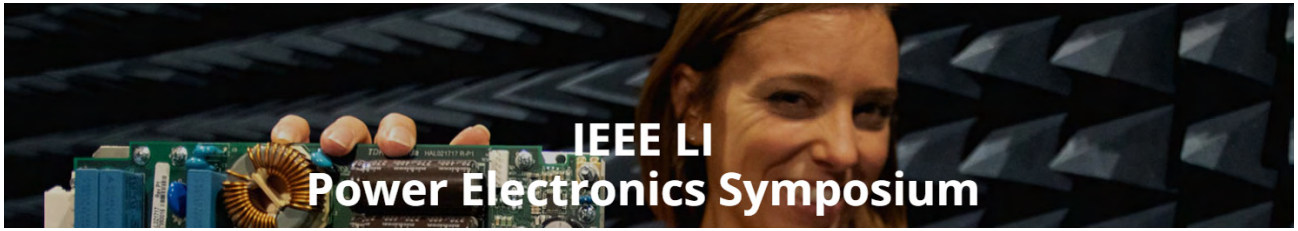

PowerRox™

LECTURE #2B:
Enabling the IoT / IIoT with Energy Harvesting

Thursday, November 3, 2022

Brian Zahnstecher, Principal, IEEE Senior Member

Chair [Emeritus], *SF Bay IEEE Power Electronics Society (PELS)*
Chair [Emeritus], *PELS Technical Committee (TC) 7*
Regional Chair*, IEEE PELS Regions 1-3*
Board of Directors*, Power Sources Manufacturers Association (PSMA)*
Co-chair*, PSMA Energy Harvesting Committee*
Co-founder/Co-chair*, EnerHarv Workshop*
Chair [Emeritus]*, PSMA Reliability Committee*
Co-chair*, IEEE 5G Initiative Roadmap, Energy Efficiency WG*
Co-chair*, IEEE Future Networks Initiative (FNI) Webinar Series*
Co-chair*, IEEE 5G Energy Efficiency Tutorial*

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Food for Thought

the ONION HOME LATEST NEWS LOCAL ENTERTAINMENT POLITICS SPORTS OPINION VIDEO

NEWS IN BRIEF

New Department Of Energy Program Incentivizes Pedestrians, Cyclists To Switch To Electric Vehicles

| Today 7:00AM | Alerts

WASHINGTON—In keeping with its mission to address the nation's environmental challenges, the Department of Energy introduced a new program Monday that provides pedestrians and cyclists with economic incentives to switch to electric vehicles. "As the effects of climate change worsen, we can no longer rely upon technologies as outdated as a bicycle or our own two feet," said Energy Secretary Jennifer M. Granholm, explaining that the plan provides tax credits to those make the switch to a Chevrolet Bolt, Tesla, or other EV prior to the department's proposed elimination of all bike lanes and sidewalks in 2028. "We simply cannot stay stuck in the past—biking to work or walking our kids to

Red Cross Unveils

Here's The Perfect Tri To Post Whenever The Kid Dies

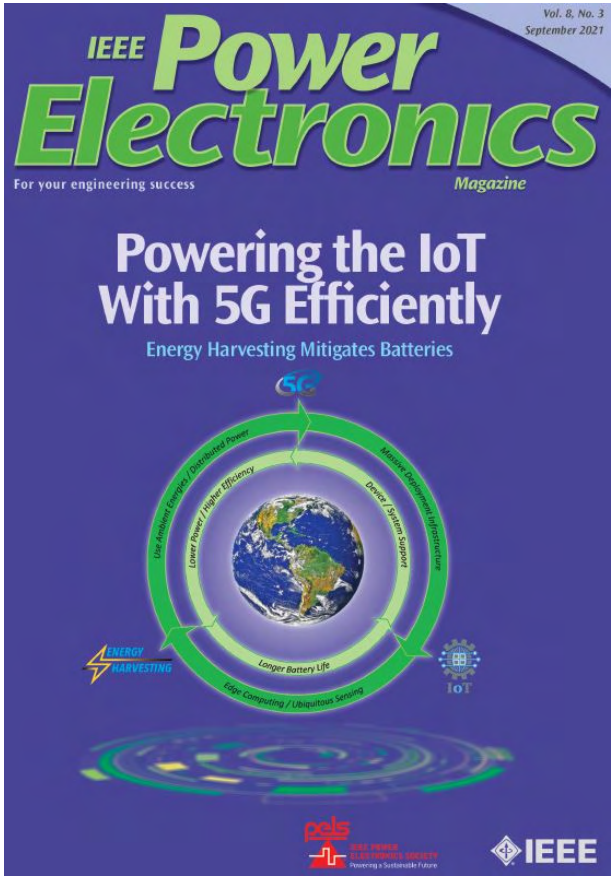
Wednesday 4:08PM

Progress?!?

☺

IMAGE CREDIT: *"New Department Of Energy Program Incentivizes Pedestrians, Cyclists To Switch To Electric Vehicles," The Onion, June 13, 2022. [Online]. Available: https://www.theonion.com/new-department-of-energy-program-incentivizes-pedestria-1848968853.*

The 5G Virtuous Circle



Progress!!!

IMAGE CREDIT: *M. Hayes and B. Zahnstecher, "The Virtuous Circle of 5G, IoT and Energy Harvesting [Cover Story]," in IEEE Power Electronics Magazine, vol. 8, no. 3, Sept. 2021.*

A Quick Poll

Raise your hand if you think it is critical to mitigate losses of…

…1 W?

…1 mW?

…1 µW?

Disclaimer

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

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

Presenter

Brian Zahnstecher

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Niantic, CT

Brian Zahnstecher is a Sr. Member of the IEEE, Chair (Emeritus) of the IEEE SFBAC Power Electronics Society (PELS) awarded 2017 Best Chapter awards at the local/national/worldwide levels concurrently (an unprecedented achievement), IEEE PELS North America Regional (R1-3) Chair, sits on the Power Sources Manufacturers Association (PSMA) Board of Directors, is Co-founder & Chair (Emeritus) of the PSMA Reliability Committee, Co-chair of the PSMA Energy Harvesting Committee, 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 Co-chairs the IEEE Future Directions (formerly 5G) Initiative webinar series and is the founding Co-chair of the IEEE 5G Roadmap Energy Efficiency Working Group, authored the Group's position paper, and has lectured on this topic at major industry conferences.

He has successfully handled assignments in system design/architecting, ac/dc front-end power, EMC/EMI design/debug, embedded dc/dc 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 Advanced Energy), 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 keynote speaker, author, workshop participant, session host, roundtable moderator, and volunteer. He has nearly 20 years of industry experience and holds Master of Engineering and Bachelor of Science degrees from Worcester Polytechnic Institute.

Overview

- The Global Footprint Impact of Tiny “Things”
- Assessing System Energy Utilization/Budgets
- Extending Battery Life
- An Intro to Energy Harvesting (EH)
- There *IS* An Ecosystem to Support You
- Testing & Validation
- Market-Focused Use Cases *(time permitting)*
- Summary & Conclusions
- Q & A

“How thoughtlessly we dissipate our energies

Perhaps we'll help fulfill each other's fantasies

And as we stand upon the ledges of our lives with our respective similarities

It's either sadness or euphoria”

– Billy Joel, Summer, Highland Falls

The Global Footprint Impact of Tiny “Things”

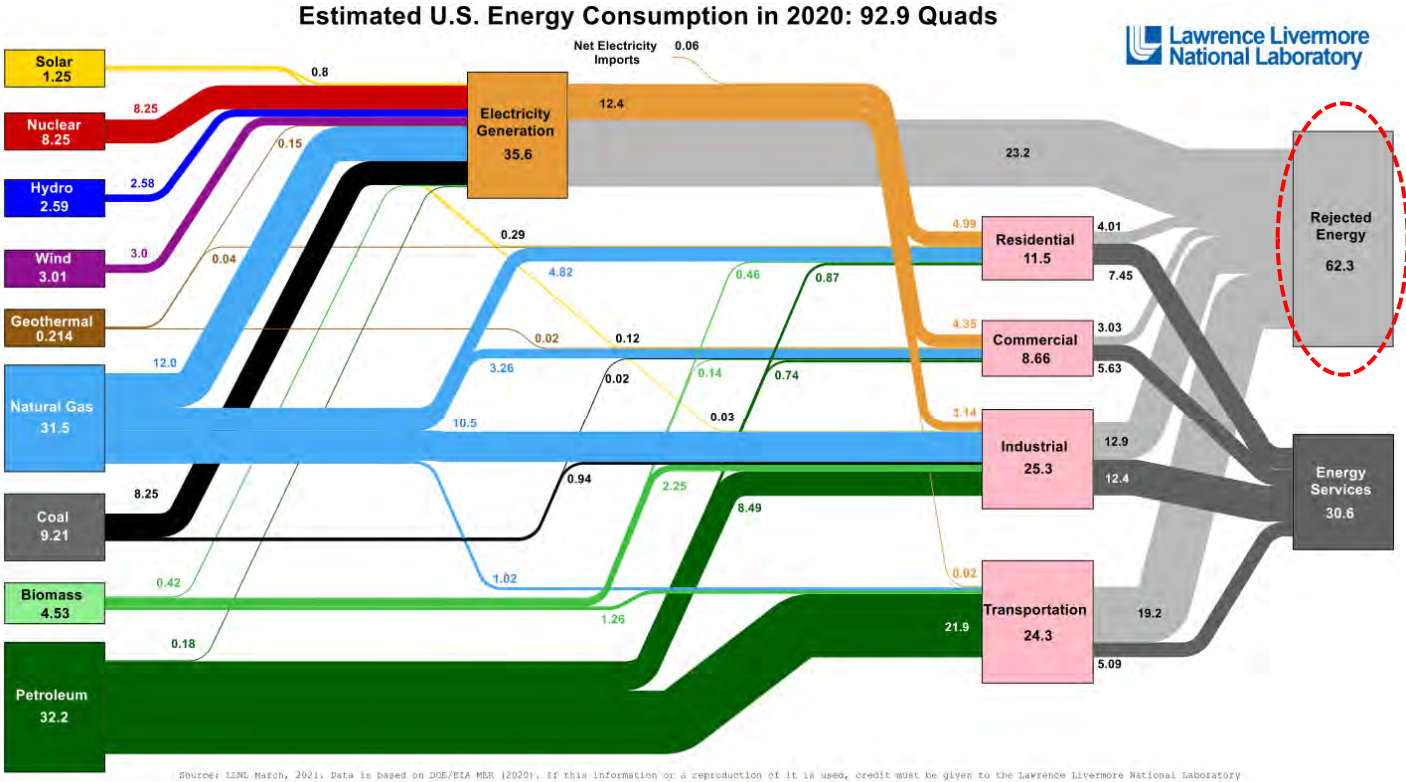


IMAGE CREDIT: *"Estimated U.S. Energy Consumption in 2020" Lawrence Livermore National Laboratory, March 2021.*

The Global Footprint Impact of Tiny “Things”

R_x Transitioning to a Trillion-Sensor World

- Highly Semantical, But 10s of B, 100s of B, or 1 T…HUGE NUMBERS!
- Gig Economy Driving Economic Paradigm Shifts
- “*Data is the new oil.*”

QUOTE CREDIT: *Wikipedia contributors, "Clive Humby," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Clive_Humby&oldid=1067348557 (accessed April 15, 2022).*

- Discussing EH…*“Freeing the IoT from battery power will be a key enabler in reaching a trillion devices.”* – Rob Aitken, ARM

QUOTE CREDIT: *Rob Aitken "Predictions for a connected 2018," ARM Company Blog, Posted 8 Jan 2018.*

The Global Footprint Impact of Tiny “Things”

R_x 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!!!

The Global Footprint Impact of Tiny "Things"

R_x The True Cost of a mW at the Edge *(maybe a nW?)*

- Most Losses Attributed to Wireless Transmission
  - Radio Protocol Specs Can Be ~-100 dBm (10^{-10} W)
- The key is assessing energy consumption AT THE POINT OF UTILIZATION!

(Modified) Friis Transmission Equation

$$P_R = \frac{P_T G_T G_R c^2}{(4\pi R f)^2}$$

SOURCE: *Friis Equation - (aka Friis Transmission Formula) =* *http://www.antenna-theory.com/basics/friis.php.*

- 0 dBm = 1 mW reference
- 10 dBm per power order of magnitude
- ***Rx power falls dramatically with distance and/or frequency***

IMAGE CREDIT: *https://commons.wikimedia.org/wiki/File:Base_transceiver_station.jpg*

IMAGE CREDIT: *https://www.flickr.com/photos/alpat/8798930518*

You have lost ~99.9 % of your power transmitting from base station to smartphone.

EFFICIENCY FOR THIS STAGE = ~0.1 % (BEST-CASE)

Assessing System Energy Utilization/Budgets

R_x The Power Value Chain (PVC)

- *Energy flow across all the distribution/conversion steps between source and load.*

R_x The Power Cost Factor (PCF)

- *Unitless number to assess the overall cost of energy **utilization** at any given point within the PVC.*

CREDIT: IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency, 2021 Edition" International Network Generations Roadmap (INGR), Apr. 9 2021.

Assessing System Energy Utilization/Budgets

R_x What is a Power Value Chain (PVC)?

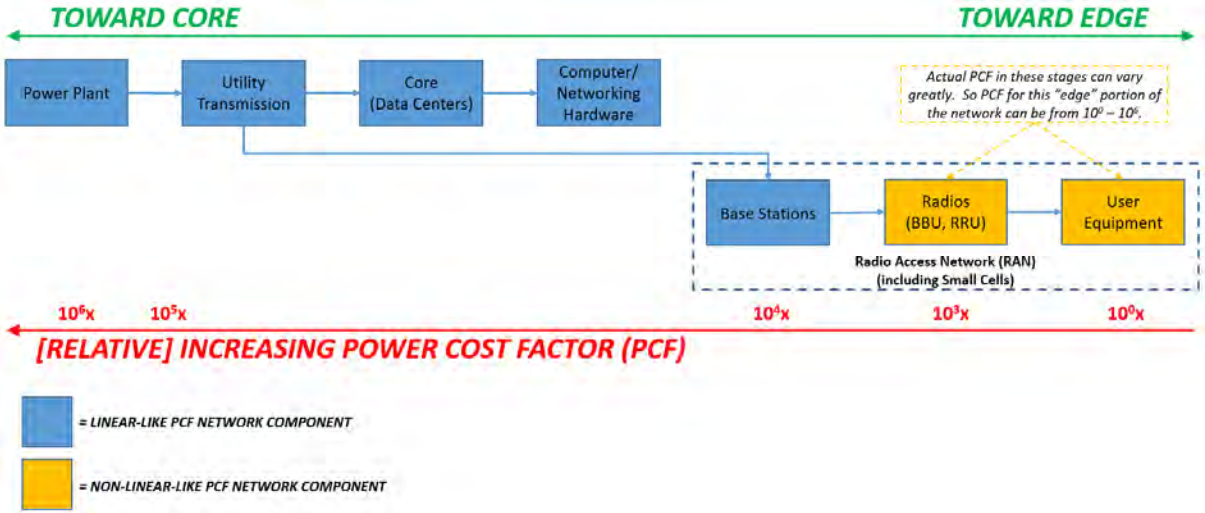


IMAGE CREDIT: *IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency - 1st Edition White Paper," International Network Generations Roadmap (INGR), Apr. 2020.*

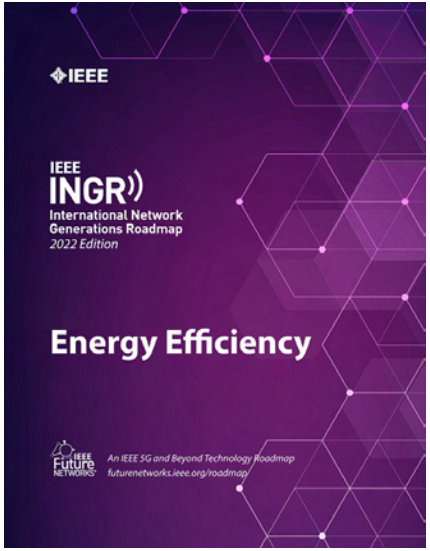


IMAGE CREDIT: *IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency, 2022 Edition" International Network Generations Roadmap (INGR), Mar. 22 2022. [Online]. Available: https://futurenetworks.ieee.org/roadmap.*

Assessing System Energy Utilization/Budgets

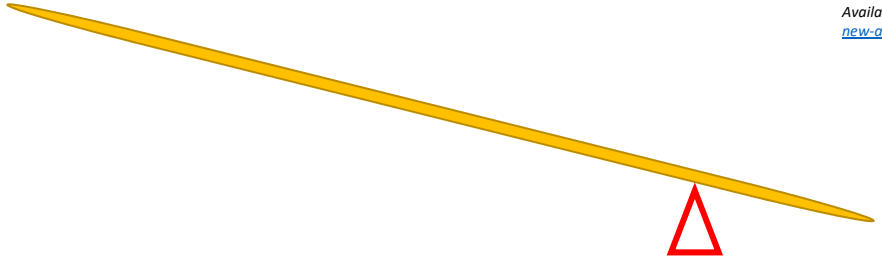
R_x What is the Entire Power Value Chain (PVC)?

- The Complete Power Picture from End-to-End
- Some Examples:
  - **Chip** → Power Subsystem → Battery → Adapter → Home → Grid → **Power Plant**
  - **Display** → PMIC → Battery → Adapter → Home → Grid → **Power Plant**
  - **Antenna** → SoC → PMIC → Battery → Adapter → Home → Grid → **Power Plant**
  - **ASIC** → Power Subsystem → System → Rack → Data Center → Grid → **Power Plant**
  - **ASIC** → Advanced Non-isolated DC/DC (i.e. – VRM) → Upstream Non-isolated DC/DC → Isolated DC/DC → Front-end → PDU → UPS → Grid/Generator → **Power Plant**

Assessing System Energy Utilization/Budgets

R_x The Disproportionate Impact of Tiny Power on Big Power

IMAGE CREDIT: *Monroe, Jazz, "Public Enemy Announce New Album, Return to Def Jam," Pitchfork, August 28, 2020. [Online]. Available: https://pitchfork.com/news/public-enemy-announce-new-album-return-to-def-jam/.*



Assessing System Energy Utilization/Budgets

Does anyone know what THE MOST efficient power conversion solution in the world is?

(FYI – this is not a subjective question.)

CLUE: A better question "***Does anyone know which power conversion device dissipates the least heat?***"

Does anyone know what THE SECOND MOST efficient power conversion solution in the world is?

Assessing System Energy Utilization/Budgets

R_x The "Official" Power Supply Design Process

- ***STEP 1***: All system stakeholders (*typically minus the Power stakeholder*) get together and architect a system.
- ***STEP 2***: Determine system power budget by summing maxima of all major loads in the system.
- ***STEP 3***: Confirm with the Mechanical/Thermal stakeholder it seems feasible.
- ***STEP 4***: Provide power budget, volumetric constraints, and project timeline to Power Stakeholder.
- ***STEP 5***: Magic?!? *(i.e. – screw physics and reality)*

Assessing System Energy Utilization/Budgets

R_x Separating the Source from the Load

- Best Approach to Understanding/Optimizing Power Consumption (e.g. – Intelligent Power Management or IPM techniques)
- Think of **Sources** and **Loads** as Independent Black Boxes That "Talk"

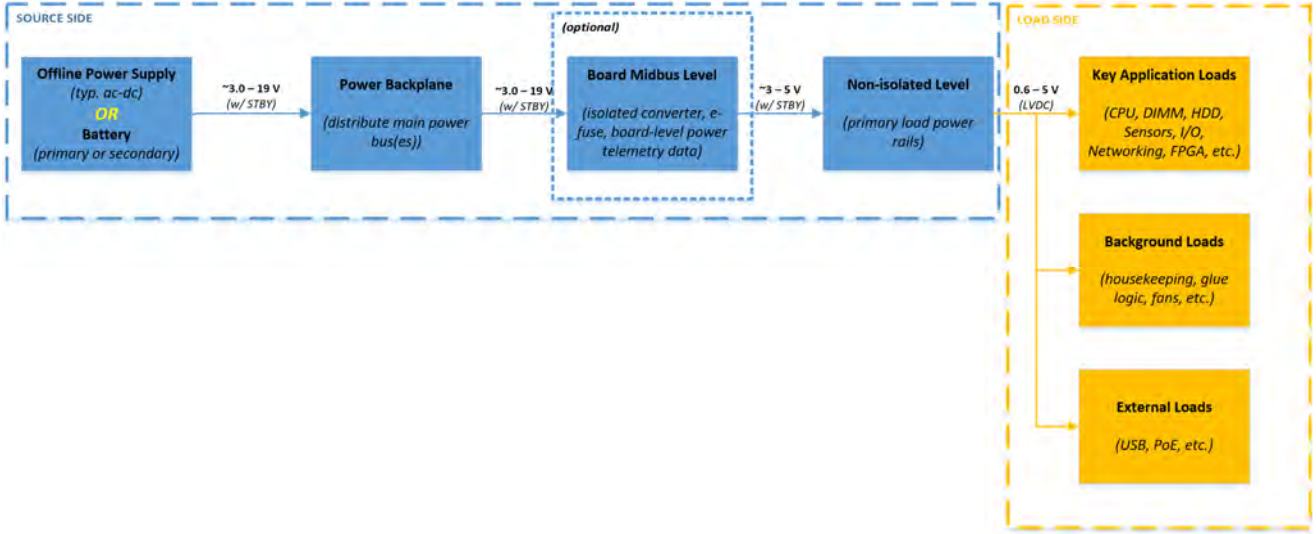


IMAGE CREDIT: System Source Vs. Load Breakdown Diagram, *courtesy of PowerRox*

Assessing System Energy Utilization/Budgets

R_x When It Comes to IoT/IIoT, This Primarily Refers to:

- *Processors* (CPUs, GPUs, microcontrollers, FPGAs, etc.)
- *Radios* (Wi-Fi, BLE, 4G-LTE/5G, NB-IoT, LoRa, etc.)
- *Sensors* (accelerometers/gyros, temp/humidity, biometrics, etc.)
- *Displays* (LCDs, TFTs, e-paper, etc.)

Extending Battery Life

- **Commonly One of the Most *Criminally-Neglected* Aspects of the Design**
  - Energy storage is not merely a dumb, two-terminal, dc source!
  - Managing Energy Storage, Especially Secondary (a.k.a. – rechargeable)
  - No Moore's Law for Energy Storage
    - Just Chemistry & Physics

- **A very common mistake is to not prioritize energy storage design considerations early in the architecting/prototyping processes.**
  - Measured Data = *Too Late…more on this later*

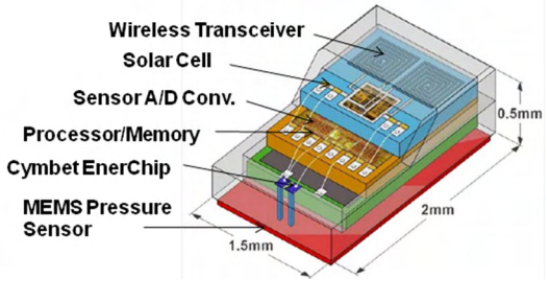
Extending Battery Life

R_x Energy Storage in the IoT

- Primary Cells
- Secondary Cells
- Supercaps
- Hybrid Li-ion Solutions

IMAGES CREDIT: *C. Ho, "Flexible Energy Storage Considerations," Imprint Energy, 2017FLEX Short Course, Monterey, CA, June 19, 2017.*

IMAGE CREDIT: *P. Mars, "Supercapacitors support low power Energy Harvesters & Coin Cells," CAP-XX, EnerHarv 2018, Cork, Ireland, May 30, 2018.*



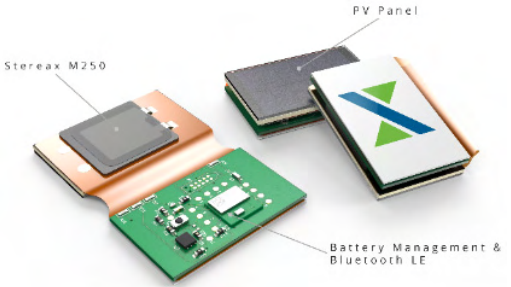


IMAGE CREDIT: *D. Pasero, "IoT sensors powered by solid state batteries and harvested energy," Ilika Technologies, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.*

Extending Battery Life

R_x Understanding the *MANY* Factors Driving Battery Performance Characteristics

- C-rate, SOC, DOD, Cycle Rate/Depth, Lifetime # Cycles, ESR, Cell Balancing, etc.
- **DIFFERS FOR**: Li-Ion/Po, SLA, NiMH, NiCad, LiFePO4 or LFP, etc.

MAIN GOAL = *KEEP THE CHEMISTRY HAPPY!!!*

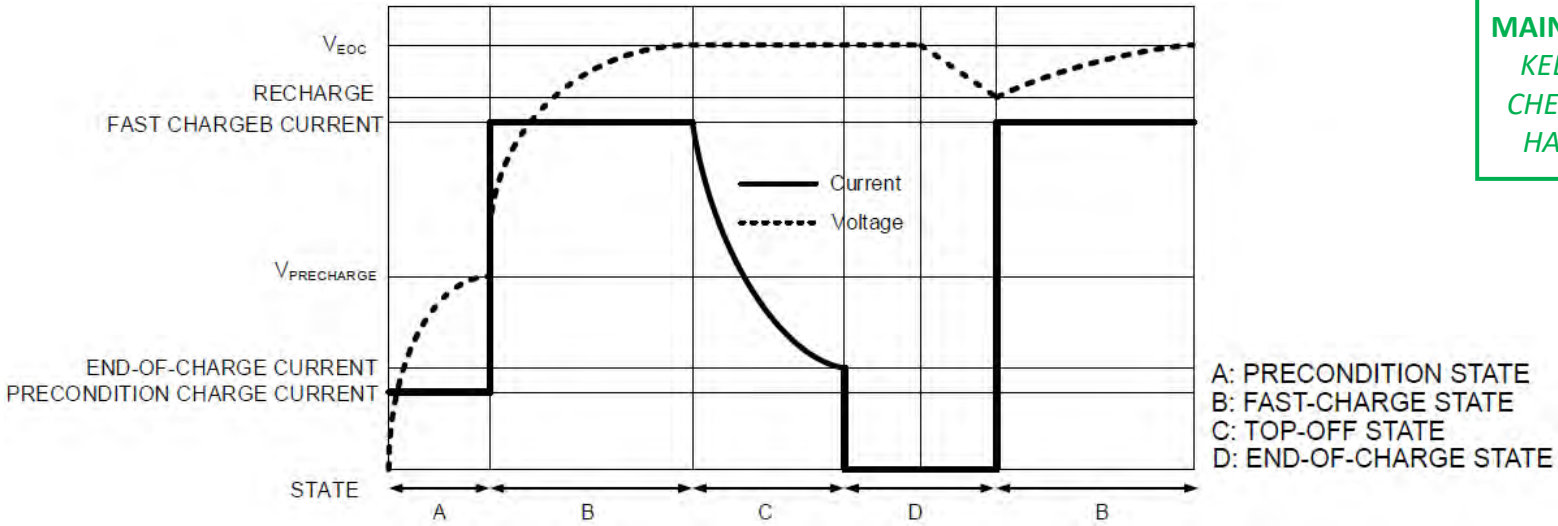


IMAGE CREDIT: *Typical Li+ Charge Profile, from Qorvo ACT2801 Spec Sheet. [Online]. Available: https://www.qorvo.com/products/d/da006751.*

Extending Battery Life

R_x Battery Life Calculations

- Highly Subjective, Highly Variable (see 40 mAh battery example below)

	ESTIMATED BATTERY LIFE (hrs)			NOTES
	MAX	NOM	MIN	
ESTIMATED BATTERY LIFE (hrs)	1.50	0.36	0.11	- MIN/NOM/MAX directly correlate to loading range - need to add derate factors (i.e. - environmental/usage factors, etc.) to calc tool **- add plots? 3.7/3.0 (nom/cutoff V)** **- wake vs. sleep loading?**
[OVER MFG TOLERANCE] *NOMINAL* ESTIMATED BATTERY LIFE (hrs)	0.44	0.36	0.29	- MIN/NOM/MAX is +/-20 %.
[OVER TEMPERATURE] *NOMINAL* ESTIMATED BATTERY LIFE (hrs)	0.36	0.36	0.18	- MIN/NOM/MAX for temp range used is 0/25/50 °C, which translate to 50/100/85 % at respective temps.
[CHARGE RATE] *NOMINAL* ESTIMATED BATTERY LIFE (hrs)	???	0.36	???	- MIN/NOM/MAX for battery charge rates used is 0.1/0.2/0.5 C.
[CHARGE CYCLES] *NOMINAL* ESTIMATED BATTERY LIFE (hrs)	???	0.36	???	- MIN/NOM/MAX for lifetime number of charge cycles used is #/#/500 recharge cycles.
[OVER TIME] *NOMINAL* ESTIMATED BATTERY LIFE (hrs)	???	0.36	???	- MIN/NOM/MAX for lifetime used is #/#/1825 days.

IMAGE CREDIT: Battery Life Estimation Tool Example, *courtesy of PowerRox*

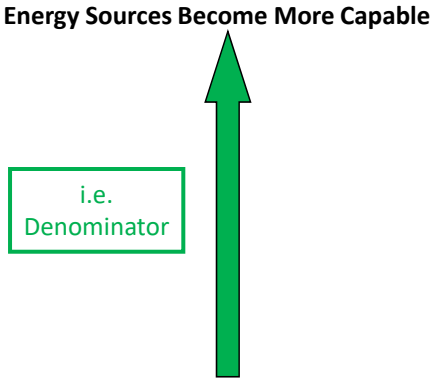
R_x Typical Derate Factors

- System Power Budget Creep
- Manufacturing Tolerance
- Operating/Non-Operating Temperature
- Charge/Discharge Rates
- Depth of Discharge (DOD)
- Charge Cycles
- Equivalent Series Resistance (ESR)
- Electrical Over Stress (EOS)

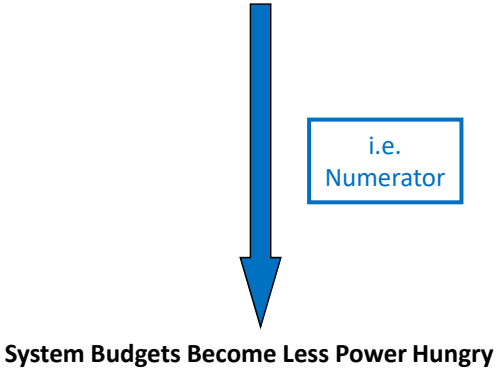
Extending Battery Life

R_x Source Versus Load

- Where is the point of inflection?
- Which tends to have a faster rate of change?



$$\boldsymbol{Utilization} = \frac{System\ \boldsymbol{Load}}{Energy\ \boldsymbol{Source}}$$



Extending Battery Life

R_x It is all about utilization!

- Rarely Does Your Peak Power Occur at the Peak Point on the Efficiency Curve
- Even if it Does, Your Load is Typically Transient in Nature
- The Real Low-Hanging Fruit is **Intelligent Power Management (IPM)**
  - Characterize Your Systems/Loads To Understand Where Operating on Load Curve
    - More Accurate Thermal Modeling (*and everything that comes with it*)
  - Put the Maniacal Focus on ***Reducing*** the System Power Budget
  - Do **NOT** Put the Maniacal Focus on ***Increasing*** the Available Power

Extending Battery Life

R_x An In-Depth Look at Power Supply Efficiency

- If optimizing efficiency is important, …
  - …then utilization (area under the efficiency curve) is what counts!
  - …then you can more realistically predict/model power usage.
  - …then you have a better idea of what improvements in system-level power conversion have actual value.
  - …then you are better enabled to provide cost benefit analyses at all levels.
  - …then you will have much better input for your SW people to implement more intelligent power management algorithms.

FYI: If this point is getting redundant to the point of nausea, then GOOD, we are making progress!

An Intro to Energy Harvesting (EH)

R_x Energy Savings

- Waste = Opportunity
- Put Reclaimed Energy To Better Use
- Reduce Infrastructure / CAPEX

*"There is no such thing as **waste heat**…just underutilized **energy recycling opportunities**."*

– Brian Zahnstecher

An Intro to Energy Harvesting (EH)

R_x 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-***ISH***

An Intro to Energy Harvesting (EH)

R_x Energy Harvesting

- 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

An Intro to Energy Harvesting (EH)

Rx 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

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

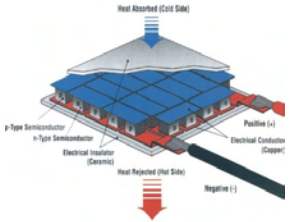


IMAGE CREDIT: *How to Build a Homemade Thermoelectric Generator, 2017. [Online]. Available:* https://topmagneticgenerator.com/build-homemade-thermoelectric-generator/.

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

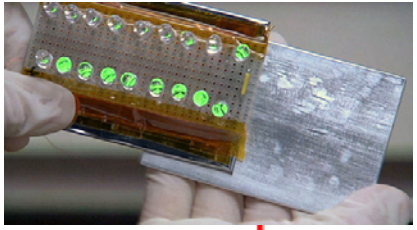


IMAGE CREDIT: *Inertia Films*

An Intro to Energy Harvesting (EH)

R_x Critical Environmental Factors

- Device/Application Success HIGHLY Dependent on Operating Environment
- The Power Management IC (PMIC) is the Key
  - Multiple Inputs

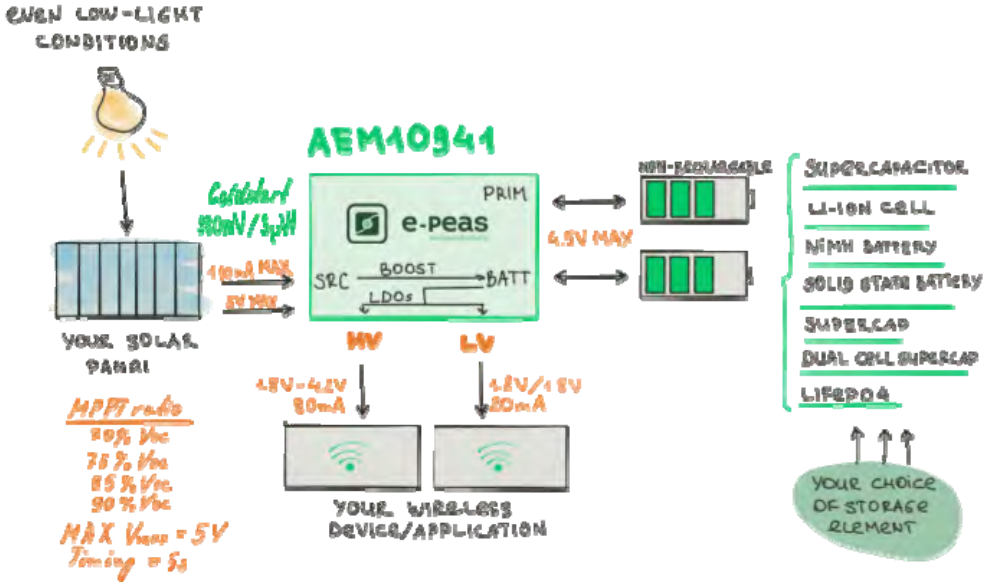


IMAGE CREDIT: *"AEM10941," e-peas Product Overview, Viewed January 12, 2020.*

An Intro to Energy Harvesting (EH)

R_x Critical Environmental Factors

- Harsh Environments
- Inaccessible / Difficult to Access Sensors / Batteries
- Monitoring Data on Steroids
- Truly Permanent Installations

An Intro to Energy Harvesting (EH)

R_x Mapping EH Sources to IoT/IIoT Loads

Energy Harvesters become more capable

i.e. Denominator

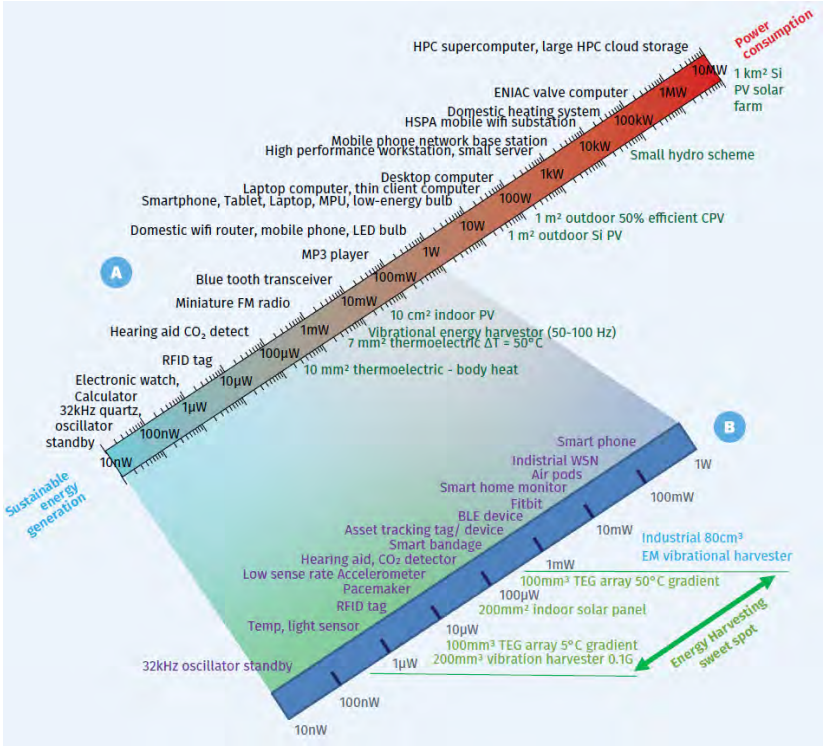


IMAGE CREDIT: *EU EnABLES Project, "Research Infrastructure Position Paper, European Infrastructure Powering the Internet of Things" EU EnABLES Project, February 2021.*

i.e. Numerator

Electronic devices become less power hungry

An Intro to Energy Harvesting (EH)

R_x Mapping EH Sources to IoT/IIoT Loads

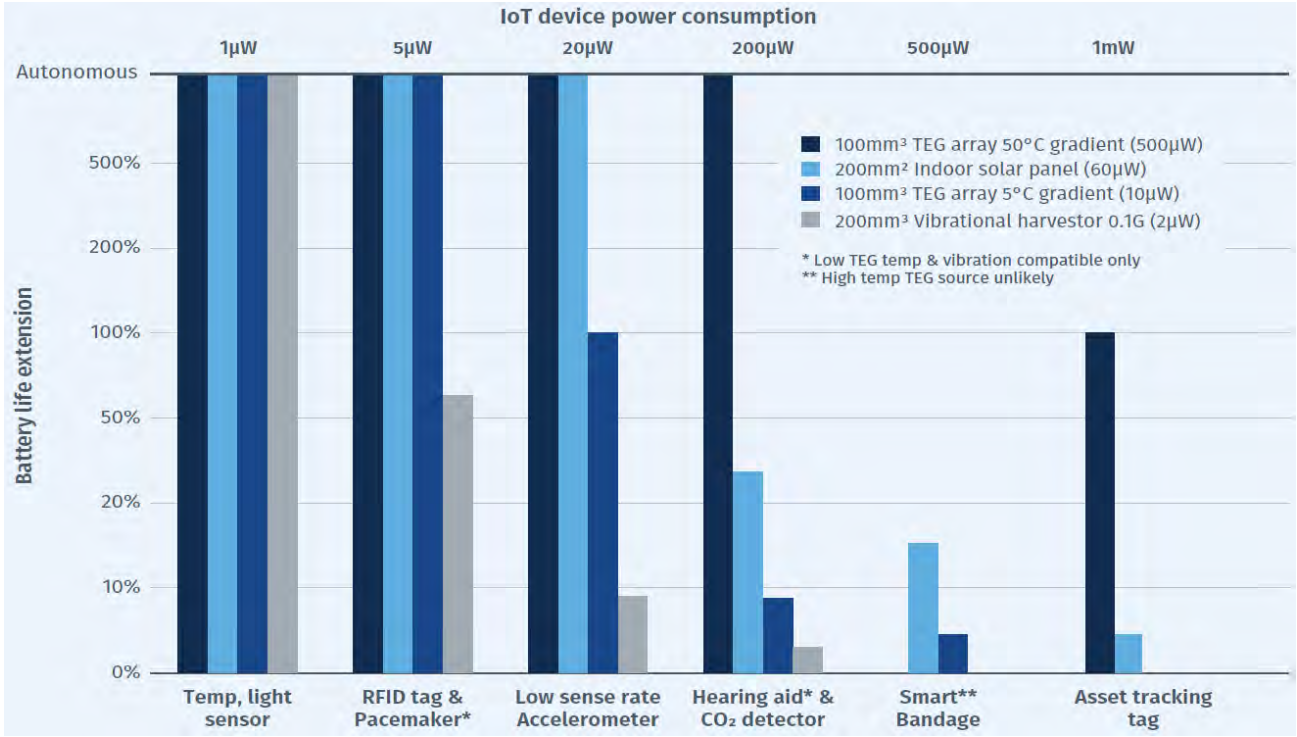


IMAGE CREDIT: *EU EnABLES Project, "Research Infrastructure Position Paper, European Infrastructure Powering the Internet of Things" EU EnABLES Project, February 2021.*

There *IS* An Ecosystem to Support You

R_x The Power IoT Ecosystem

- Extending Battery Life is Key
  - Increase Energy Density
  - Reduce System Power Budget Demands
  - Supplement with External Sources (e.g. – Energy Harvesting)

- Getting Into a “Zero Power” Mentality
  - Vampire Power
  - Want Vs. Need
  - Creative Repurposing
  - Optimizing for Efficiency ***AND*** Utilization

There *IS* An Ecosystem to Support You

R_x The Power IoT Ecosystem

- It Takes a Village…
- …Here is Ours

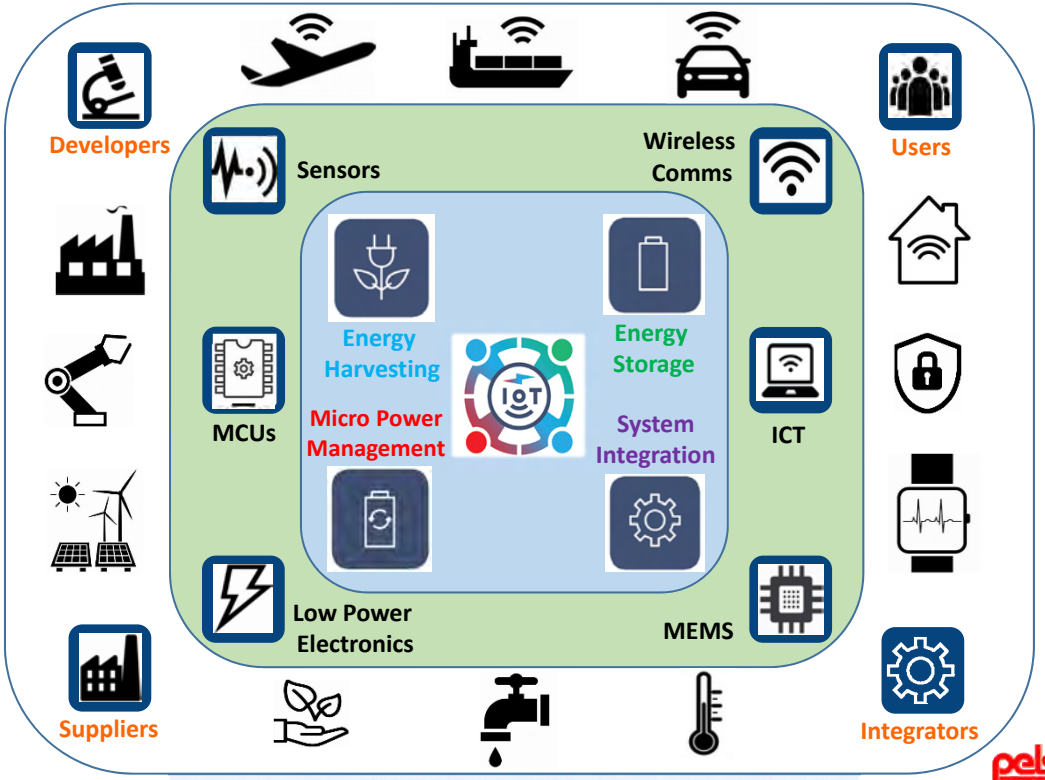


IMAGE CREDIT: *M. Hayes and B. Zahnstecher, "The Virtuous Circle of 5G, IoT and Energy Harvesting," IEEE Power Electronics Webinar, Nov. 10, 2021.*

There *IS* An Ecosystem to Support You

R_x "EH for a Green IoT" White Paper

- SECTION 1. State-of-The-Art from the Perspective of the User
- SECTION 2. Developing for a Use Case
- SECTION 3. Key Missing Elements for Industrial Adoption
- SECTION 4. Key Advantages
- SECTION 5. Innovation & Future Research

- https://www.psma.com/technical-forums/energy-harvesting

"Powering the Internet of Things"

IMAGE CREDIT: *Becker T, Borjesson V, Cetinkaya O, et al., "Energy Harvesting for a Green Internet of Things," Power Sources Manufacturers Association (PSMA) White Paper, Oct. 2021.*

There *IS* An Ecosystem to Support You

R_x Challenges

- Efficiency Dependent on Input / Can Fall Off Dramatically with Load
- PMICs with Multiple Input Support
- Energy Intermittency
- Software Having Energy Awareness
- Cold Start-up
- Asynchronous HW & SW, working together? Asynchronously?!?
- Developing Ecosystem
- Wariness to Adoption
- Philosophical Approach to Waste Vs. Source
- Maximize Rechargeable Battery Utilization/Compatibility

There *IS* An Ecosystem to Support You

R_x Perhaps You Do Not Feel Like Training To Become A:

- Power Electronics Engineer
- Electrochemist
- Energy Harvesting Expert
- Embedded/FW Engineer
- Mechanical Engineer
- And likely more…

There *IS* An Ecosystem to Support You

R_x Luckily, You Do Not Have To!

- Lots of Eval Kits and Prefabricated IoT Design Blocks/Tools
- Focus on Optimizing Your Application, Not Purely Circuit Design/Layout

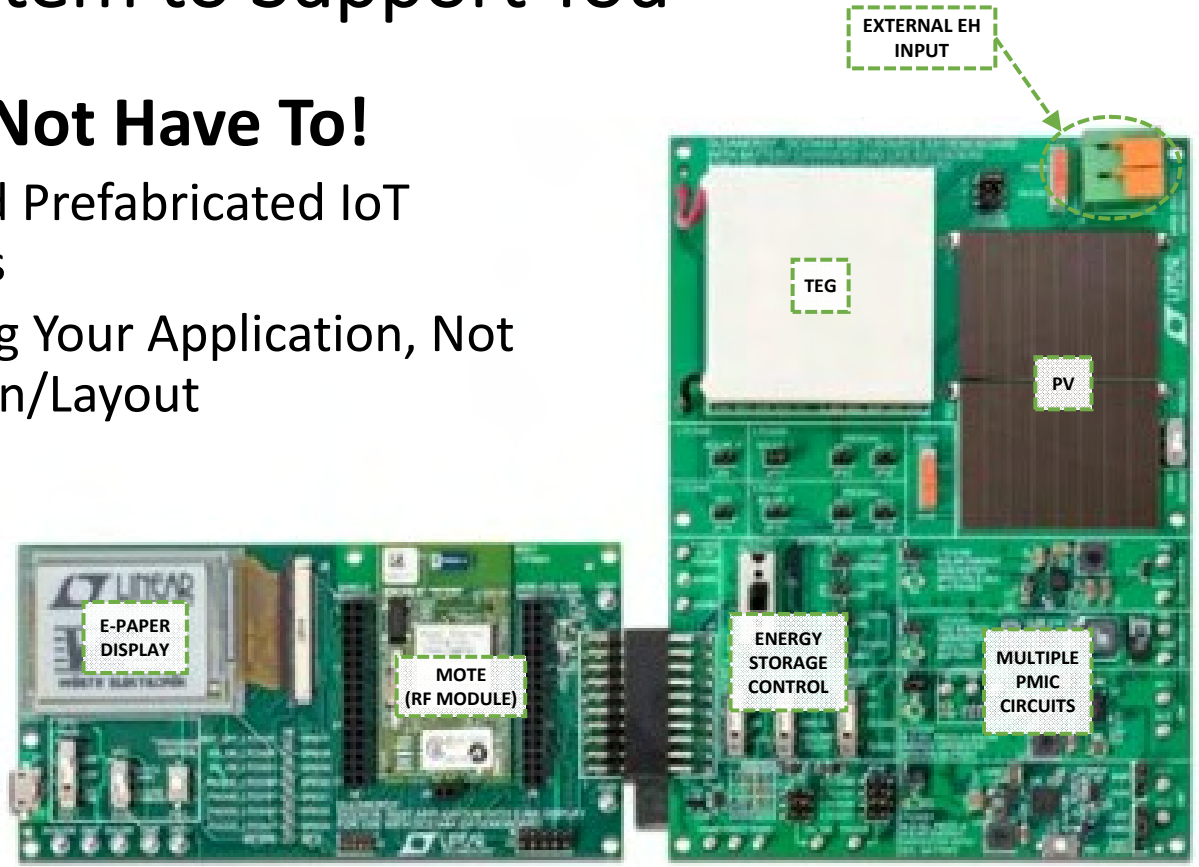


IMAGE CREDIT: *Würth Elektronik Gleanergy = http://www.we-online.com/web/en/electronic_components/produkte_pb/demoboards/gleanergy/gleanergy.php.*

There *IS* An Ecosystem to Support You

R_x Development / Evaluation Kits

- Würth Elektronik Gleanergy / EH Solution To Go
- TI CC2650 SimpleLink Eval Kit
- Cypress (Infineon) Solar BLE Kit CYALKIT-E02
- ADI ADP5090/1/2 Eval Board
- LT (ADI) DC2080A Eval Board
- EnOcean EDK 350 Dev Kit

IMAGE CREDIT: CYALKIT-E02 Solar-Powered BLE Sensor Beacon Reference Design Kit (RDK) = http://www.cypress.com/documentation/development-kitsboards/cyalkit-e02-solar-powered-ble-sensor-beacon-reference-design.

There *IS* An Ecosystem to Support You

R_x Embedded Code Power Estimation Tools

- No Blind Faith, Ask the Tough Questions to Assess Tool Integrity

R_x Micro-power Meters

- There Are Expensive Solutions, But Not a Requirement

IMAGE CREDIT: *NanoRanger Product Overview, https://www.altonovus.com/nanoranger.*

There *IS* An Ecosystem to Support You

R_x Characterize Complex Sources

- University of Southampton (UK) Enspect EH Characterization & Analysis Tools
  - http://www.enspect.ecs.soton.ac.uk/

Data Collection Unit

Analysis Tool

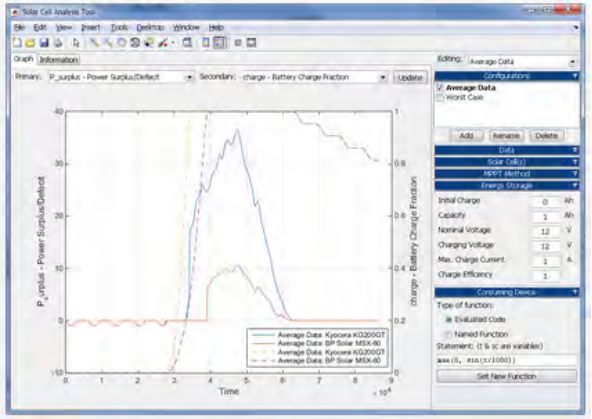


IMAGE CREDIT: *Enspect - Tool for predicting the output of energy harvesting systems. [Online]. Available: http://www.enspect.ecs.soton.ac.uk/. Accessed 7/12/19.*

- Micro Solar Evaluation
  - A specialised tool for micro PV cells, <1% error (current and voltage)

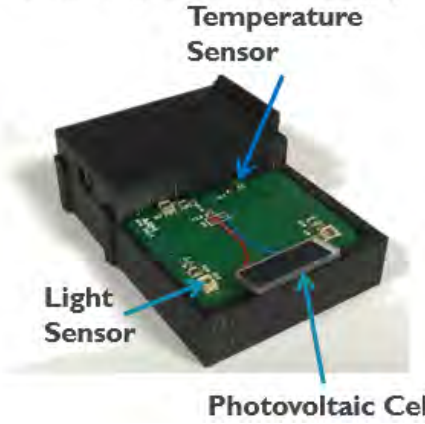


IMAGE CREDIT: *A. S. Weddell, "Energy Harvesting in Future IoT Devices," University of Southampton / ARM-ECS Research Centre, 2018 EnerHarv Workshop, Cork, Ireland, May 31, 2018.*

There *IS* An Ecosystem to Support You

R_x EH-specific Design Calculator

- PowerFilm Custom Solar Panel Design Tool
  - https://www.powerfilmsolar.com/custom-solutions/custom-solar-panel-design-tool

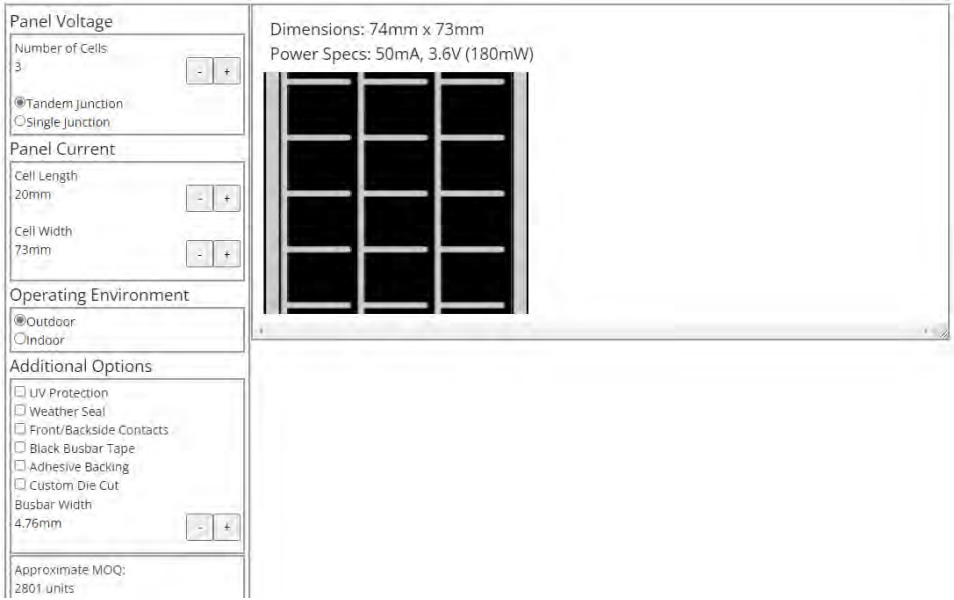


IMAGE CREDIT: Custom Solar Panel Design Tool. *[Online]. Available: https://www.powerfilmsolar.com/custom-solutions/custom-solar-panel-design-tool. Accessed 8/16/22.*

Testing & Validation

R_x Crud In = Crud Out

- If you cannot accurately instrument and characterize power performance (particularly in ULP systems), then you are setting up for failure.
- Battery Life "Buyer's Remorse"
  - A quick analysis…
    - **TAKEAWAY LESSON** = Never underestimate the complexity, analysis, and **characterization** required to properly implement energy storage solutions!

Testing & Validation

R_x Measurement & Characterization

- How does one visualize such high dynamic ratio, while maintaining resolution?
- How does one ensure you are triggering two waveforms off the same event?

IMAGE CREDIT: *"N2820A/21A High-Sensitivity, High Dynamic Range Current Probes," Keysight Data Sheet, Downloaded December 20, 2016.*

Testing & Validation

R_x Measurement & Characterization

- 10,000+ Dynamic Range Ratios (i.e. – nA to mA)
- Just as Critical as the Design
- Errors Inversely Proportional to Power Levels

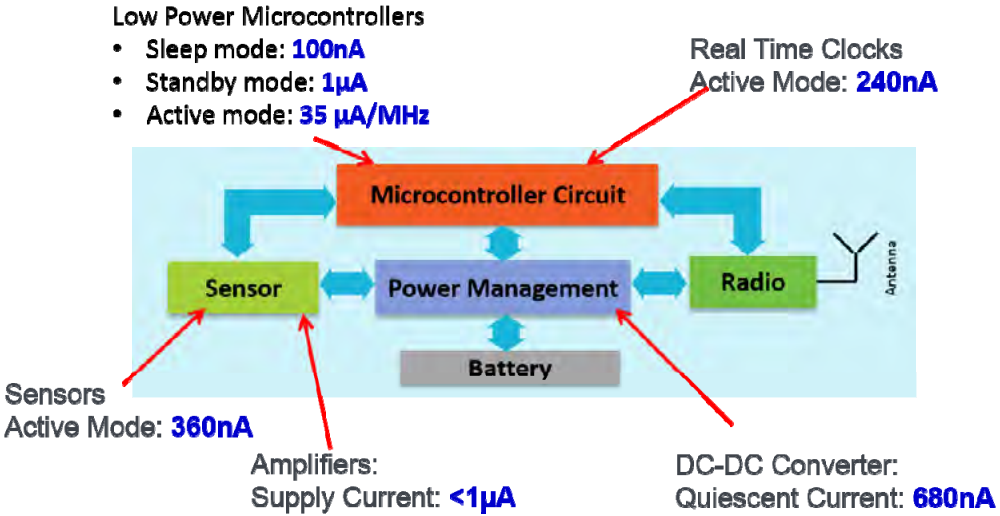


IMAGE CREDIT: Seshank Malap, "Energy Harvesting & IoT Power Analysis," Tektronix, IEEE PELS Energy Harvesting Workshop, April 20, 2017.

Market-Focused Use Cases

R_x IoT / IIoT

- Low Power/Latency/Bandwidth Networks
  - So Many Options to Enable Ultra-Low Power (ULP) Applications, Huge Opportunities

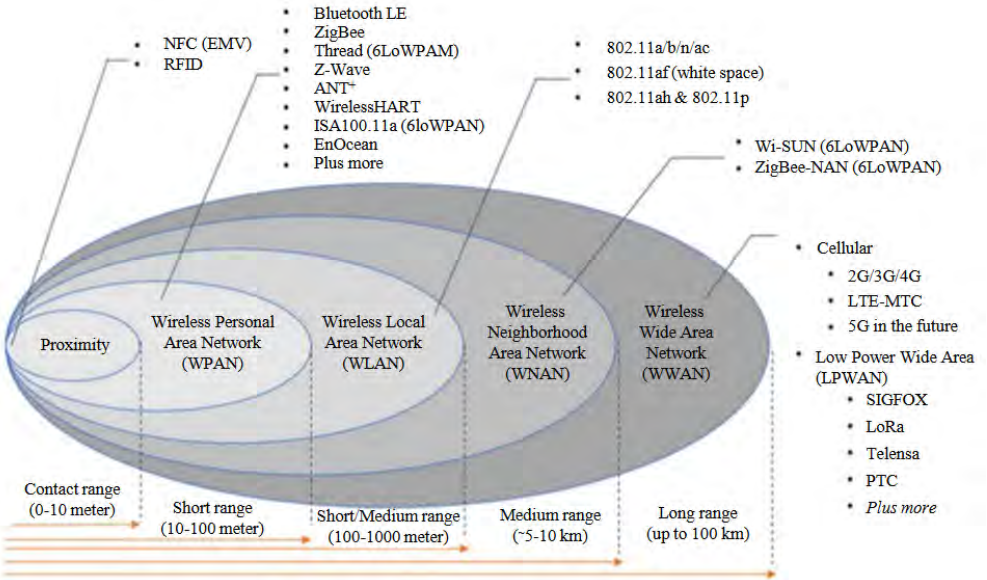


IMAGE CREDIT: *Mahmoud, M.S. and Mohamad, A.A.H. (2016) A Study of Efficient Power Consumption Wireless Communication Techniques/Modules for Internet of Things (IoT) Applications. Advances in Internet of Things, 6, 19-29.*

Market-Focused Use Cases

R_x IoT / IIoT

- Thermoelectric Generator (TEG)
  - Chip-scale TEG
    - Imagine If You Reclaimed Even Just 1% of Global IC Power Utilization
    - Extend Life / Operating Temperature Range
    - Reduce Cooling Infrastructure AND/OR Increase Density Footprints
    - Reduce Leakage Currents

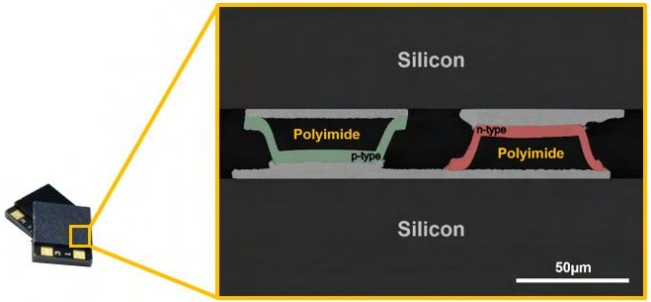
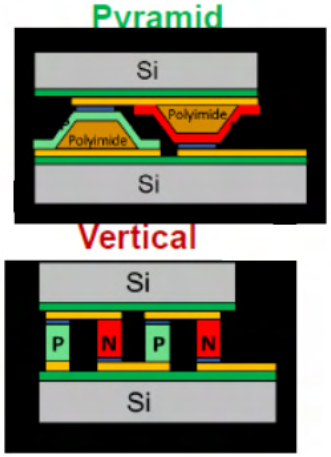
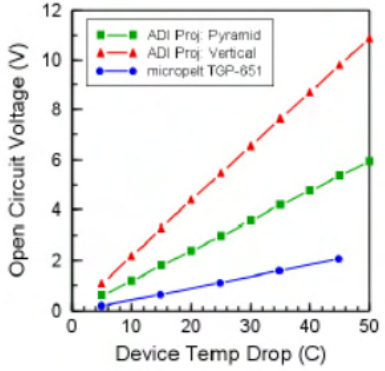


IMAGE CREDIT: *B. Chen, "Powering the IoT: An Energy Harvesting Perspective," Analog Devices, EnerHarv 2022 Keynote, Raleigh, NC, April 7, 2022.*





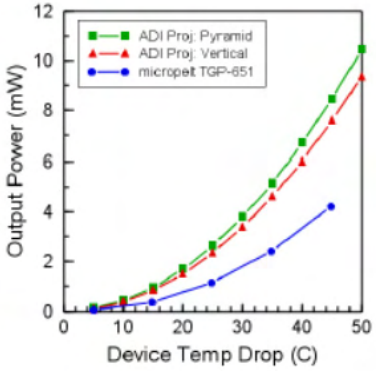
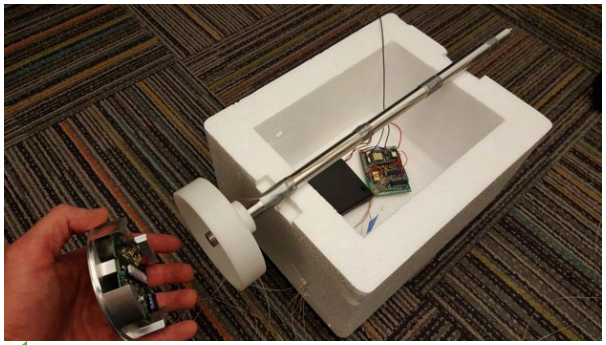


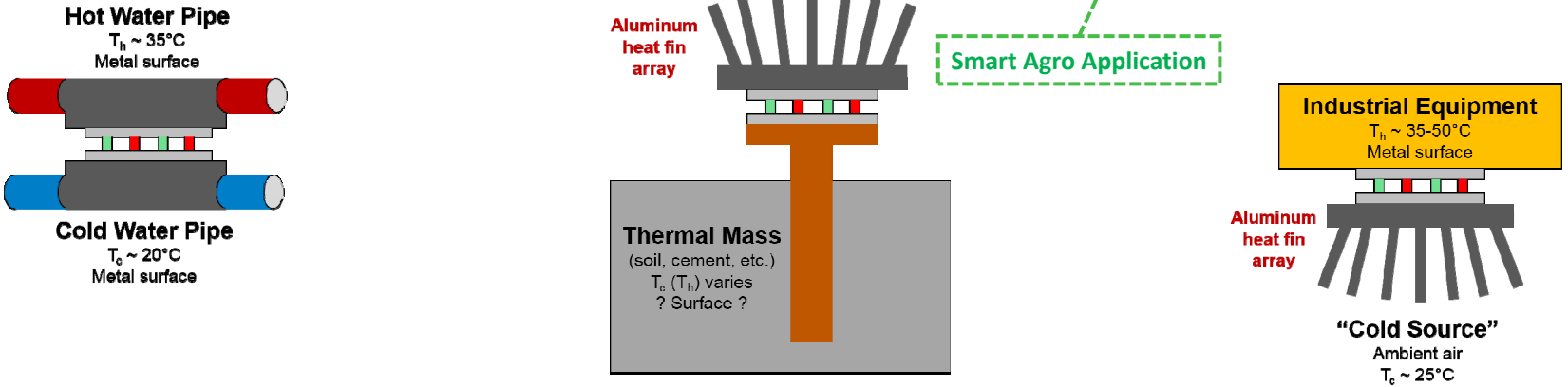
IMAGE CREDIT: *B. Chen, J. Cornett, "Chip Scale TEG and its Use for a Wireless Machine Health Monitoring System," Analog Devices, APEC 2017 Industry Session, Tampa, FL, March 30, 2017.*

Market-Focused Use Cases

R_x IoT / IIoT

- Wireless Sensor Networks (WSN)
  - Thermal **Differentials** are Everywhere





IMAGES CREDIT: M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.

Market-Focused Use Cases

R_x IoT / IIoT

- System-Based Approach to Application Engineering

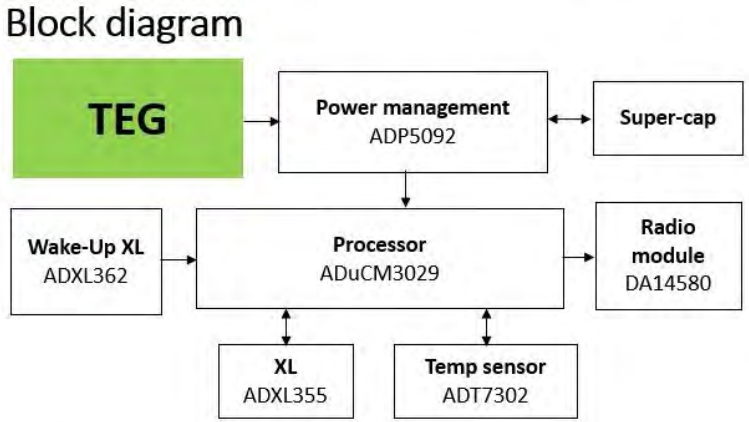


IMAGE CREDIT: *M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.*

Market-Focused Use Cases

R_x IoT / IIoT

- Evaluating the Tradeoffs
  - Condition-Based Monitoring

Power consumption

Update rate	DA14580 *BLE*	ADuCM3029 *uC*	ADXL355 *XL*	ADXL362 *Wake-up*	ADT7302 *Temp*	Total
30 sec	172	16.1	5.56	4.89	0.24	199
30 min	5.82	0.433	0.093	5.39	0.004	11.7

Average power in µW

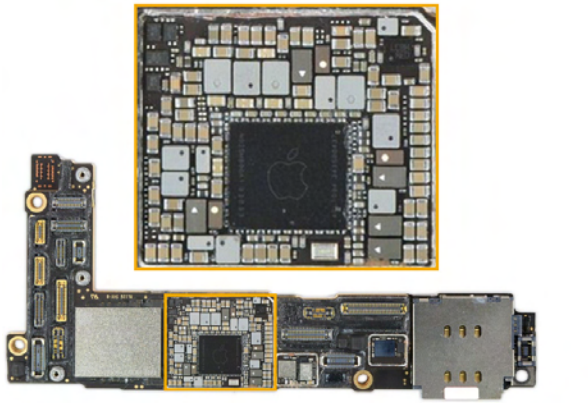
- **Data updates every 30 sec:** Power consumption dominated by transmission → ΔT ~ ***10°C***
- **Data updates every 30 min:** Wake-up XL power consumption comparable to BLE → ΔT ~ ***2°C***

IMAGE CREDIT: *M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.*

Market-Focused Use Cases

R_x Industry 4.0 / Smart Manufacturing

- Consolidation/Density Drives IPM
- Achieving Quality/Yield With Analytics
  - Sensor-based Raw/Pre-processed Data



Apple iPhone 12 teardown (ifixit.com)
Miniaturization, 3D high density, power & thermal management

IMAGES CREDIT: *M. Kelly, R. Fishbune, "Factory of the Future Technologies and Approaches Applied to Solve Today's Power Density Challenges," IPC/IBM Collaboration, APEC 2021 Industry Session, Phoenix, AZ, June 10, 2021.*

Market-Focused Use Cases

R_x Industry 4.0 / Smart Manufacturing

- Power Electronics Design Meets Parameterized Manufacturing
  - From Schematic to Build & Test

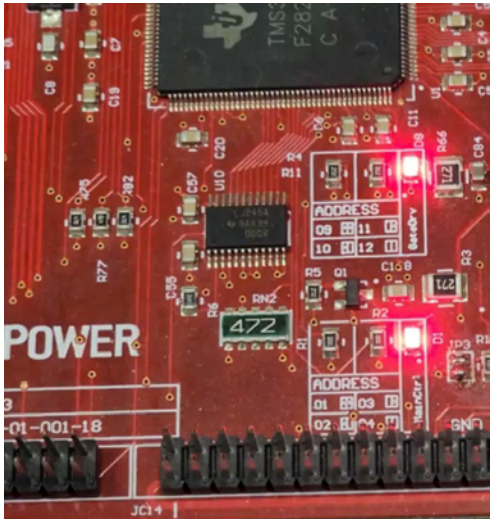


IMAGE CREDIT: *G. Pitel, "Power Electronics Hardware Design For Manufacturability," Magna-Power, IEEE SFBAC PELS Monthly Meeting, Mountain View, CA, September 15, 2022.*

SIDE NOTE:
If you ever get the chance to tour the Magna-Power factory in Flemington, NJ, then I HIGHLY recommend it!

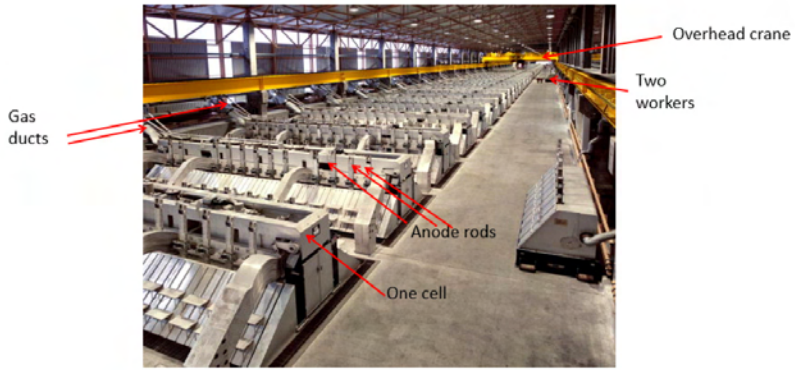
Market-Focused Use Cases

R_x Industry 4.0 / Smart Manufacturing

- Harsh Environments
  - Industrial IoT (IIoT) Applications
  - Inaccessible Scenarios
  - Replacement Costs >> Unit Costs

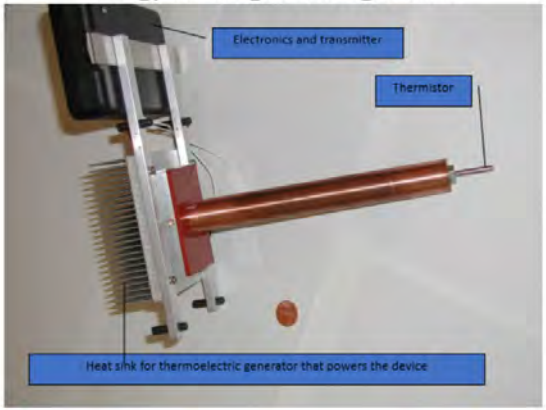
Aluminum plant

Few hundred cells connected in series – DC current about 300,000 Amps.~4 volts/cell = safety hazard (inhibition of use of signal wires). Energy inefficient (~50%).



Typical wireless, self-powered, device – duct gas temperature measurement

Energy scavenged from gas itself



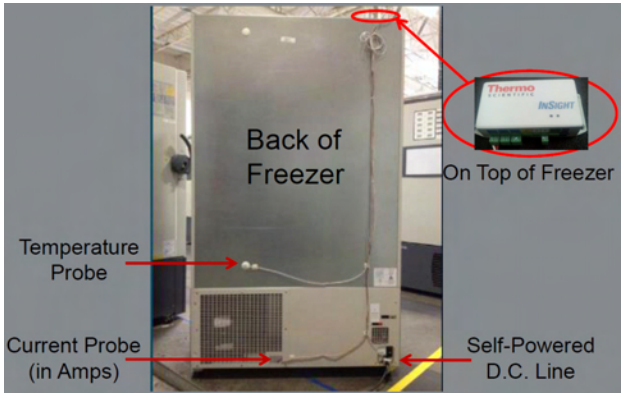
IMAGES CREDIT: J. W. Evans, "Industrial IOT – some examples," UC Berkeley, 2017FLEX Short Course, Monterey, CA, June 19, 2017.

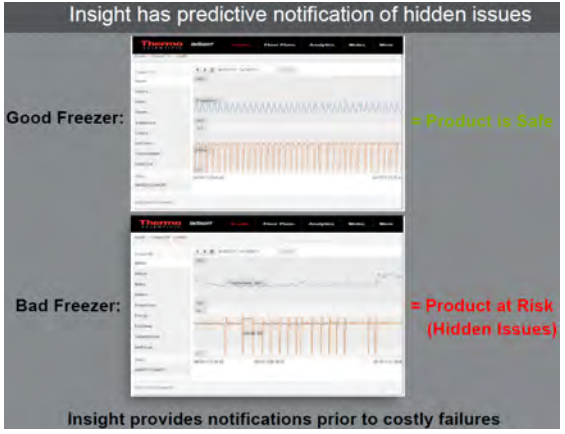
Market-Focused Use Cases

R_x Preventative Maintenance

- Monitor for Equipment Failures
- Mitigate Maintenance/Replacement Costs

IMAGE CREDIT: M. Hayes, "Powering the Internet of Things," Tyndall National Institute, Cork Literary & Scientific Society Presentation, Cork, Ireland, January 28, 2021.



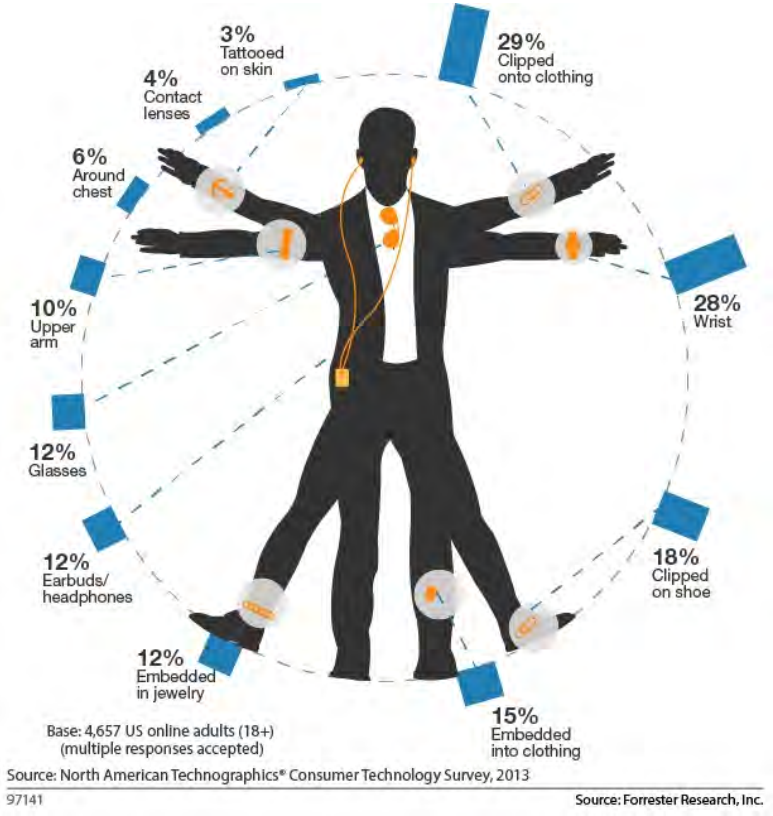


IMAGES CREDIT: L. Newman, "Using Predictive Temperature Monitoring to Reduce Costs & Risk with Refrigerated Storage," ThermoFisher Scientific, IDTechEx US Show 2018, Santa Clara, CA, November 15, 2018.

Market-Focused Use Cases

R_x Wearables / Medical

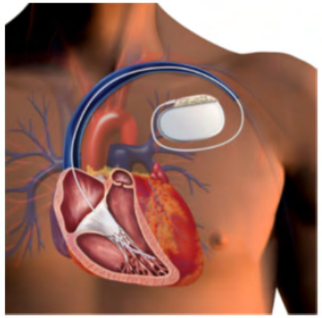
- "Smart" Everything
- You Will See This Stuff Everywhere
- Some You Will Not See At All



Market-Focused Use Cases

R_x Wearables / Medical

- Power is Always the Gate



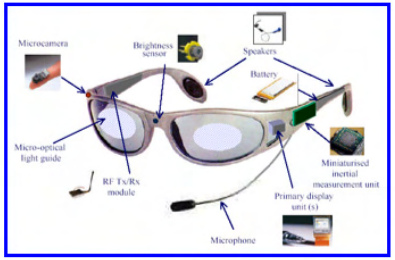
Pacemaker

Sports performance

Assisted living

Smart patch/bandage

Gait monitoring (sports, rehabilitation)



Smart glasses

IMAGE CREDIT: *M. Hayes, "Powering the Internet of Things," Tyndall National Institute, Cork Literary & Scientific Society Presentation, Cork, Ireland, January 28, 2021.*

Market-Focused Use Cases

R_x Wearables / Medical

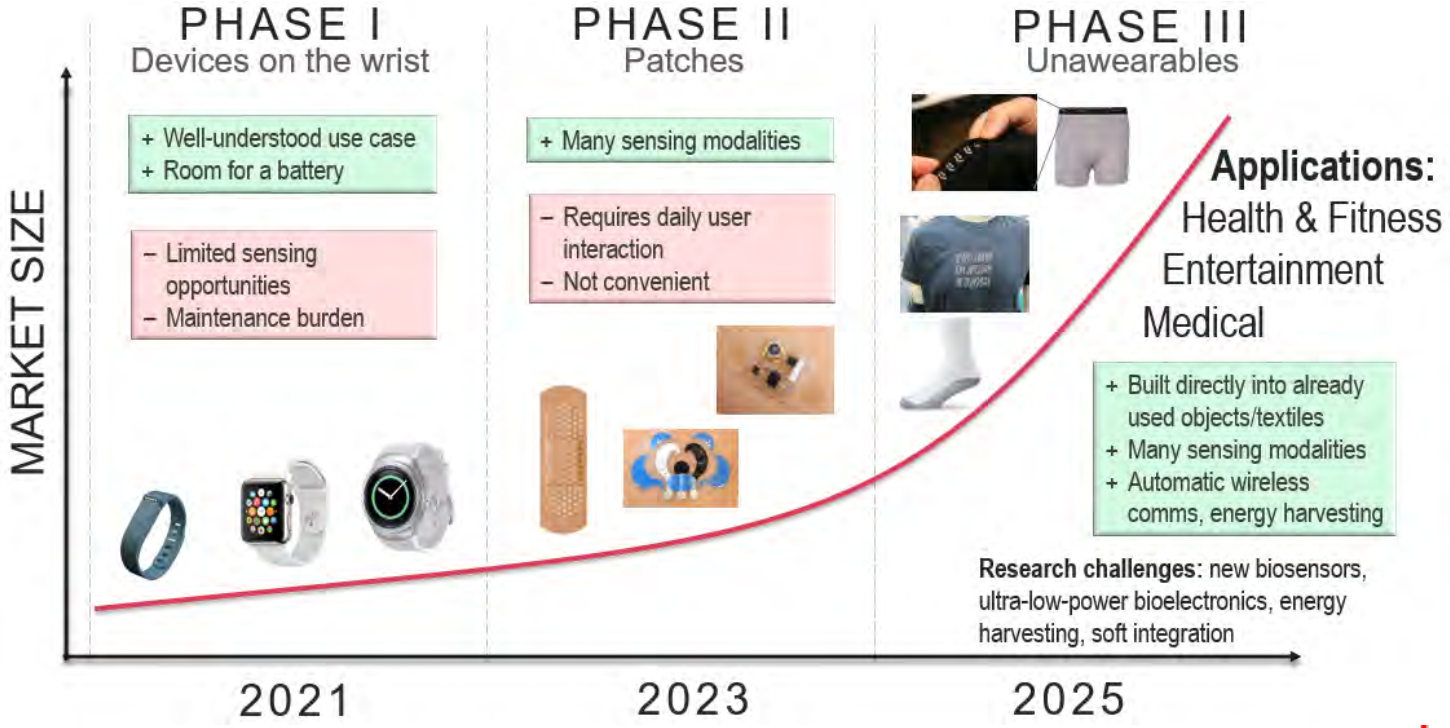


IMAGE CREDIT: *P. Mercier, "Energy Harvesting and Self-Powered Sensing for Next-Generation "Unaware-ables" and IoT," UC San Diego, EnerHarv 2022 Keynote, Raleigh, NC, April 5, 2022.*

Market-Focused Use Cases

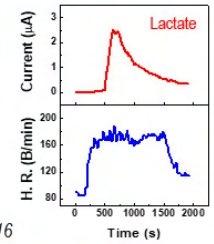
R_x Wearables / Medical

- A Beautiful Convergence of Sensors & Wireless Comms

Non-invasive glucose and alcohol sensing

J. Kim et al., Advanced Science'18

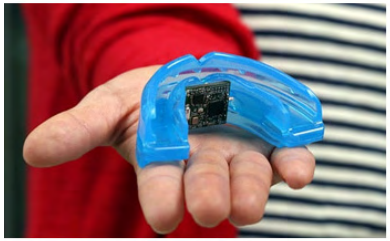
Hybrid physiochemical & electrophysiological sensing



First demonstration of real-time ECG+lactate recording

S. Imani et al., Nature Communications'16

Real-time saliva sensors

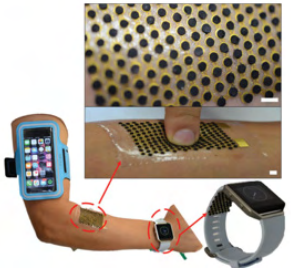


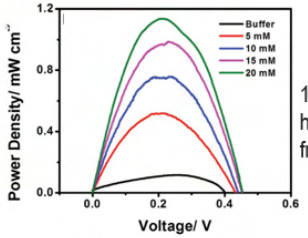
Physiochemical analysis in saliva

Startup company: TRAQ

J. Kim et al., Biosensors & Bioelectronics'15

Bio-energy harvesting





1mW/cm2 harvested from sweat

A.J. Bandodkhar et al., EES'17

IMAGE CREDIT: *P. Mercier, "Energy Harvesting and Self-Powered Sensing for Next-Generation "Unaware-ables" and IoT," UC San Diego, EnerHarv 2022 Keynote, Raleigh, NC, April 5, 2022.*

Summary & Conclusions

- **Tiny Devices at Scale Can Cause BIG Problems**
  - This Energy Gap May Cause Billions of Tiny Things to be a Risk to Utility Grid Stability
- **It is all about utilization and consolidation! Reducing power demand yields far more benefits than simply a bigger battery.**
- **It is important to FIRST reduce the system budget as much as possible before trying to size the source to the load.**
- **EH is highly salient in today's IoT/IIoT applications, whether complimentary or comprehensive to the application.**
  - Supported by a Robust and Growing Power IoT Ecosystem
- **Test/Measurement/Characterization just as critical to system's success as the design.**
- **While not always well known, there are many resources for accelerating a low-power (IoT/IIoT) product development.**

A Closing Poll

Raise your hand if you think it is critical to mitigate losses of…

…1 W?

…1 mW?

…1 µW?

Q & A

Thanks a lot for your time and attention!

Any questions and/or comments?

PRx™
PowerRox

References

- "New Department Of Energy Program Incentivizes Pedestrians, Cyclists To Switch To Electric Vehicles," The Onion, June 13, 2022. [Online]. Available: https://www.theonion.com/new-department-of-energy-program-incentivizes-pedestria-1848968853.
- M. Hayes and B. Zahnstecher, "The Virtuous Circle of 5G, IoT and Energy Harvesting [Cover Story]," in IEEE Power Electronics Magazine, vol. 8, no. 3, Sept. 2021.
- "Estimated U.S. Energy Consumption in 2020," Lawrence Livermore National Laboratory, March 2021.
- Wikipedia contributors, "Clive Humby," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Clive_Humby&oldid=1067348557 (accessed April 15, 2022).
- Rob Aitken "Predictions for a connected 2018," ARM Company Blog, Posted 8 Jan 2018.
- Friis Equation - (aka Friis Transmission Formula) = http://www.antenna-theory.com/basics/friis.php
- IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency, 2021 Edition" International Network Generations Roadmap (INGR), Apr. 9 2021.
- IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency - 1st Edition White Paper," International Network Generations Roadmap (INGR), Apr. 2020.
- IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency, 2022 Edition" International Network Generations Roadmap (INGR), Mar. 22 2022. [Online]. Available: https://futurenetworks.ieee.org/roadmap.
- Monroe, Jazz, "Public Enemy Announce New Album, Return to Def Jam," Pitchfork, August 28, 2020. [Online]. Available: https://pitchfork.com/news/public-enemy-announce-new-album-return-to-def-jam/.
- C. Ho, "Flexible Energy Storage Considerations," Imprint Energy, 2017FLEX Short Course, Monterey, CA, June 19, 2017.
- P. Mars, "Supercapacitors support low power Energy Harvesters & Coin Cells," CAP-XX, EnerHarv 2018, Cork, Ireland, May 30, 2018.
- D. Pasero, "IoT sensors powered by solid state batteries and harvested energy," Ilika Technologies, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.
- Typical Li+ Charge Profile, from Qorvo ACT2801 Spec Sheet. [Online]. Available: https://www.qorvo.com/products/d/da006751.
- Ascent Solar EnerPlex Surfr phone charging case. http://www.goenerplex.com/products/solar-and-battery-phone-cases/surfr-for-iphone-6-6s.
- How to Build a Homemade Thermoelectric Generator, 2017. [Online]. Available: https://topmagneticgenerator.com/build-homemade-thermoelectric-generator/.
- "AEM10941," e-peas Product Overview, Viewed January 12, 2020.
- EU EnABLES Project, "Research Infrastructure Position Paper, European Infrastructure Powering the Internet of Things" EU EnABLES Project, February 2021.
- M. Hayes and B. Zahnstecher, "The Virtuous Circle of 5G, IoT and Energy Harvesting," IEEE Power Electronics Webinar, Nov. 10, 2021.
- Becker T, Borjesson V, Cetinkaya O, et al., "Energy Harvesting for a Green Internet of Things," Power Sources Manufacturers Association (PSMA) White Paper, Oct. 2021.

References

- Würth Elektronik Gleanergy = http://www.we-online.com/web/en/electronic_components/produkte_pb/demoboards/gleanergy/gleanergy.php.
- CYALKIT-E02 Solar-Powered BLE Sensor Beacon Reference Design Kit (RDK) = http://www.cypress.com/documentation/development-kitsboards/cyalkit-e02-solar-powered-ble-sensor-beacon-reference-design.
- NanoRanger Product Overview, https://www.altonovus.com/nanoranger.
- Enspect - Tool for predicting the output of energy harvesting systems. [Online]. Available: http://www.enspect.ecs.soton.ac.uk/. Accessed 7/12/19.
- A. S. Weddell, "Energy Harvesting in Future IoT Devices," University of Southampton / ARM-ECS Research Centre, 2018 EnerHarv Workshop, Cork, Ireland, May 31, 2018.
- Custom Solar Panel Design Tool. [Online]. Available: https://www.powerfilmsolar.com/custom-solutions/custom-solar-panel-design-tool. Accessed 8/16/22.
- "N2820A/21A High-Sensitivity, High Dynamic Range Current Probes," Keysight Data Sheet, Downloaded December 20, 2016.
- Seshank Malap, “Energy Harvesting & IoT Power Analysis," Tektronix, IEEE PELS Energy Harvesting Workshop, April 20, 2017.
- Mahmoud, M.S. and Mohamad, A.A.H. (2016) A Study of Efficient Power Consumption Wireless Communication Techniques/Modules for Internet of Things (IoT) Applications. Advances in Internet of Things, 6, 19-29.
- B. Chen, "Powering the IoT: An Energy Harvesting Perspective," Analog Devices, EnerHarv 2022 Keynote, Raleigh, NC, April 7, 2022.
- 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.
- M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.
- M. Kelly, R. Fishbune, "Factory of the Future Technologies and Approaches Applied to Solve Today’s Power Density Challenges," IPC/IBM Collaboration, APEC 2021 Industry Session, Phoenix, AZ, June 10, 2021.
- G. Pitel, "Power Electronics Hardware Design For Manufacturability," Magna-Power, IEEE SFBAC PELS Monthly Meeting, Mountain View, CA, September 15, 2022.
- J. W. Evans, "Industrial IOT – some examples," UC Berkeley, 2017FLEX Short Course, Monterey, CA, June 19, 2017.
- M. Hayes, "Powering the Internet of Things," Tyndall National Institute, Cork Literary & Scientific Society Presentation, Cork, Ireland, January 28, 2021.
- L. Newman, "Using Predictive Temperature Monitoring to Reduce Costs & Risk with Refrigerated Storage," ThermoFisher Scientific, IDTechEx US Show 2018, Santa Clara, CA, November 15, 2018.
- P. Mercier, "Energy Harvesting and Self-Powered Sensing for Next-Generation “Unaware-ables” and IoT," UC San Diego, EnerHarv 2022 Keynote, Raleigh, NC, April 5, 2022.