Forging Ahead: Global Commercialization of Energy Harvesting Technology

March 19, 2013

APEC 2013 Industry Session Presented by:

PSMA Energy Harvesting Forum

Energy Harvesting Info & Resources for the Power Electronics Industry

Commercialization of EH Technologies

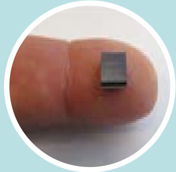
- Identify key trends and market forces driving the need for Energy Harvesting-based power
- The economics behind Energy Harvesting
- Diagram the system architecture of an EH-based system – networked or stand-alone
- What are the high level design considerations
- Energy Harvesting technology that enables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

Key Trends Driving Innovation

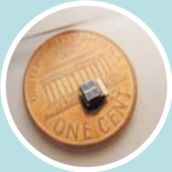
Ultra Low Power Processors & Electronics

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 Powering solutions are required

Introducing Energy Harvesting:

Life of Product Energy Generation and Storage…

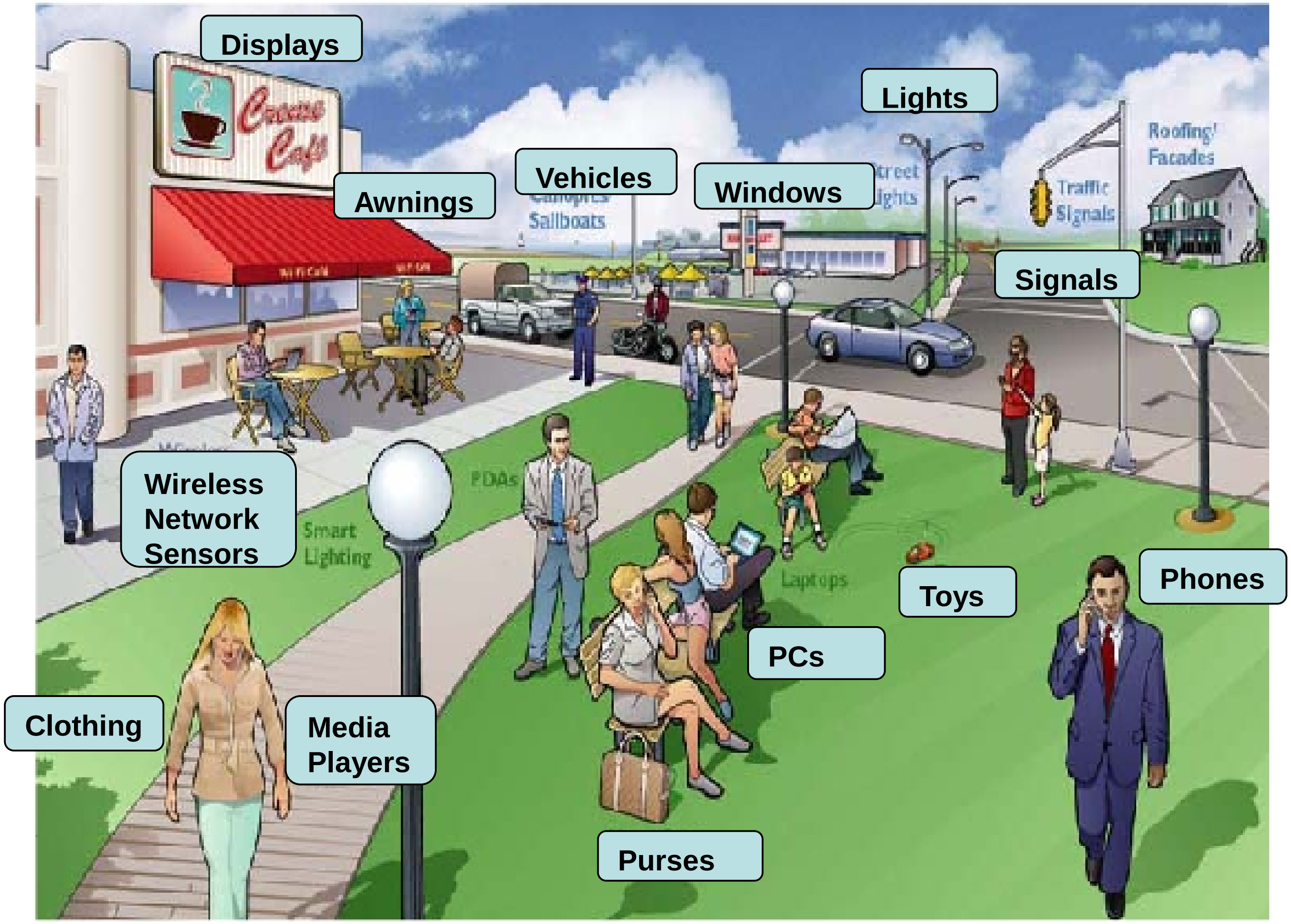
- Energy can be harvested from almost any environment:
  - Light, vibration, flow, motion, pressure, magnetic fields, RF, etc.

- 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"



Source Konarka

HP CeNSE, IBM Smarter Planet

Giving the Planet a Voice with Sensors

CeNSE

Central Nervous System for the Earth

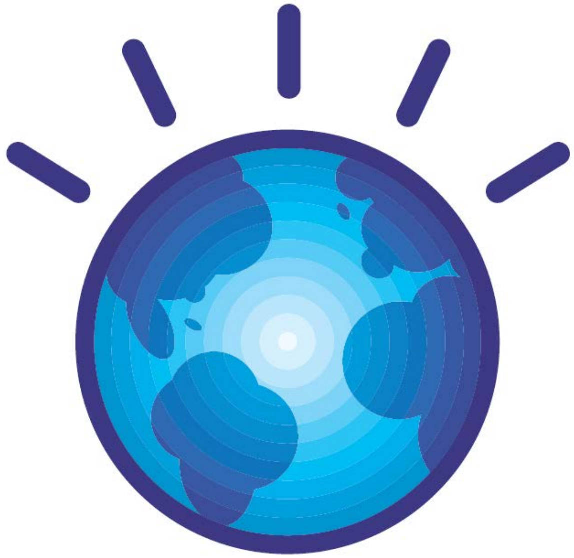
– Awareness of planet
– Measurement of impact
– Taste/Smell/Touch/Sound/Sight

– Safety
– Sustainability
– Security

~1 trillion sensor network

Quantity of data creates quality of data

IBM Smarter Planet

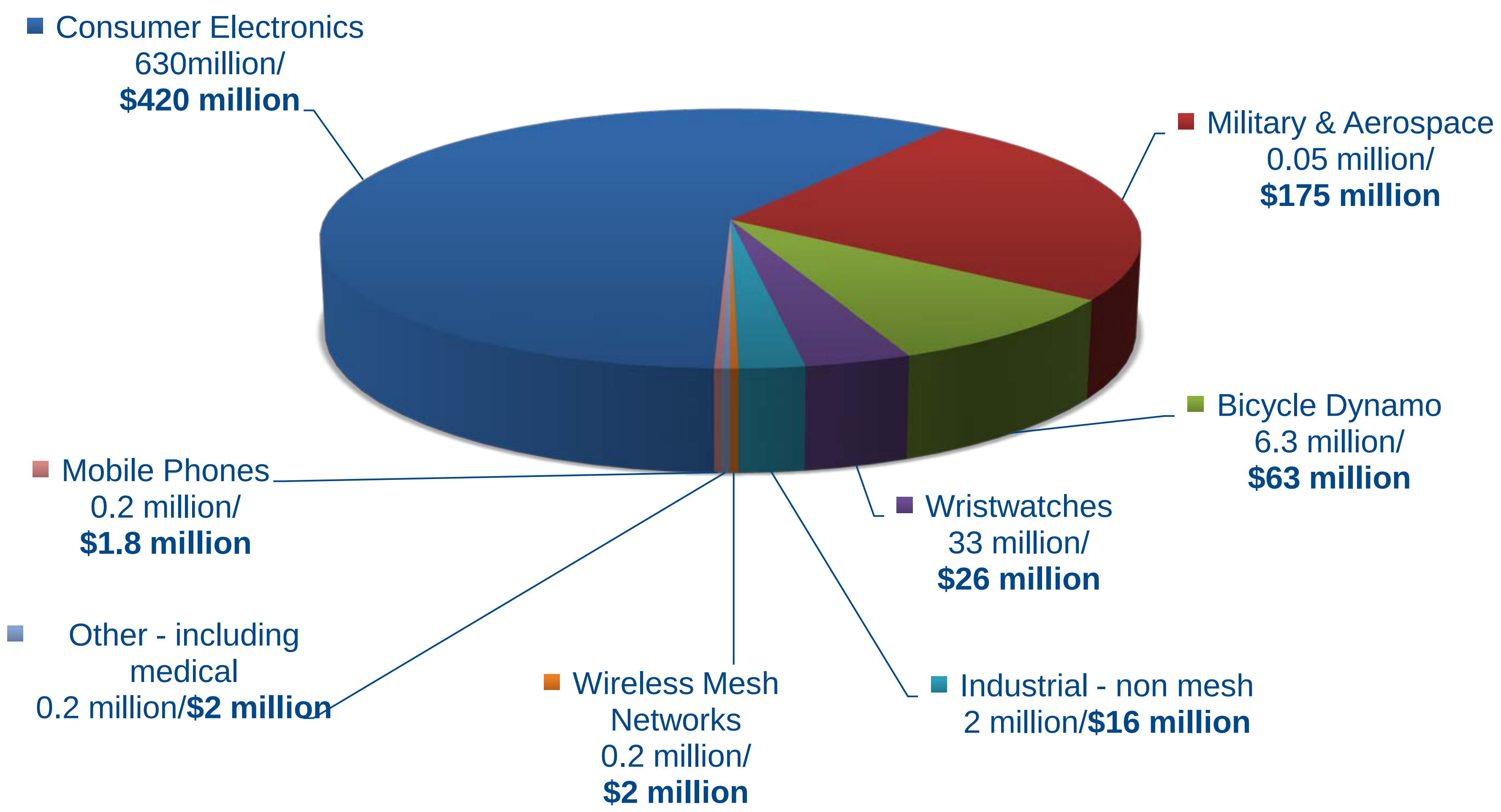


"Trillions of digital devices connected to the Internet, are producing a vast ocean of data…"

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

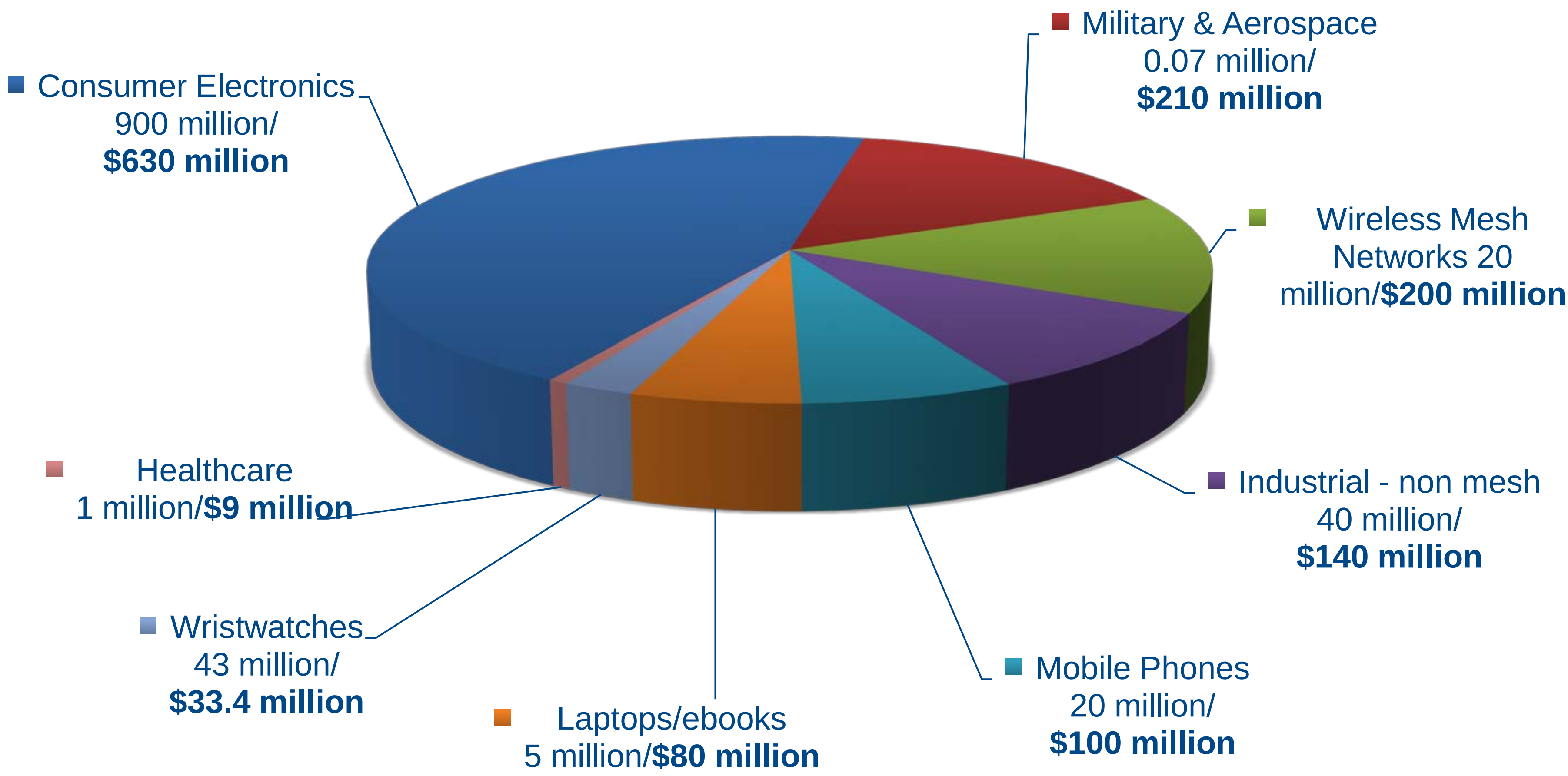
Energy Harvesting Market in 2012 $0.7Bn

Source: IDTechEx Energy Harvesting Report

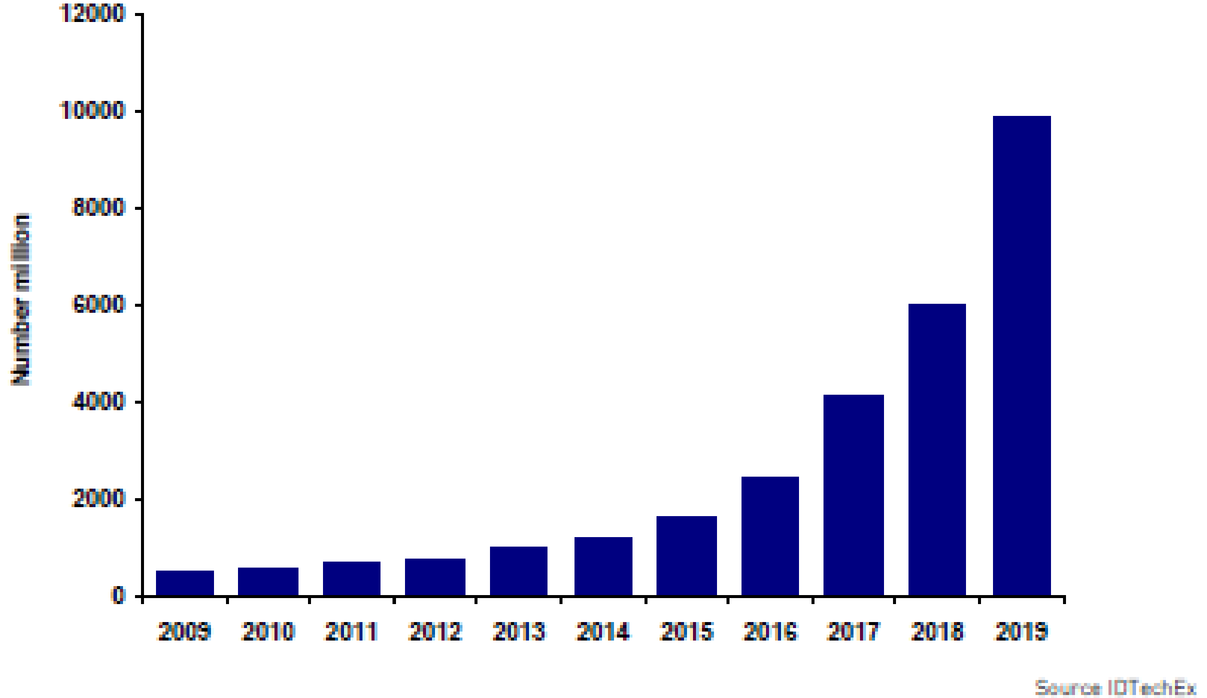


Energy Harvesting Market in 2017 $1.5Bn

Source: IDTechEx Energy Harvesting Report



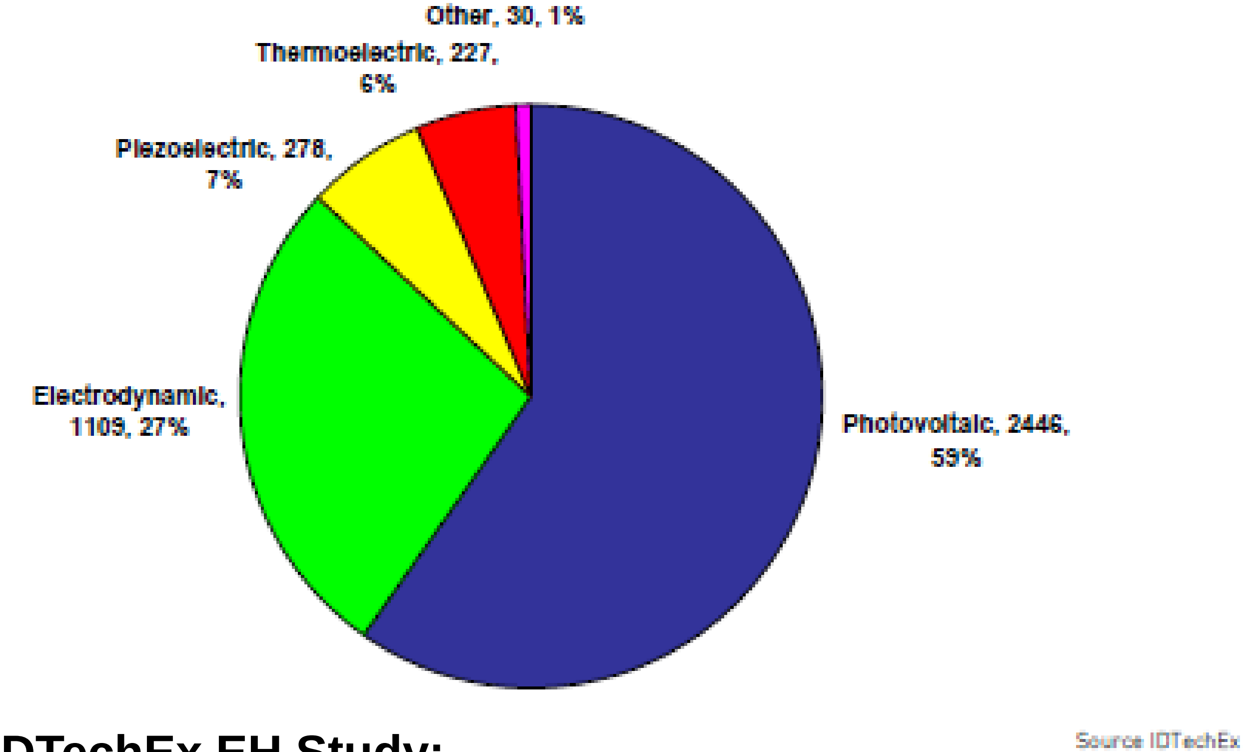
Energy Harvesting Market Forecasts



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**

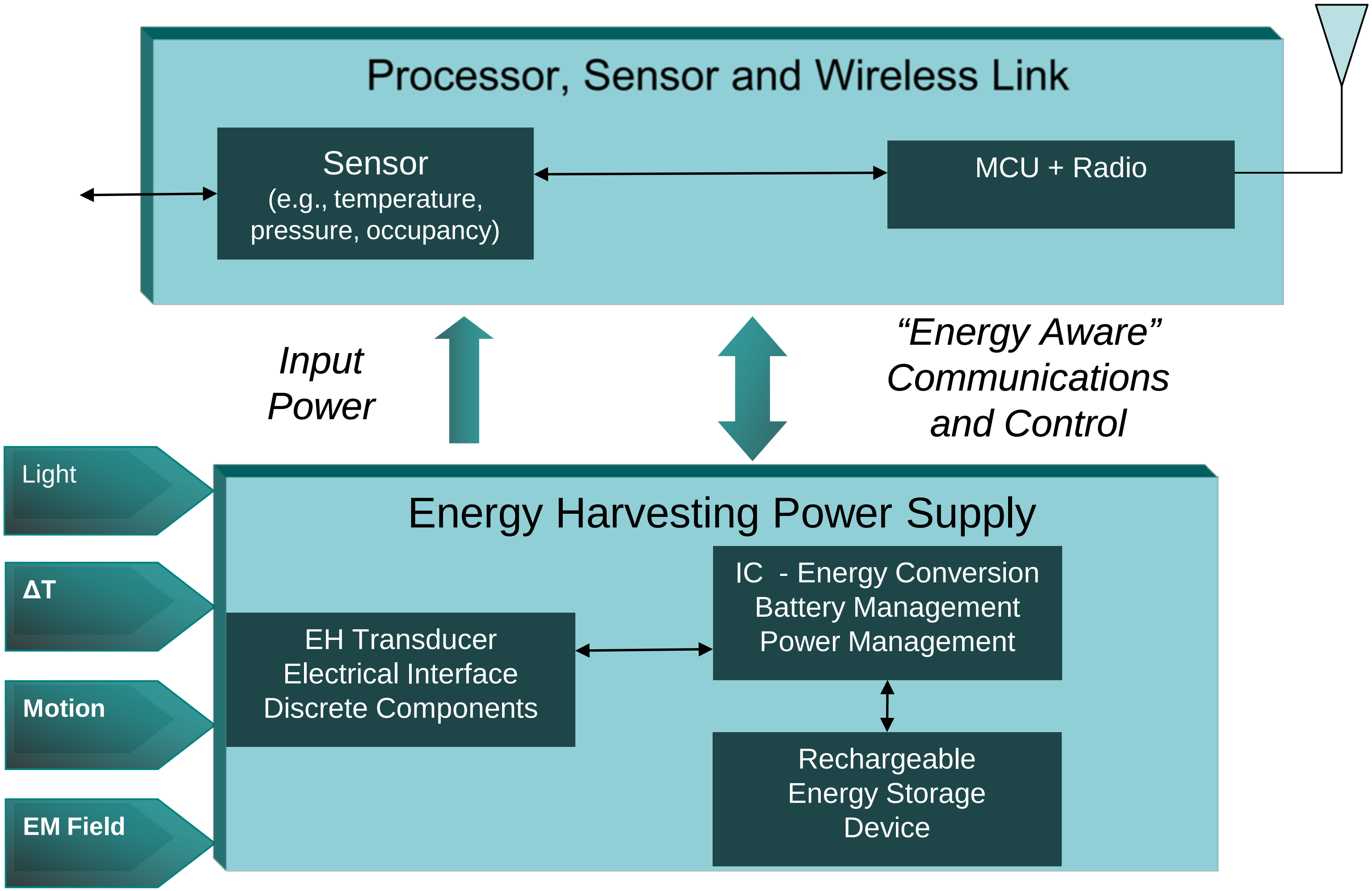
Total Market Value by EH Technology 2019



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



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/mm^3 - 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

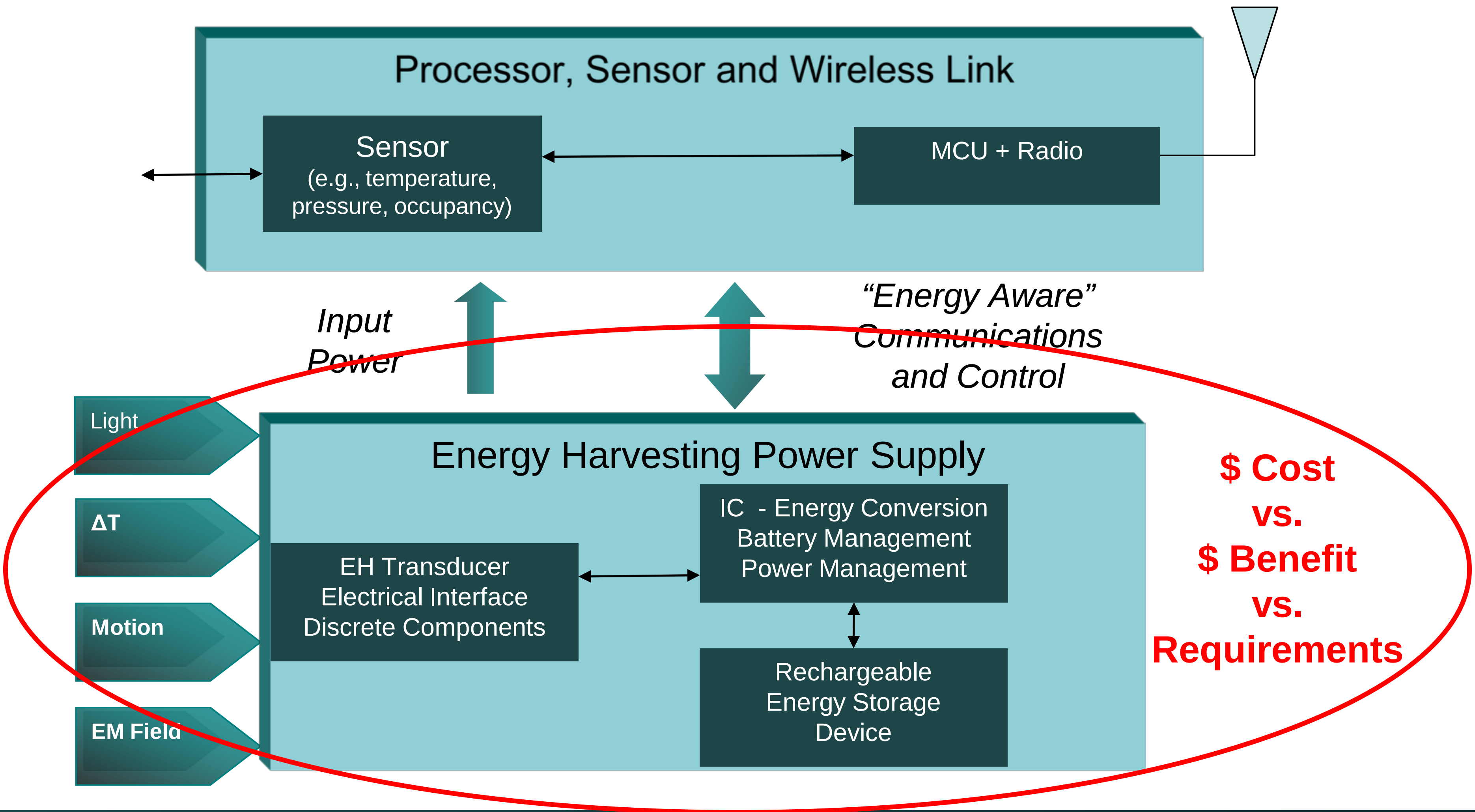
Energy Harvesting Transducers

What Ambient Energy is Available?

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.

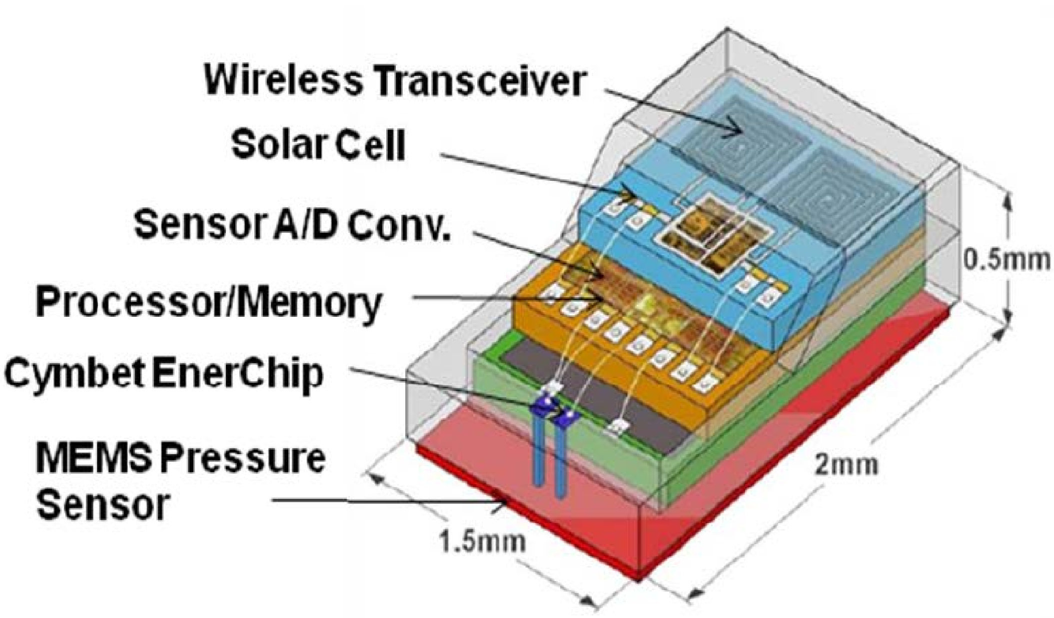
EH Power System Cost vs. Benefit

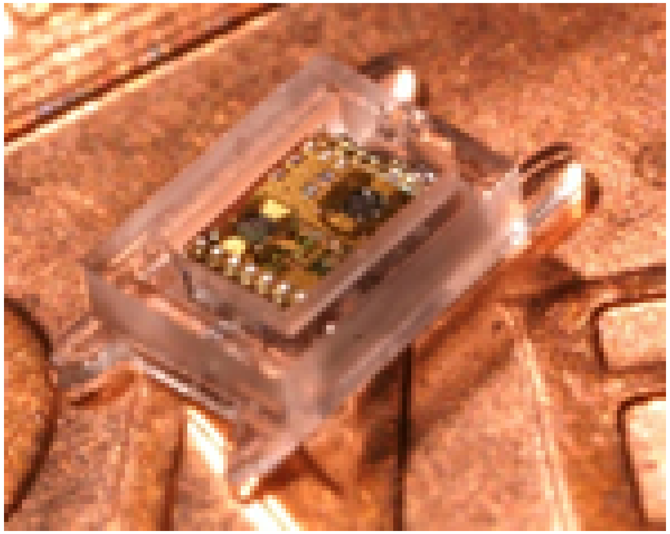


Industry is Providing Cost Effective Sensor Building Blocks

- 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



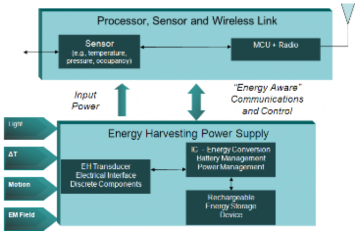


University of Michigan ISSCC Paper: ***http://www.cymbet.com/design-center/wireless-sensors.php***

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