Commercial Energy Harvesting Deployments
   Harry Zervos – IDTechEX
7. Audience Questions and Table Top Demo Explanations
   Speakers Roundtable

Session Chair – Arnold Alderman – Anagenesis