3D-PEIM
3D Power Electronics Integration and Manufacturing

PowerRox™

PSMA

"Powering the Internet of Things"

3D-PEIM KEYNOTE:
Energy Harvesting at the Edge: When the Package *IS* the System

Friday, February 3, 2023

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Presenter

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***Chair**, IEEE Future Networks Initiative (FNI) Webinar Series*
***Co-chair**, IEEE 5G Energy Efficiency Tutorial*
***Chair (Emeritus),** SF Bay IEEE Power Electronics Society (PELS)*
***Chair (Emeritus),** PELS Technical Committee (TC) 7*
***Regional Chair,** PELS Regions 1-3*

Food For Thought

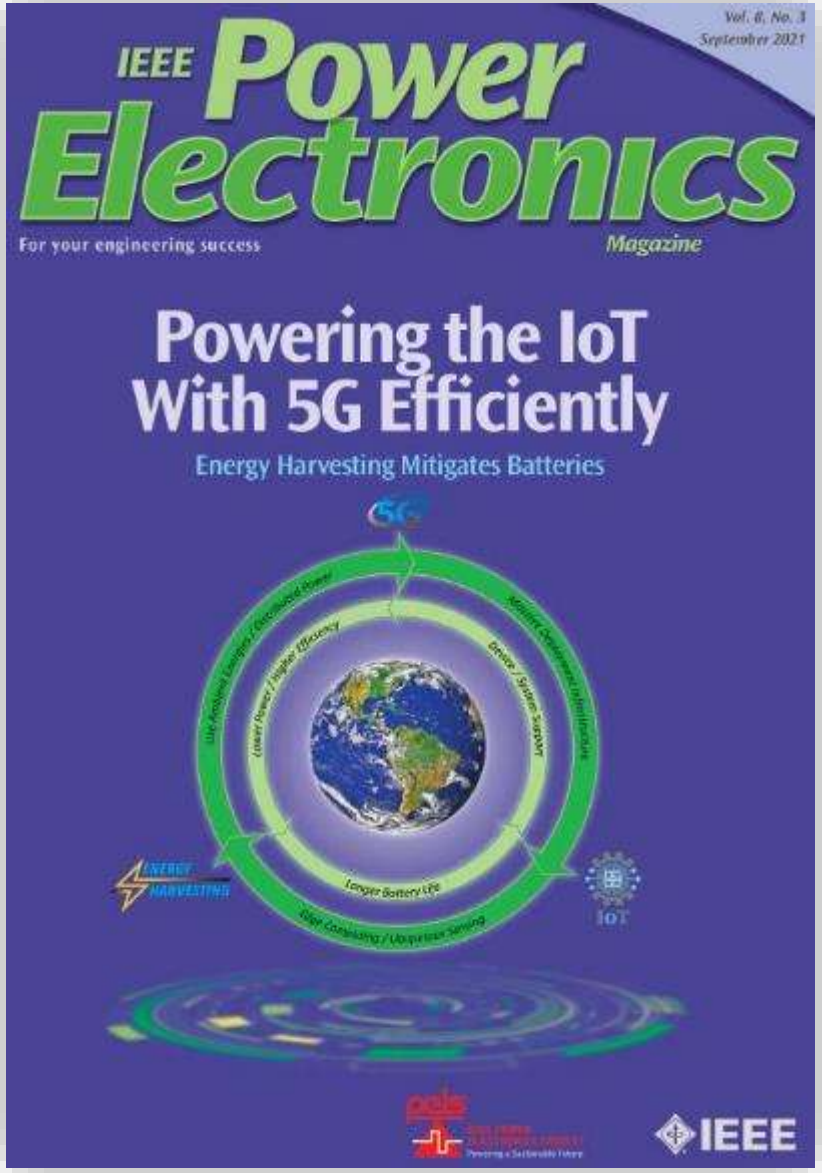
IMAGE CREDIT: *"Nation's Monster Truck Rally Organizers Vow To Crush 100% Electric Cars By 2030," The Onion, March 1, 2021. [Online]. Available: https://www.theonion.com/nation-s-monster-truck-rally-organizers-vow-to-crush-10-1846366255.*

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.*

Progress???

☺

Food For Thought



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.*

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.

Overview

- The True Cost of Power at the Edge
- What is energy harvesting (EH)?
- Packaging's Role in EH
- Examples / Use Cases
- The Power IoT Ecosystem
- 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 True Cost of Power at the Edge

3D-PEIM

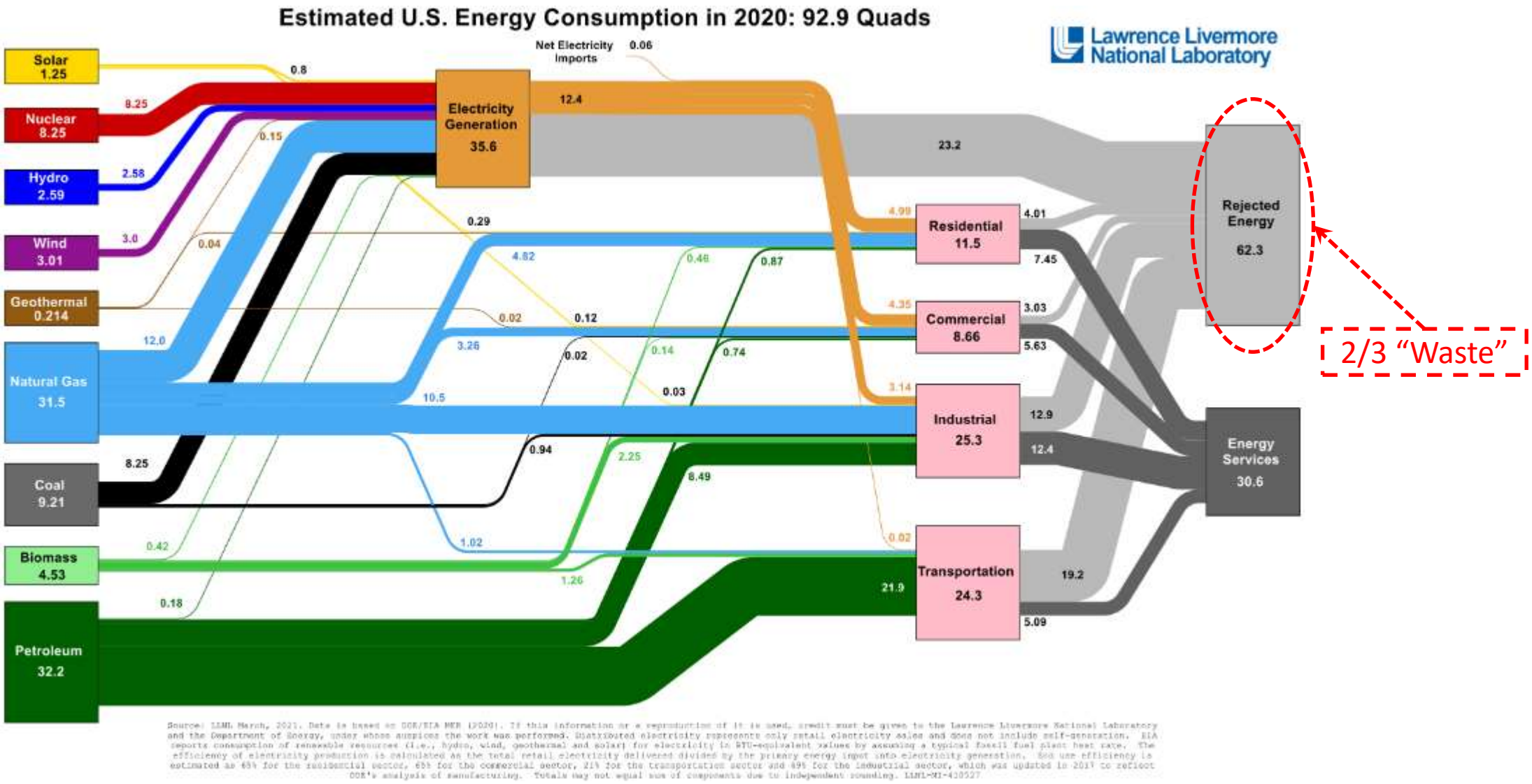


IMAGE CREDIT: *"Estimated U.S. Energy Consumption in 2020" Lawrence Livermore National Laboratory, March 2021.*

The True Cost of Power at the Edge

The Power Value Chain (PVC)

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

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.*

The True Cost of Power at the Edge

What is the Entire Power Value Chain (PVC)?

- The Complete Power Picture from End-to-End

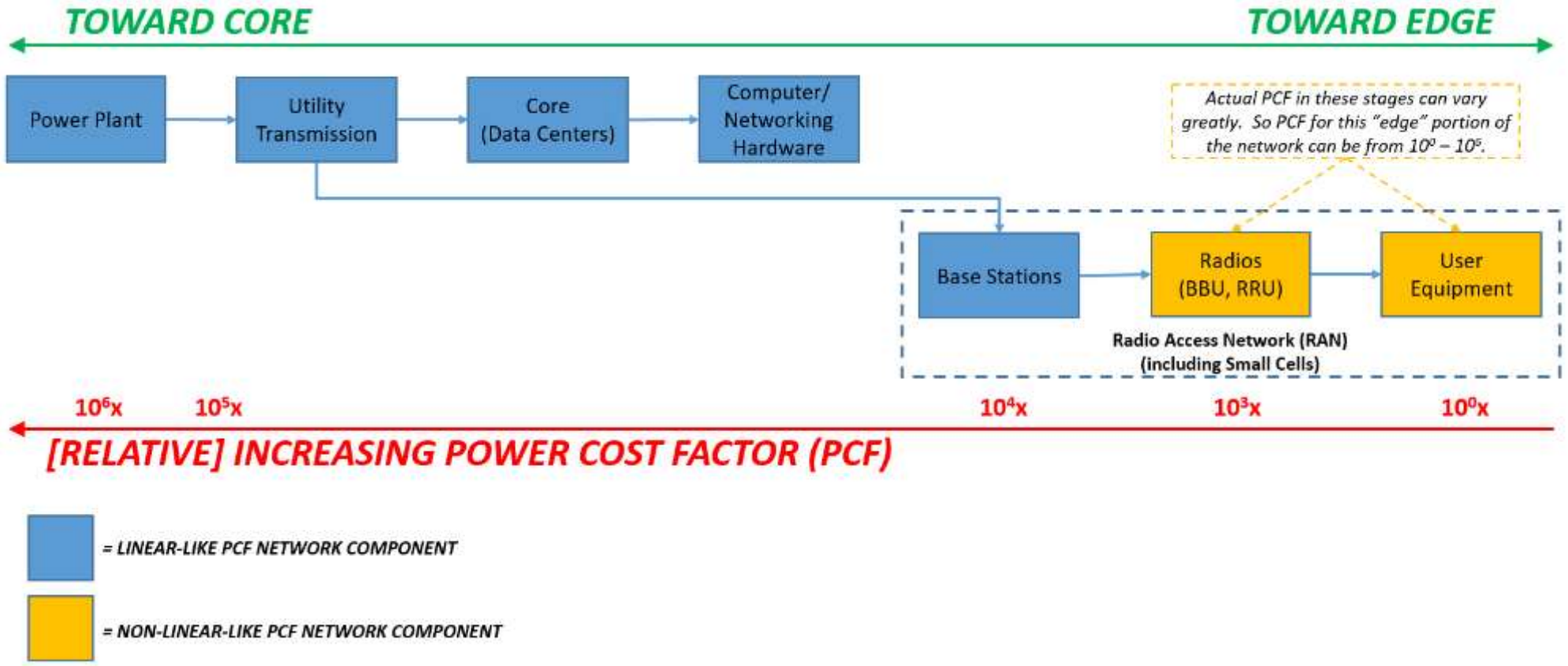


IMAGE CREDIT: IEEE Future Networks Initiative - Energy Efficiency Working Group, "Energy Efficiency - 1st Edition White Paper," International Network Generations Roadmap (INGR), Apr. 2020.

The True Cost of Power at the Edge

What is the TRUE cost of 1 mW?

- So for each 1 mW of received power at the device (i.e. – edge, mote, etc.), ***1-2 W*** need to be transmitted by the base station.
- Each 1 W of transmit power will draw of ***16.7-50 W*** at the input of the base station.
- From the utility grid, we lose 8-15 % of our power in transmission from power plant to the base station.

So the true cost of *EACH 1 mW* of received data at the edge requires *~18,000x-60,000x (18-60 W)* of power generated at the power plant!

Now, multiply that by 10s of billions or even 1 T devices!!!

The True Cost of Power at the Edge

The Disproportionate Impact of Tiny Power on Big Power

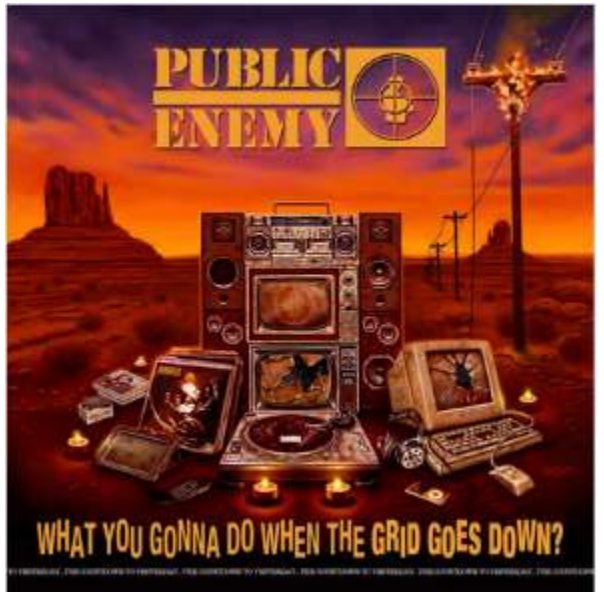
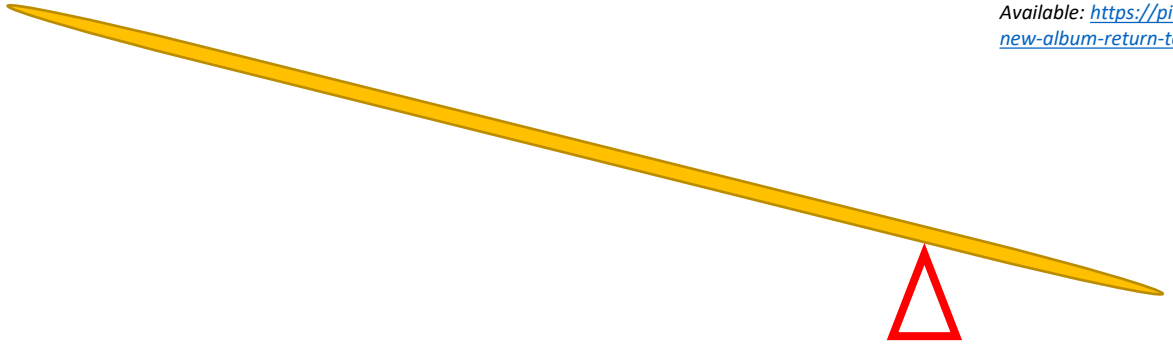


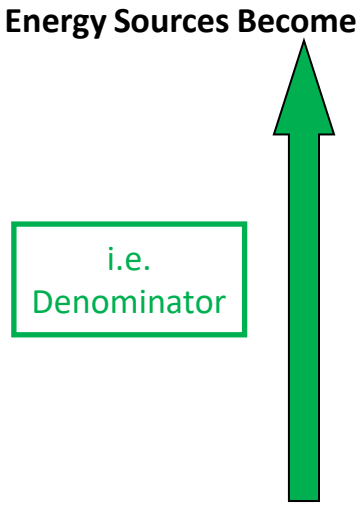
IMAGE CREDIT: *Monroe, Jazz, "Public Enemy Announce New Album, Return to Def Jam," Pitchfork, August 28, 2020. [Online]. Available: https://pitchfork.com/news/public-enemy-announce-new-album-return-to-def-jam/.*



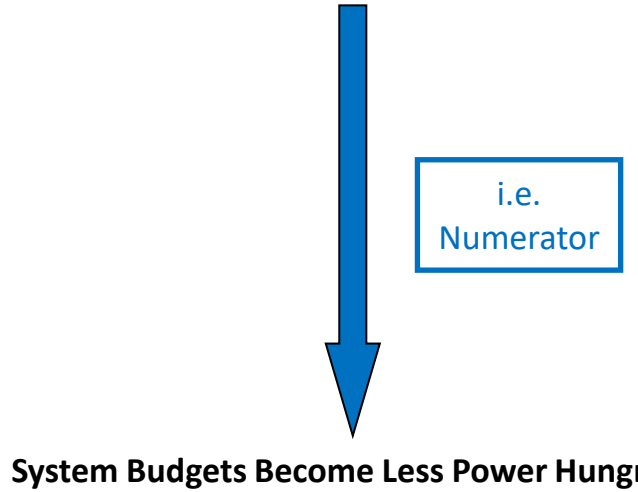
What is energy harvesting (EH)?

Source Versus Load

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



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



What is energy harvesting (EH)?

Battery Replacement Mitigation

- Primary → Secondary Energy Storage
- Garbage / Hazardous Materials
- Replacement Efforts
  - Push For Rechargeable Battery Applications
- Overall Design Effort (i.e. – Redundancy, Overprovisioning, Etc.)
- Short-, Near-, & Long-Term Strategies

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!!!

What is energy harvesting (EH)?

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

What is energy harvesting (EH)?

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

What is energy harvesting (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***-ISH***

What is energy harvesting (EH)?

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 energy harvesting (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

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.*

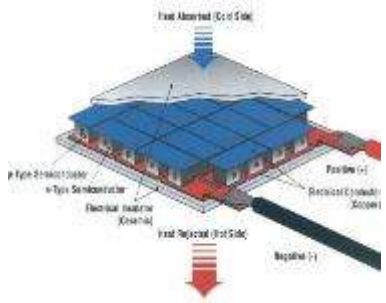


IMAGE CREDIT: *How to Build a Homemade Thermoelectric Generator, 2017. [Online]. Available: https://topmagneticgenerator.com/build-homemade-thermoelectric-generator/.*

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

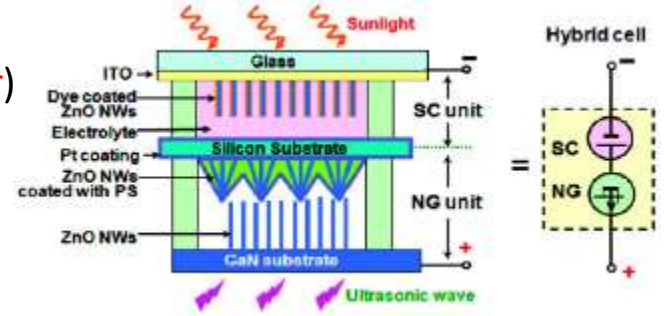


IMAGE CREDIT: *Chen Xu, Xudong Wang and Zhong Lin Wang, "Nanowire Structured Hybrid Cell for Concurrently Scavenging Solar and Mechanical Energies", J. Am. Chem. Soc., 131(2009) 5866-5872.*

IMAGE CREDIT: *Inertia Films*

What is energy harvesting (EH)?

Critical Environmental Factors

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

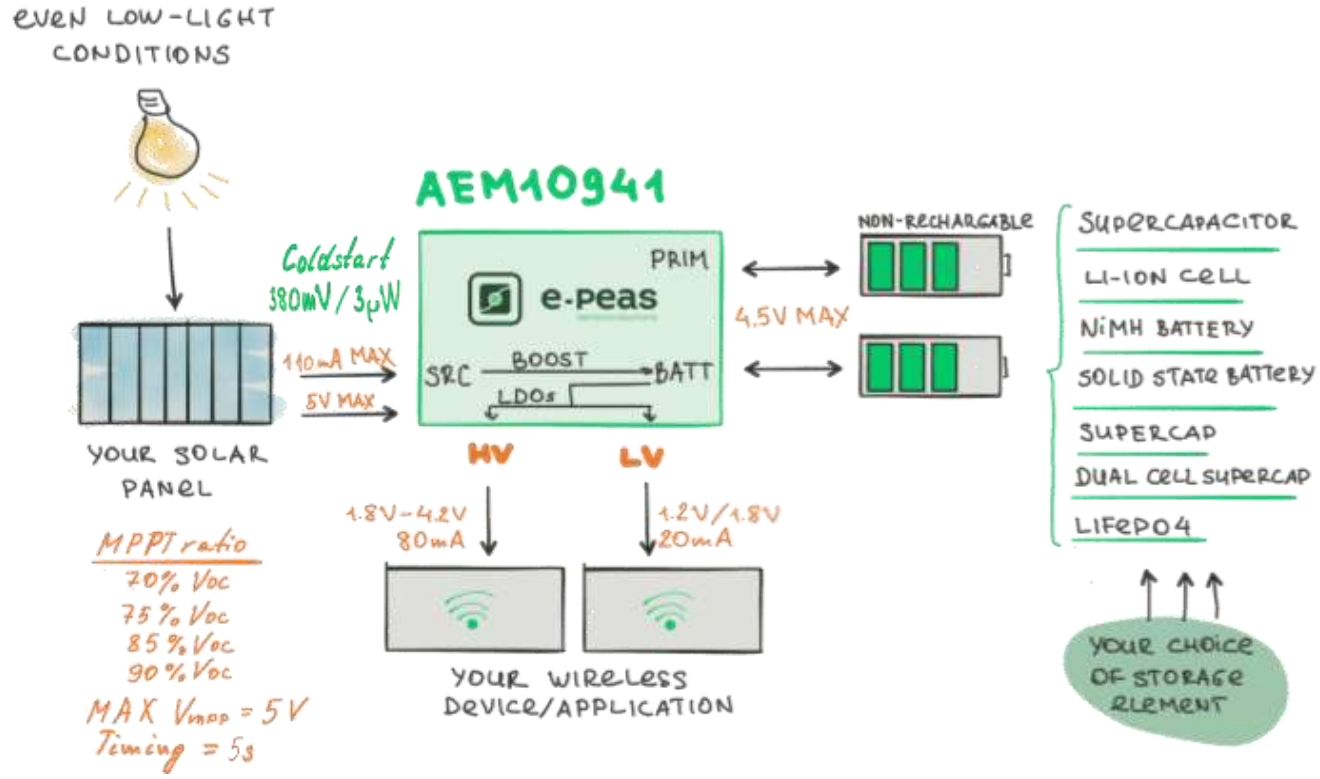


IMAGE CREDIT: *"AEM10941," e-peas Product Overview, Viewed January 12, 2020.*

What is energy harvesting (EH)?

Critical Environmental Factors

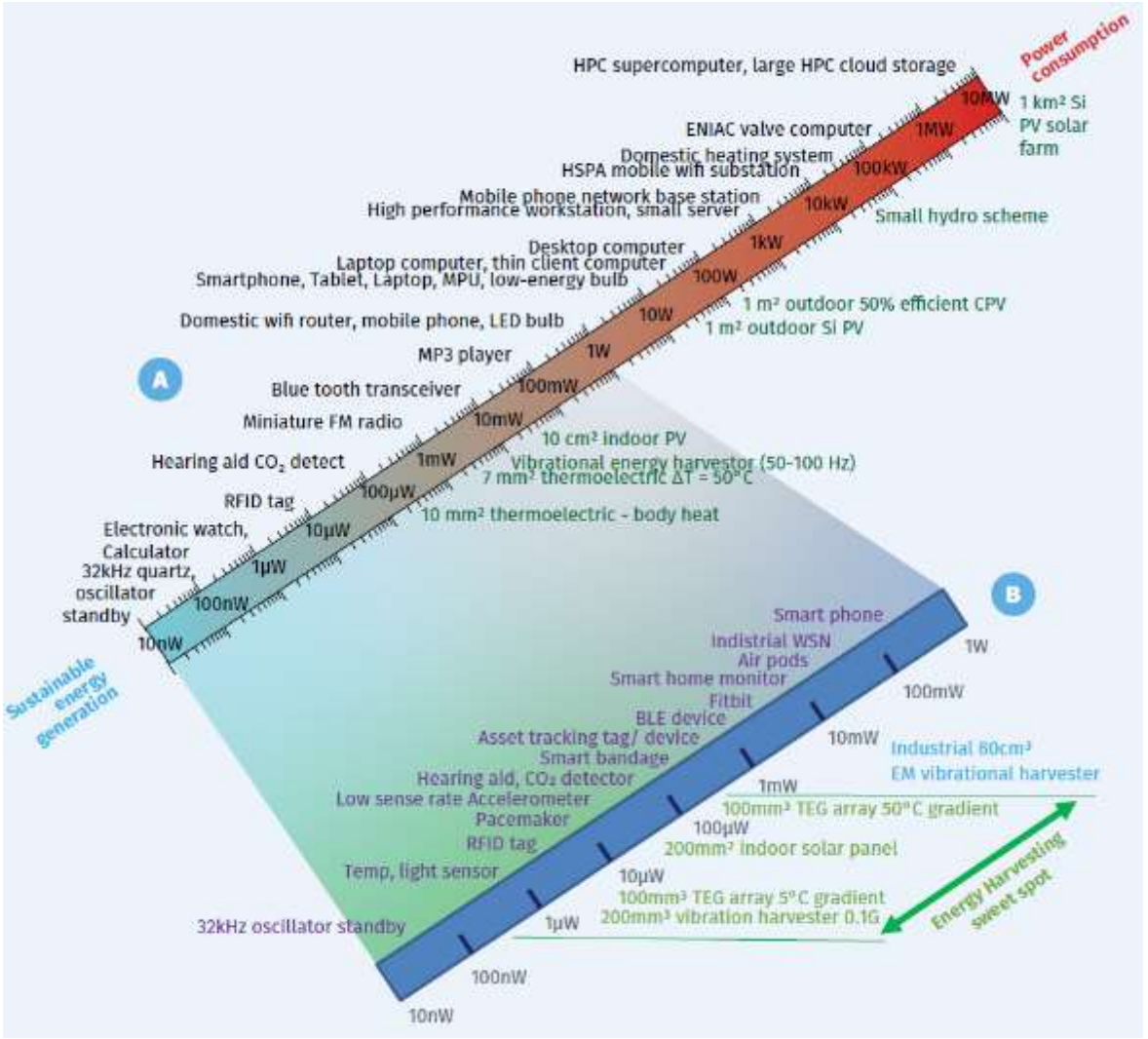
- Harsh Environments
- Inaccessible / Difficult to Access Sensors / Batteries
- Monitoring Data on Steroids
- Truly Permanent Installations

What is energy harvesting (EH)?

Mapping the Sources to the Loads

Energy Harvesters become more capable

i.e. Denominator



i.e. Numerator

Electronic devices become less power hungry

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

What is energy harvesting (EH)?

Mapping the Sources to the Loads

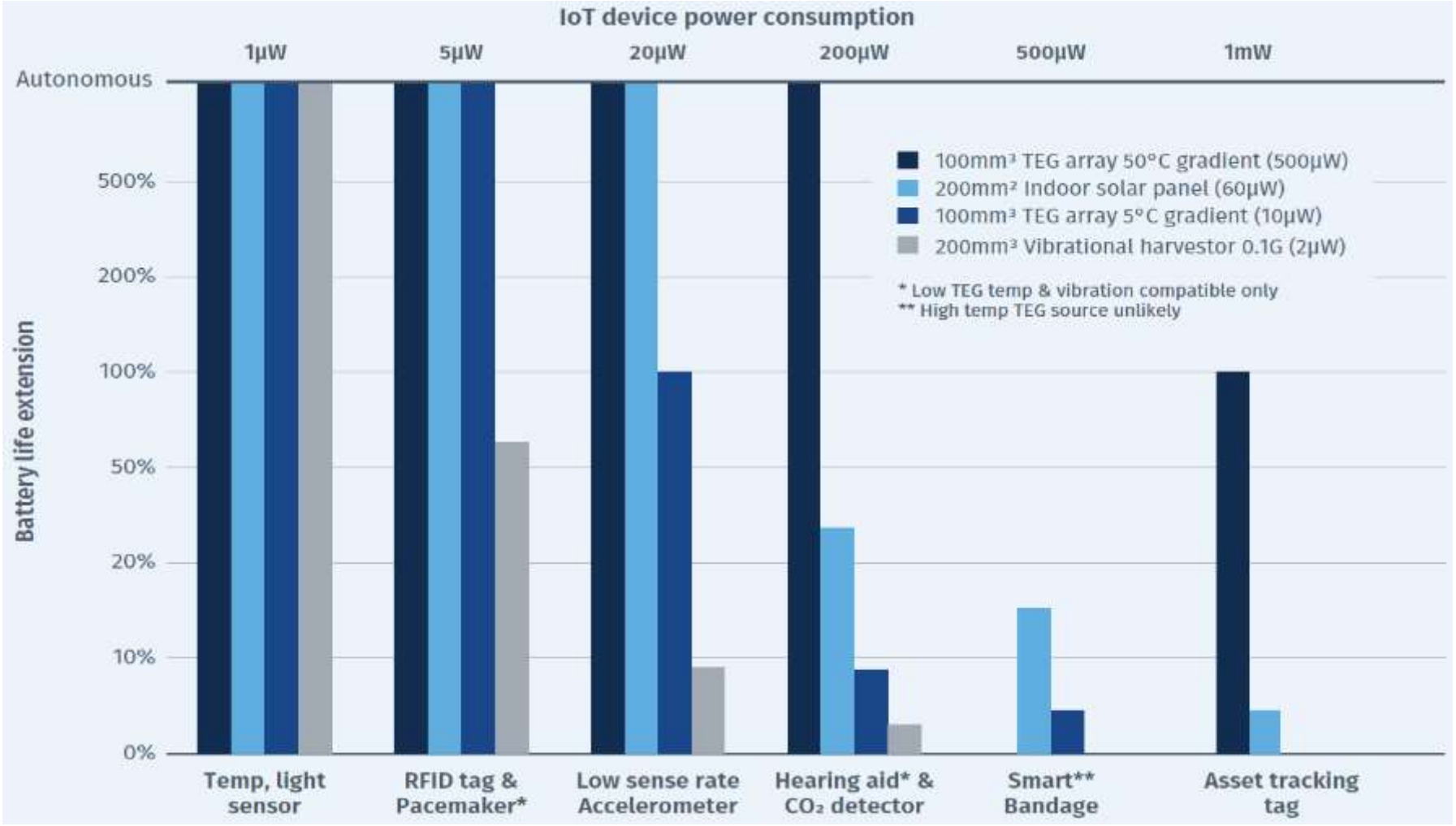


IMAGE CREDIT: *EU EnABLES Project, "Research Infrastructure Position Paper, European Infrastructure Powering the Internet of Things" EU EnABLES Project, February 2021.*

Packaging's Role in EH

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.*

- Invisible, Ubiquitous EH Integration

Packaging's Role in EH

Integrating EH

- The Package Becomes Part of the Functional System
  - Exposure to Light/Humidity
  - Thermal Transfer/Differential
  - Vibrational Energy Transfer/Absorption
  - Orientation
  - Magnetics Integration
  - Communications
  - Sensors/Transducers
  - HV Isolation (in tiny geometries)

Packaging's Role in EH

Integrating EH

- Heterogeneous Integration
  - Passives
    - Resistors
    - Capacitors
    - Inductors/Transformers (inc. planar magnetics)
    - Diodes
    - Protection Devices
    - Antennas*
  - Actives
    - Power Switches
    - Controllers/Drivers/Power Management ICs (PMIC)
    - Battery Management System ICs (BMS)
    - Sensors
    - Communications
  - Interconnects/Substrates
    - Circuit Traces/Conductors
    - Connectors
    - Pins/Bumps/Pads

IMAGE CREDIT: *PSMA Packaging Committee, "3D Power Packaging With Focus on Embedded Passive Component and Substrate Technologies," PSMA 3D Power Packaging Phase III, Power Sources Manufacturers Association (PSMA), February 2018.*

Packaging's Role in EH

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.*

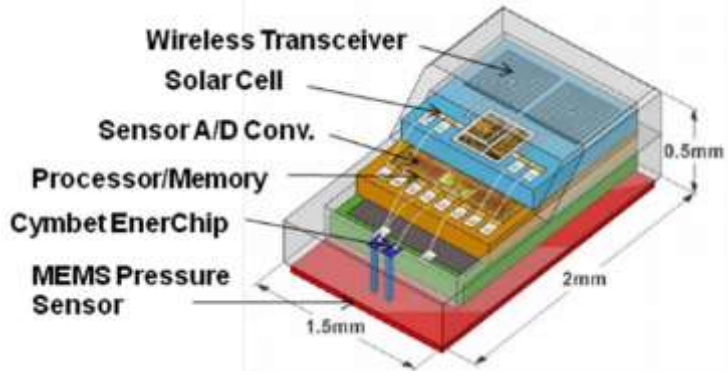
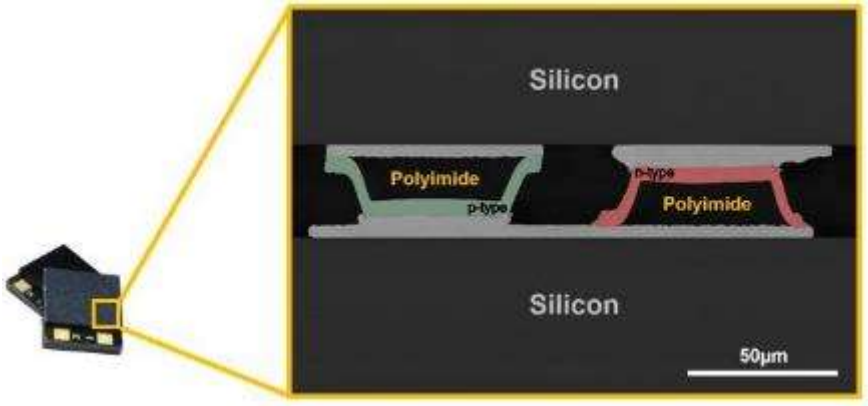


IMAGE CREDIT: *D. Pasero, "IoT sensors powered by solid state batteries and harvested energy," Ilika Technologies, APEC 2018 Industry Session, Tampa, FL, March 6, 2018.*

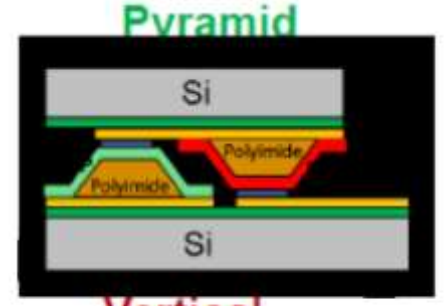
Packaging's Role in EH

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



IMAGES CREDIT: *M. Dunham, "Chip Scale Thermoelectric Generator for Smart Agriculture," Analog Devices, APEC 2018 Industry Session, San Antonio, TX, March 6, 2018.*



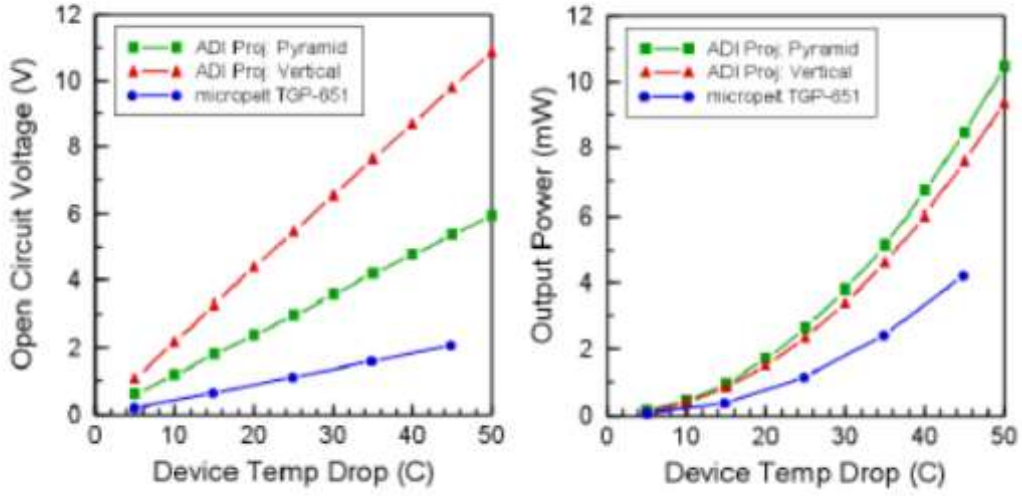
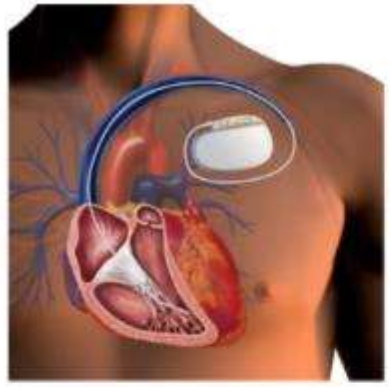


IMAGE CREDIT: *B. Chen, J. Cornett, "Chip Scale TEG and its Use for a Wireless Machine Health Monitoring System," Analog Devices, APEC 2017 Industry Session, Tampa, FL, March 30, 2017.*

Examples / Use Cases

Wearables / Medical

- Kinetic Motion
  - Move Arm
  - Take Step
  - Contract Ventricle
- Temperature
  - Internal/External Differential
- Sweat/Saliva
- Bio Battery
- WPT (RF & Ultrasonic)



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.*

Examples / Use Cases

Wearables / Medical

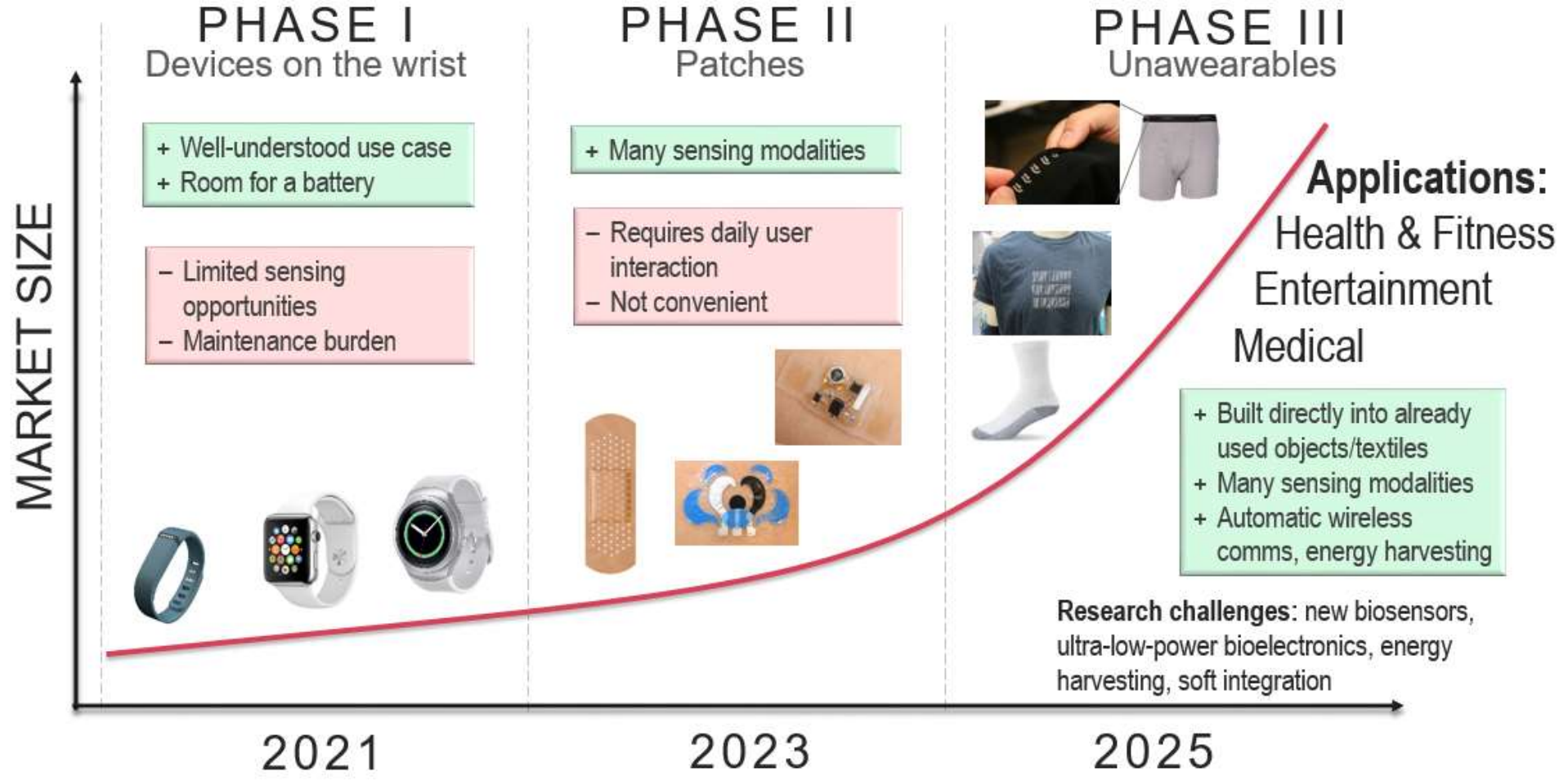


IMAGE CREDIT: *P. Mercier, "Energy Harvesting and Self-Powered Sensing for Next-Generation "Unaware-ables" and IoT," UC San Diego, EnerHarv 2022 Keynote, Raleigh, NC, April 5, 2022.*

Examples / Use Cases

Energy Harvesting Remote Control

- Integrated PV for Indoor Harvesting
- Average daily power consumption of 24µW based on:
  - 500 key presses
  - 20 voice activations
  - Continuous connectivity with TV for fast response
- Coin cell (CR2032) plus supercapacitor for harvested energy storage

IMAGE CREDIT: *"Energy Harvesting PV Remote," Atmosic Technical Overview, Atmosic Technologies, May 26, 2022.*

Examples / Use Cases

Conditional Monitoring

- Industrial Thermal Differentials
- Steam Trap Monitoring

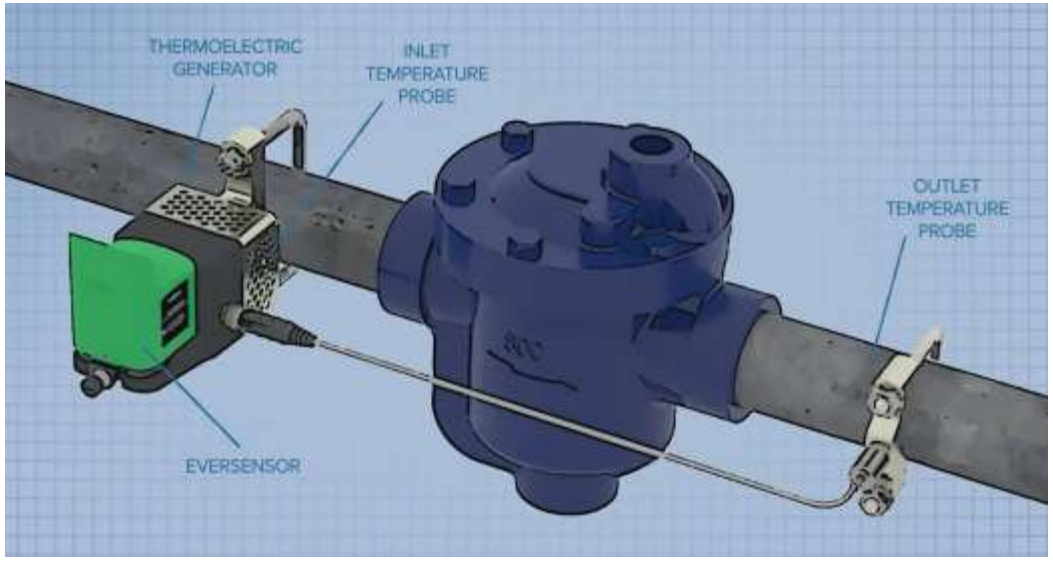
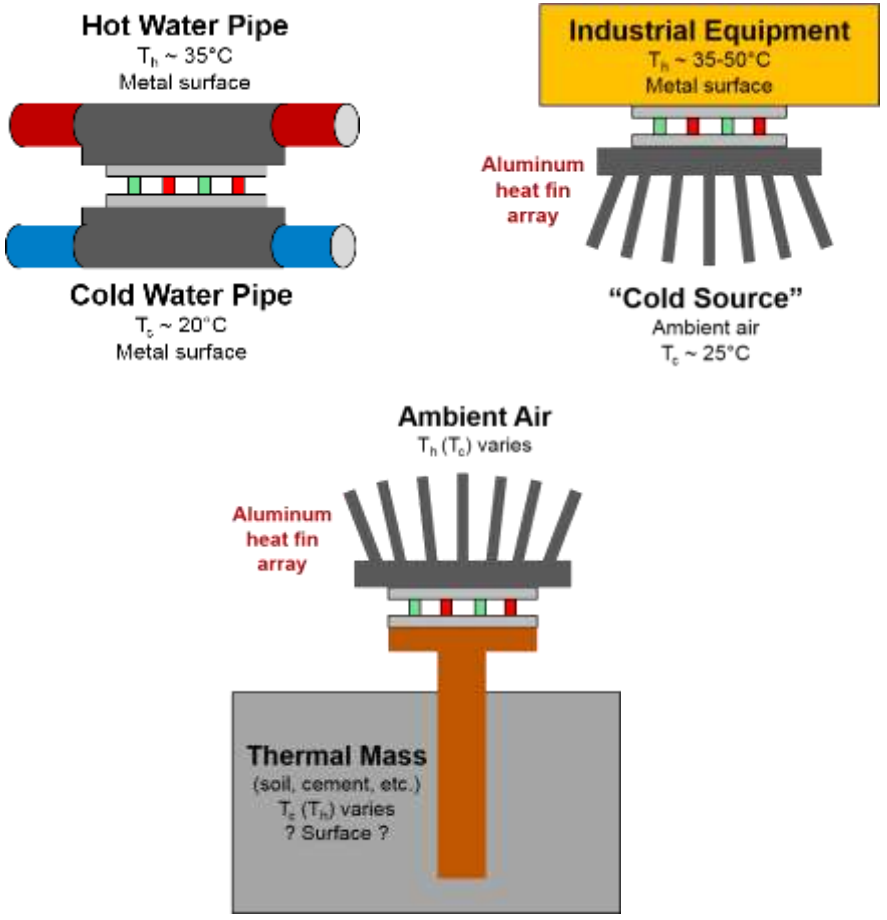


IMAGE CREDIT: "Real-Time, Continuous Steam Trap Monitoring," Everactive, Accessed January 27, 2023. [Online]. Available: https://everactive.com/applications/steam-trap-monitoring/



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

Examples / Use Cases

Predictive Maintenance

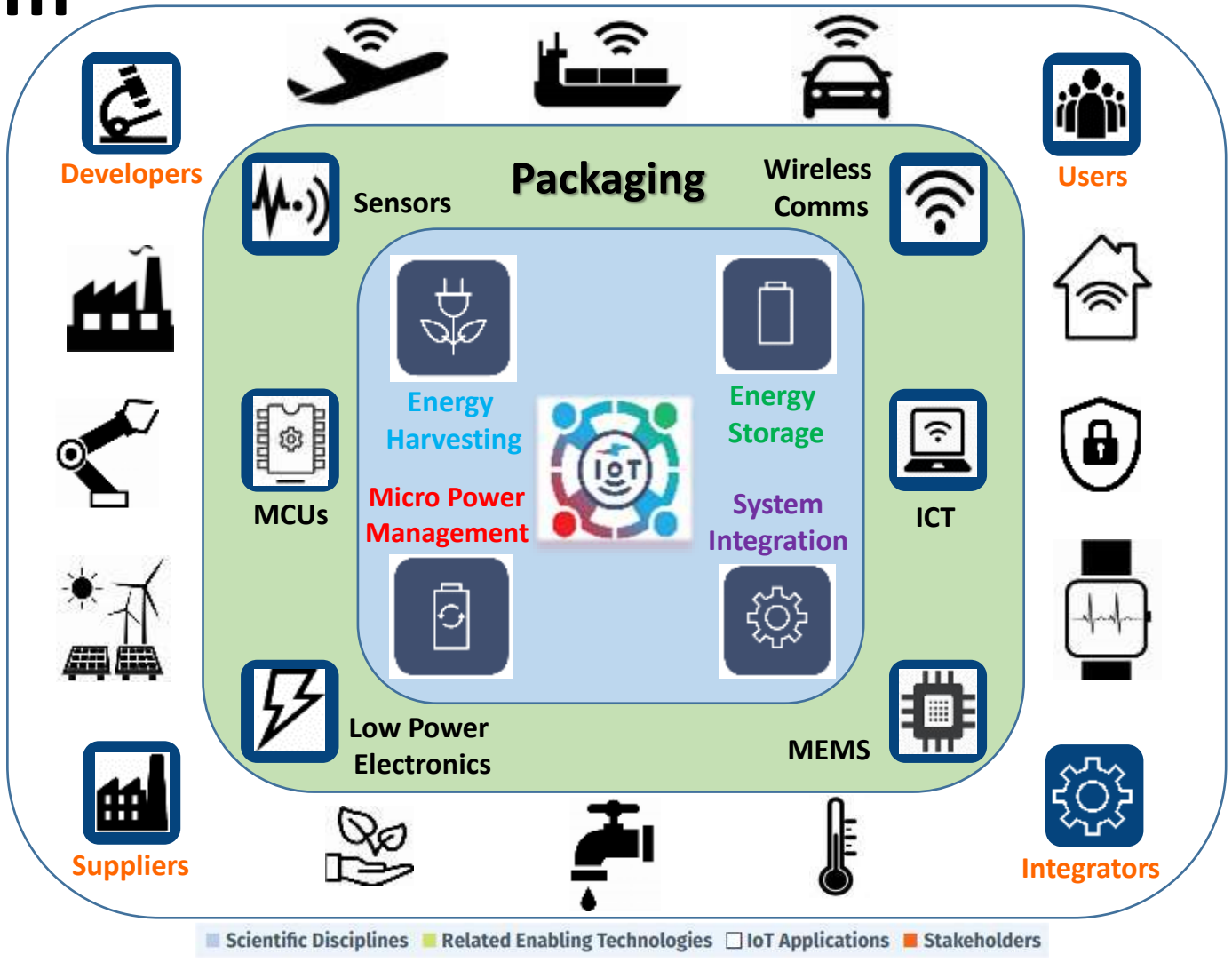
- Manufacturing Equipment Powers/Diagnoses/Reports Own Issues
- Low-to-High-Frequency Vibration

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

The Power IoT Ecosystem

The Power IoT Ecosystem

- It Takes a Village…
- …Here is Ours



The Power IoT Ecosystem

- **Our evolution**
- **Curiosity → Interest → Initiative → Drive Change**
- **Turning Skepticism Into Awareness & Excitement**
- **Harmonizing Industry & Academia**

IMAGE CREDIT: *EnerHarv 2018 PSMA Energy Harvesting Workshop = http://www.EnerHarv.com.*

The Power IoT Ecosystem

The PSMA Energy Harvesting Committee

- "*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*
- Originators of EnerHarv Workshop & Power IoT Ecosystem
- Longtime Sponsors of APEC Industry Sessions
- Co-chairs
  - Mike Hayes, Tyndall National Institute
  - Brian Zahnstecher, PowerRox
- https://www.psma.com/technical-forums/energy-harvesting

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.*

The Power IoT Ecosystem

The EnerHarv Workshop

- Inaugural Event Held May ‘18 in Cork, Ireland
- Last Event Held April ‘22 in Raleigh, NC, USA
  - Technically Co-sponsored by PELS Since Inception
- EnerHarv ’22 Strong Workshop Committee (~30 folks)
  - General Co-chairs
    - Mehmet Ozturk, NC State University
    - Brian Zahnstecher, PowerRox
  - Technical Co-chairs
    - Mike Hayes, Tyndall National Institute
    - Shad Roundy, University of Utah
- http://www.EnerHarv.com/

EnerHarv

2024 PLANNING KICKING OFF NOW!!! (SEE YOU IN EUROPE!)

The Power IoT Ecosystem

3D-PEIM

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
- North Carolina State University
  - Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST)
  - Future Renewable Electric Energy Delivery and Management (FREEDM)
  - Packaging Research in Electronic Energy Systems (PREES)

Georgia Tech | Institute for Electronics and Nanotechnology

Berkeley | EECS
Electrical Engineering and Computer Sciences

NC STATE UNIVERSITY

ASSIST

FREEDM SYSTEMS CENTER

PSMA

The Power IoT Ecosystem

3D-PEIM

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)
- EnABLES
- Energy for Smart Objects (EnSO) Consortium
- Alliance for IoT innovation (AIOTI)

Energy Harvesting
An EPSRC Funded Network

Tyndall National Institute

MCCI Microelectronic Circuits Centre Ireland

Fraunhofer IIS

PSMA

EnABLES

EnSO Energy for Smart Objects

AIOTI Alliance for Internet of Things Innovation

Summary & Conclusions

- **EH is very applicable to many applications TODAY, whether complimentary or comprehensive to the application.**
  - Supported by a Robust and Growing Power IoT Ecosystem
- **One must understand the PVC at lowest-level to accurately predict full, upstream impact (i.e. – utility/distribution).**
  - Metrics such as PCF can be utilized for this purpose.
  - **Tiny Devices at Scale Can Cause BIG Problems**
- **IoT-based & EH solutions can combine to resolve power challenges both at device and system level.**
- **Packaging (especially 3DPP) is Critical in Applications Where Power is Determined by the Surrounding Environment**

Q & A

3D-PEIM
3D Power Electronics Integration and Manufacturing

PRx™ PowerRox

PSMA
IoT
"Powering the Internet of Things"

Thanks a lot for your time and attention!

Any questions and/or comments?

"Plant a seed and harvest it!"

The Multinational Power Electronics Association

Our Mission

To integrate the resources of the power sources industry to more effectively and profitably serve the needs of the power sources users, providers and PSMA members.

i.e. to add value to our members and stakeholders as outlined by our purpose

- *Improve members' knowledge of [PE] technological and other related developments;*
- *Provide focused technical forums for power industry stakeholders to address industry challenges and develop collaborative, pragmatic, application-specific insights to drive solutions;*
- *Educate the entire [ecosystem] as to the importance of PE and paths to growing PE's role in relevant applications*

A power sources industry ecosystem for the benefit of stakeholders

BENEFITS

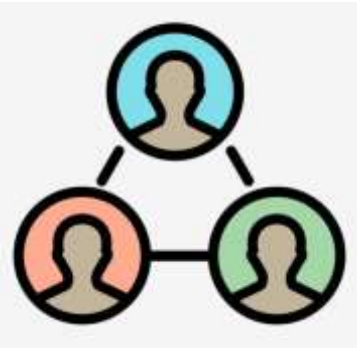
Progress
Enhance
Educate
Inform
Guide
Connect
Publish
Solve

STAKEHOLDERS

Manufacturers
Developers
Suppliers
Educators
Integrators
Users
Funders
Regulators

PSMA Membership Benefits

- **NETWORKING**: The opportunity to meet and interact with your counterparts in other companies on an on-going basis.
- **VALUABLE INFORMATION**: Members enjoy access to information in the Members Only area of the Web site. Members also receive invitations to upcoming Webinars and Workshops.
- **INVOLVEMENT**: Based on the interests of committee members, members plan and organize APEC Industry Sessions, Webinars, Workshops and Conferences.
- **PARTICIPATION**: Members participate in committees, workgroups and studies to derive a better understanding of market trends, industry trends and better operational procedures to improve performance.
- **DISCOUNTS**: Members receive discounts on registration fees for attending APEC and other PSMA-sponsored events.
- **FINDING TRENDS**: Increase awareness and knowledge of trends and factors that can impact your company.
- **COMPANY PROFILE**: Listing of your company's profile on the PSMA website with a hyperlink directly to your company website.
- **PSMA PUBLICATIONS**: Regular members receive one copy of all new PSMA publications and reports with discounts for additional copies. Affiliate members may purchase the publications and reports at the member discount price.
- **BENCHMARKING**: Improve the operation of your company by participating in benchmarking studies with other companies in your industry.
- **PSMA NEWSLETTER**: Receive "Update," the quarterly newsletter of the PSMA, with information on activities in the industry and upcoming events. You may also contribute articles for publication in the "Update."
- **MEMBER COMPANY SPOTLIGHT BANNER**: Feature your company's products on the PSMA Home Page



We are a non profit volunteer-led organization with a mission to serve and nurture the PE community

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