ESSCIRC/ESSDERC 2023
SiNANO-ICOS Workshop
"European Strengths and Gaps in Emerging Semiconductor Technologies"

Energy Harvesting: review of the main EU and international activities and technologies

Gustavo Ardila
IMEP-LaHC
Grenoble Alpes University, France
gustavo-adolfo.ardila-rodriguez@grenoble-inp.fr

Lisbon, September 11, 2023

Outline

- Introduction
- Energy harvesting technologies (IEEE-IRDS)
  - Main technologies, trends, challenges, examples
  - Most active universities / RTO
- Conclusions and perspectives

IEEE Advancing Technology for Humanity
IRDS International Roadmap for Devices and Systems™

MORE THAN MOORE

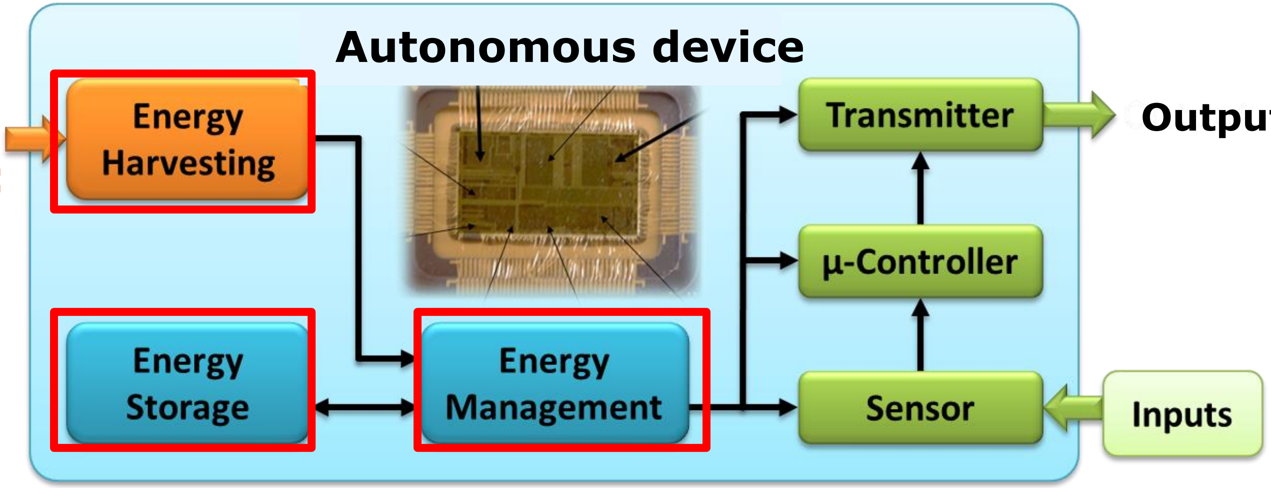
WHITE PAPER

Energy Harvesting

INTRODUCTION

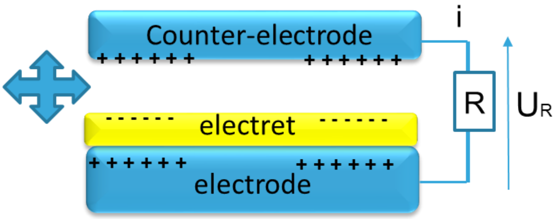
Introduction

- Market growth on connected devices : IoT (estimated 40 billion devices by 2025), healthcare, wearables, home automation…
- Energy supply is essential (<mW, tens of µW) → Energy Harvesting
- EH is important in applications with specific requirements : simple battery is not enough, cords would increase the cost / complexity, too many devices, harsh environment, implants…
  - **Mechanical**
  - **Electromagnetic**
  - **Thermal…**

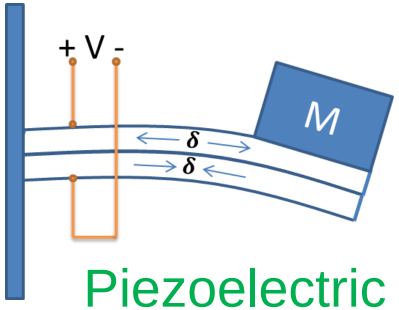


Introduction: Technologies covered so far…

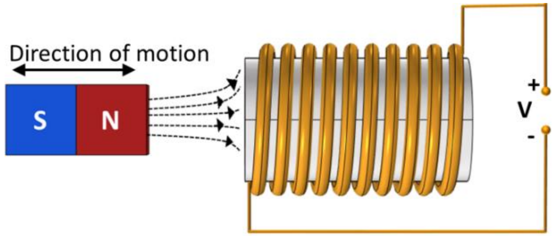
Mechanical EH



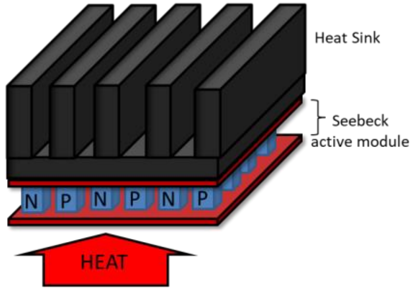
Electrostatic



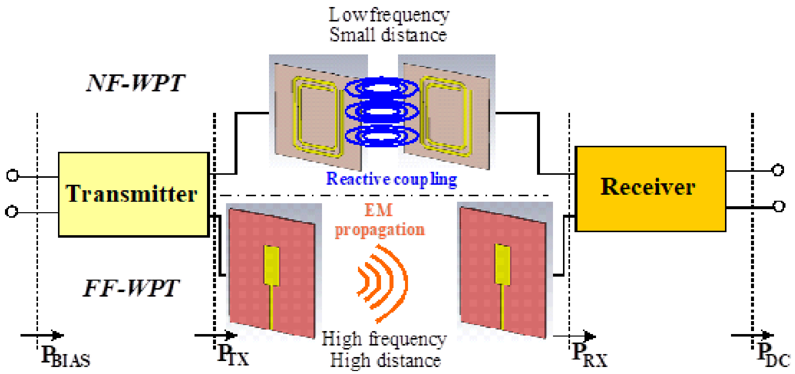
Piezoelectric



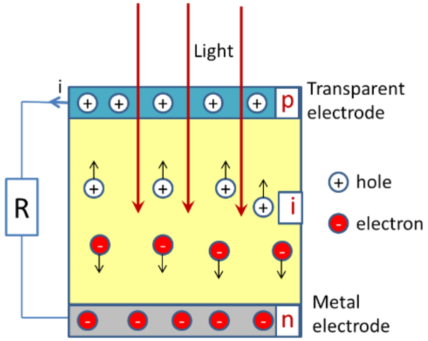
Electromagnetic



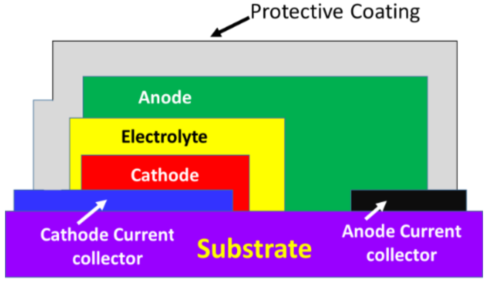
Thermal EH



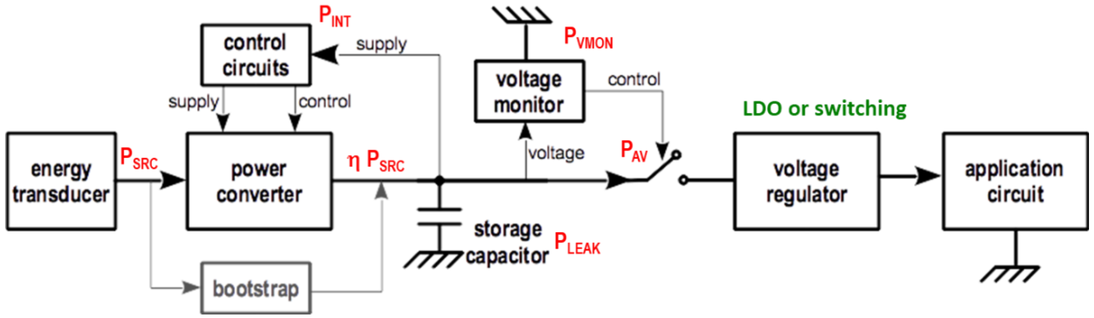
RF EH / wireless power transfer



Solar EH



Energy storage (µbatteries)

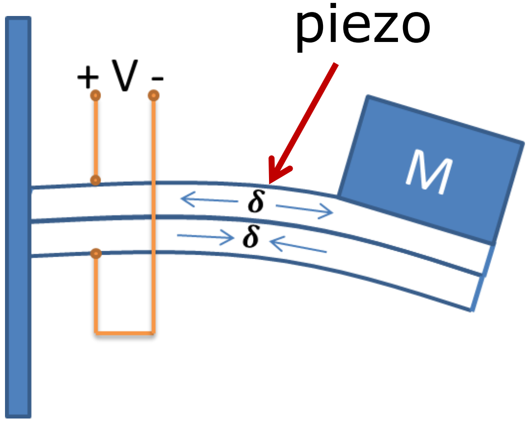


Micro power management

Energy harvesting technologies

Mechanical EH : Piezoelectric conversion

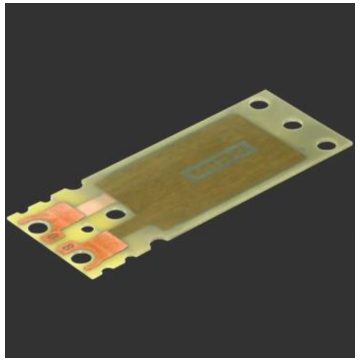
- Harvesting principle based on mechanical resonators
- Applications are linked to mechanical vibrations harvesting (movements)



- Principle

Resonant cantilever covered by a piezoelectric layer and a inertial mass attached. As the cantilever is bent, strain is transferred to the piezo layer → asymmetric charge distribution (Voltage)

MIDE (PZT)

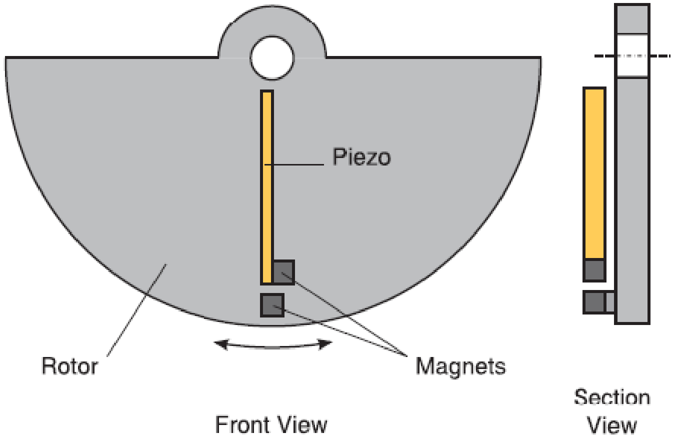


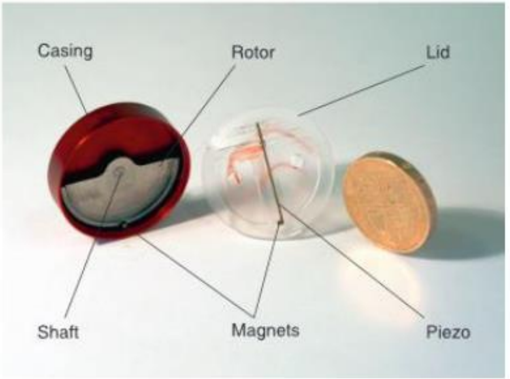
TE Connectivity (PVDF)

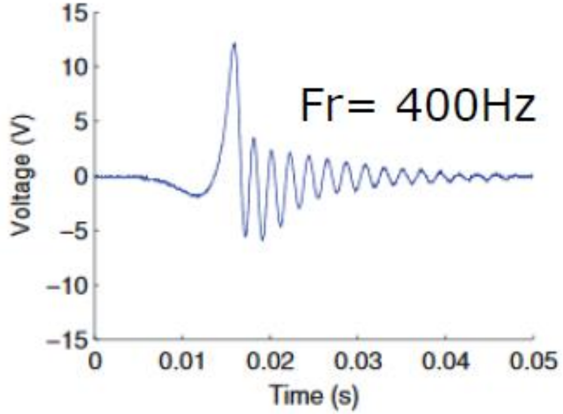
- Devices tuned at a specific vibration frequency
- Devices are easy to fabricate
- Macro-devices and MEMS are actually on the market
- Most used materials (commercial) : PZT (lead/toxic), PVDF

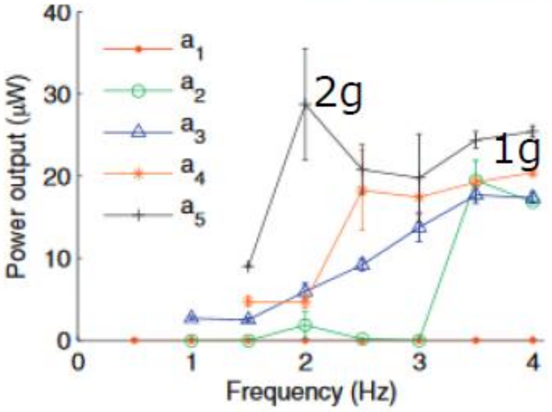
Mechanical EH : Piezoelectric conversion

- Current trends:
- Increase input bandwidth / reduce working frequency for portable applications
- Frequency-up converter (rotating systems)





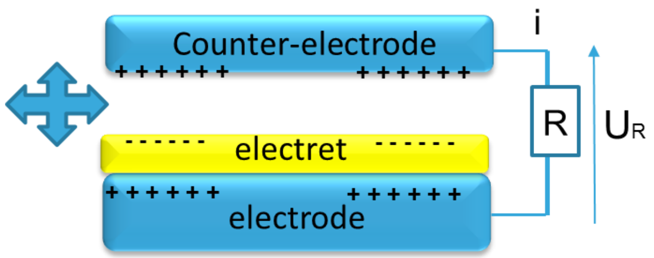


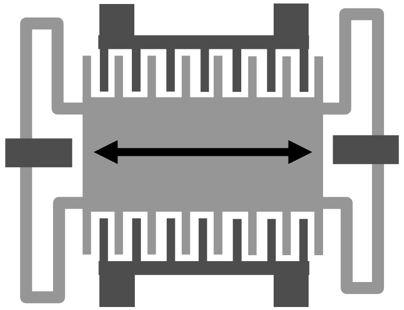


Volume: 5cm^3
Weight : 10.5gr
Performances:
30µW (>10V) at 2Hz@2g
6µW/cm^3

P. Pillatsch et al., S&A A 2014

Mechanical EH : Electrostatic conversion





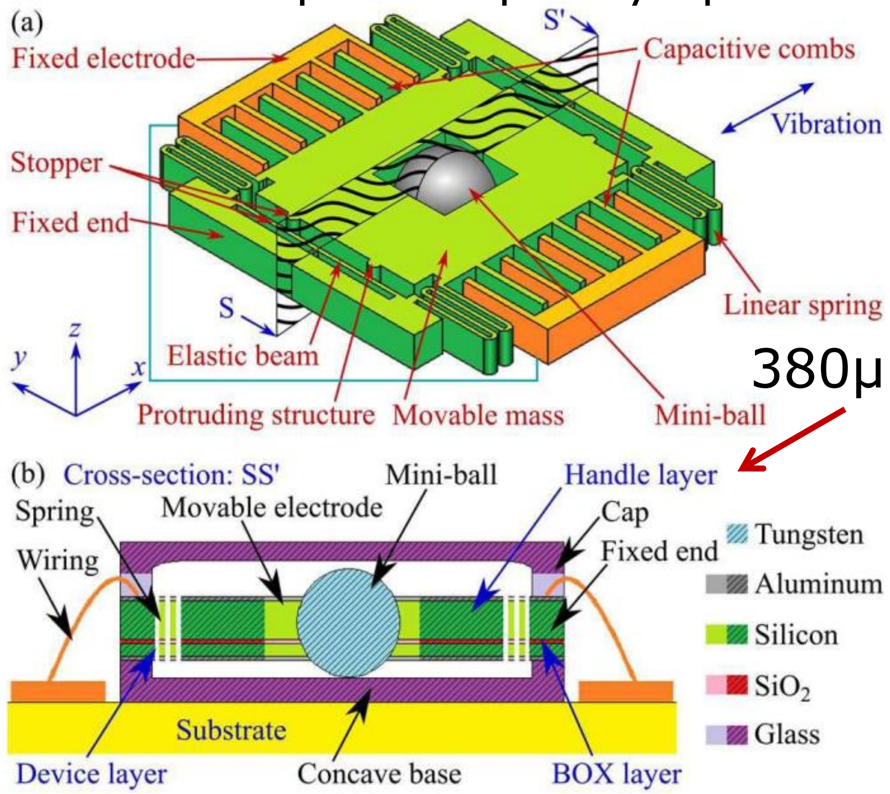
- Principle

One electrode of the capacitor is charged (electret, triboelectricity…) and the relative movement between the two electrodes causes a variation of electric capacity → charges movement

- Energy density is low at macro level but increases at micro scale (relative capacitor variation increases)
- Main challenge is related to the reliability of the material to keep the charges

Mechanical EH : Electrostatic conversion

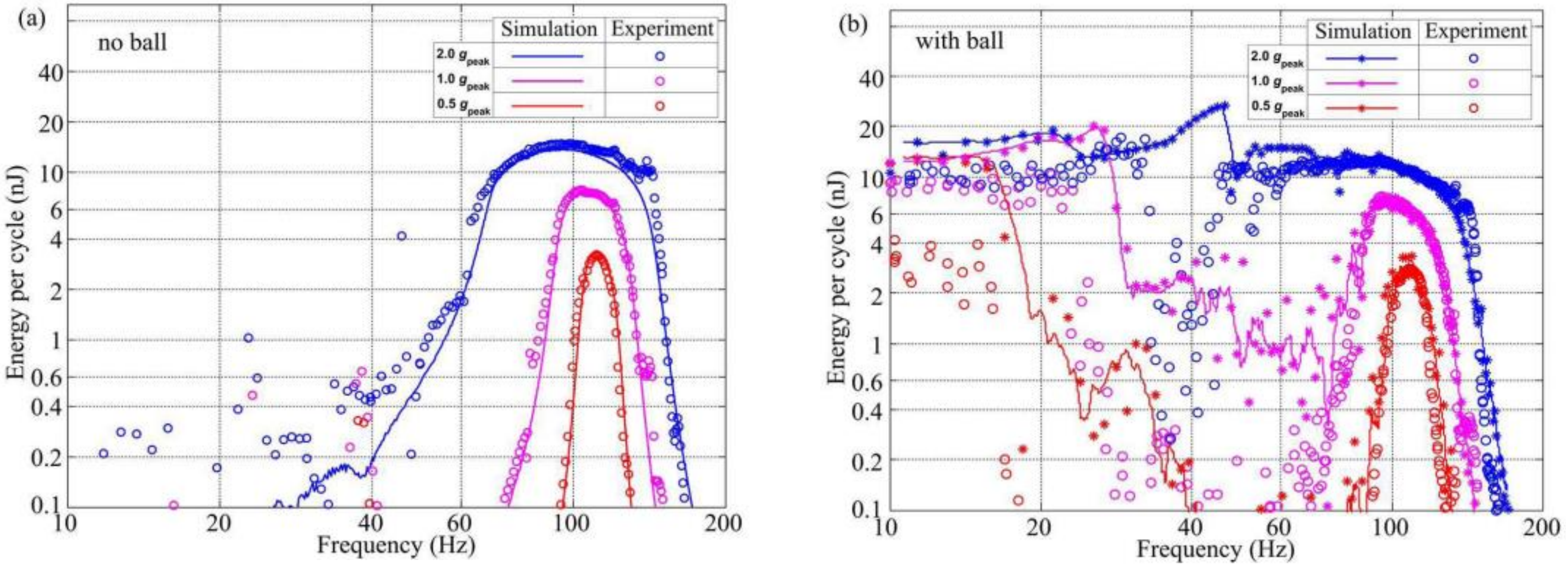
- Current trends:
- MEMS device – Increase input bandwidth
- impact frequency up converter (stoppers & balls)



380μm

(Cavity length= 3mm)

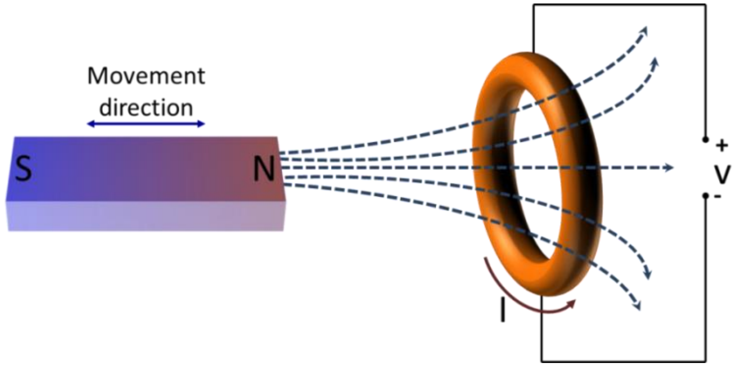
Energy / cycle



Adding the mini ball (32 mg) improves the performance at lower frequencies

Y. Lu et al., J. MEMS A 2018

Mechanical EH : Electromagnetic conversion



- Principle: Faraday's Law

Relative motion – magnetic field & coil (or change in the flux linkage) → Electromotive force

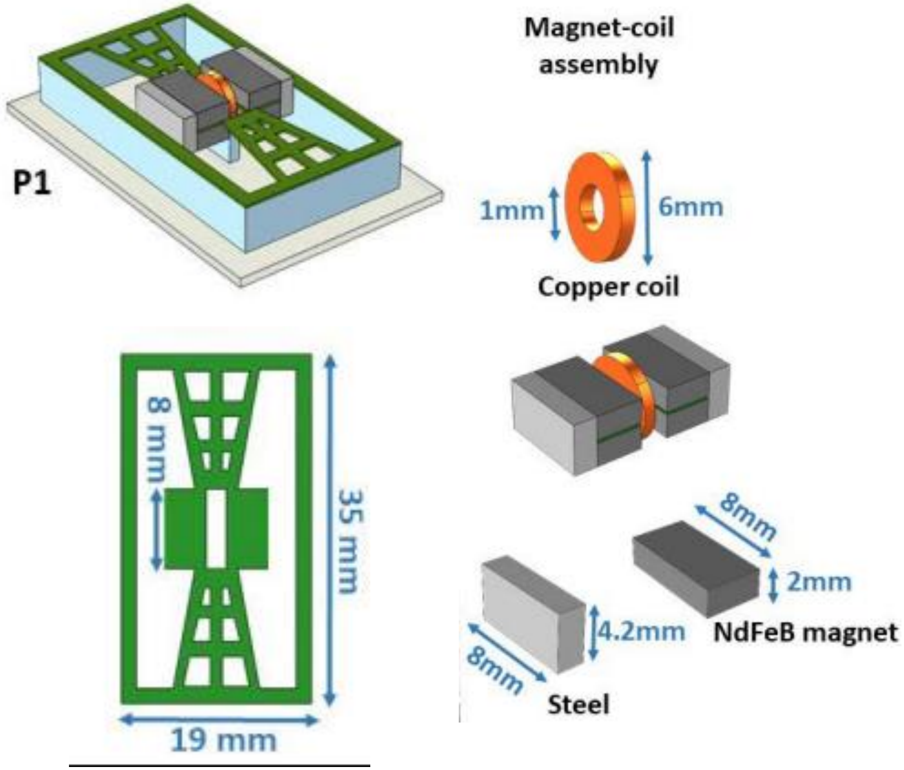
- Macro-devices are vastly developed and are on the market
- MEMS devices less explored due to drastic drop in performance
- Use of rare earth-based magnetic NdFeB

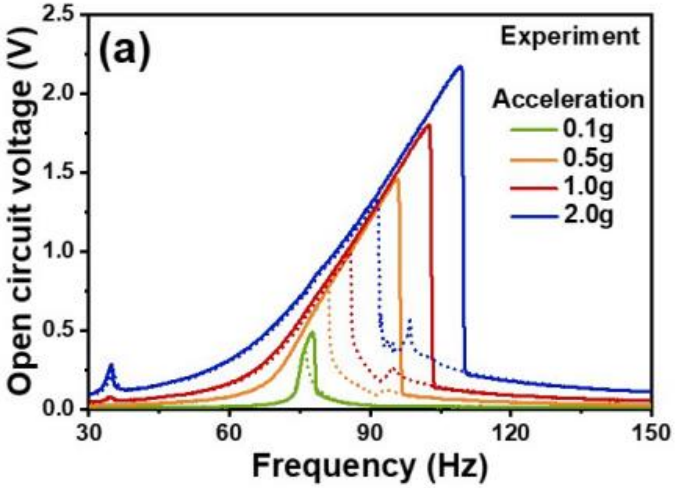
Perpetuum
68 mm x 63 mm
P < 20mW

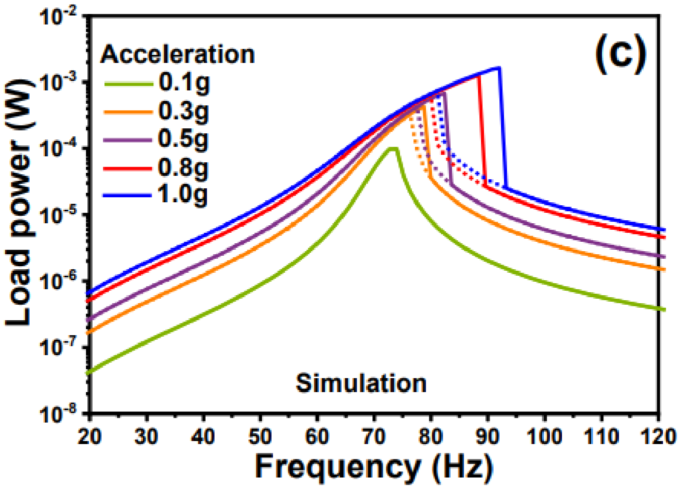
Enocean
29 x 19 x 7 mm^3
200µJ@2V

Mechanical EH : Electromagnetic conversion

- Current trends:
- Increase input bandwidth - Exploiting non-linearities (springs)

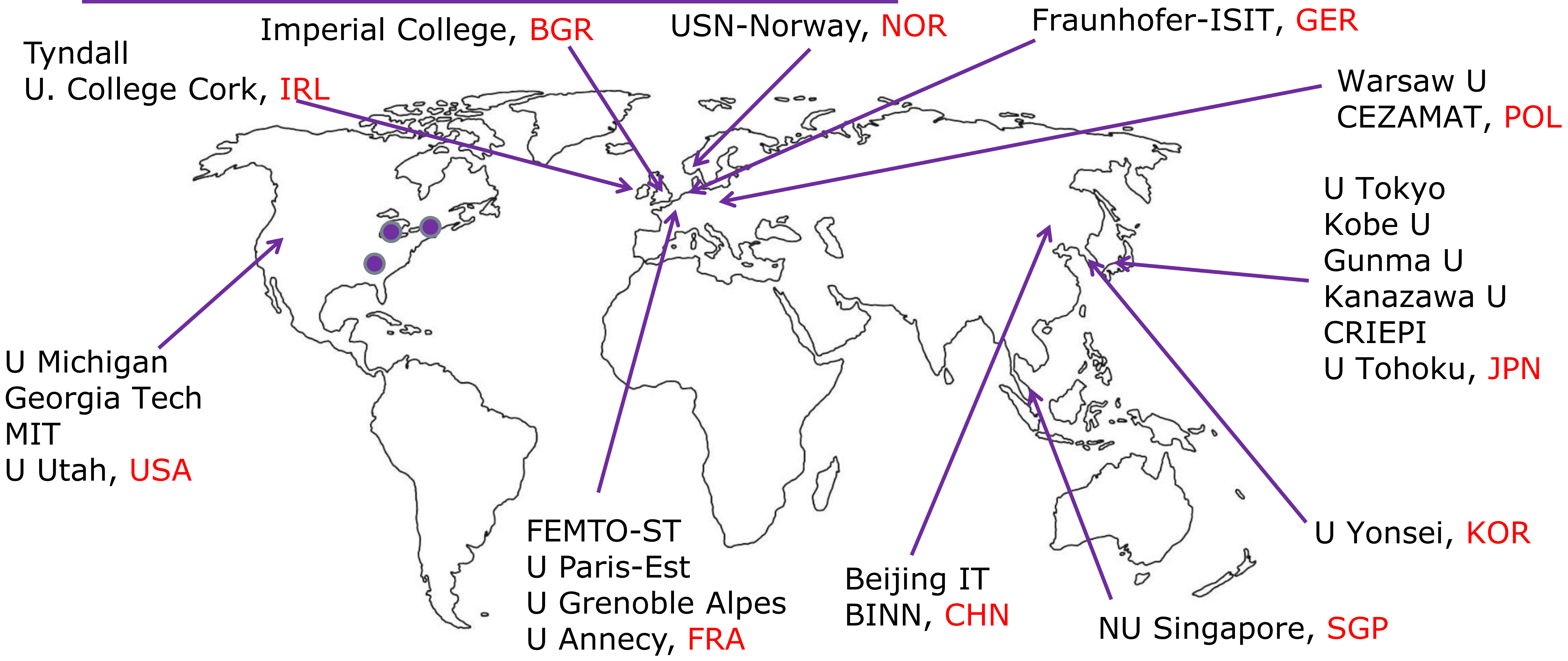




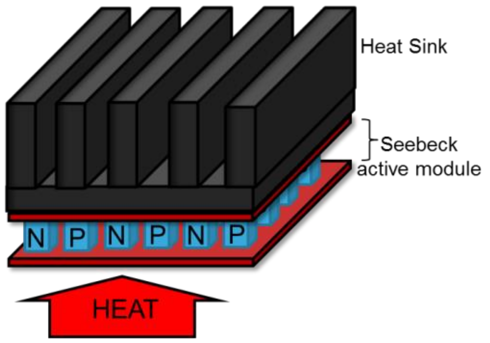


K. Paul et al., J. Appl. Energy 2021

Mechanical EH : Most active universities / RTO



Thermal EH

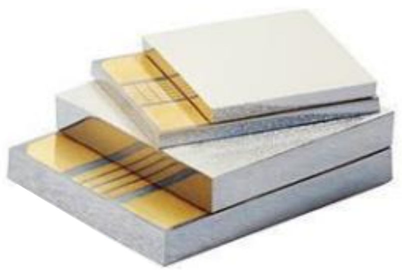


- Principle

Seebeck effect: generation of a voltage along a conductor when it is subjected to a temperature difference.

Main parameter : $zT=\sigma S^2T/\kappa$. σ : electrical conductivity (1/Ω/m), S : Seebeck coefficient (V/K), κ : thermal conductivity (W/m/K), T : temperature (K).

zT ~ 1 (now) ⟶ 3 (future)



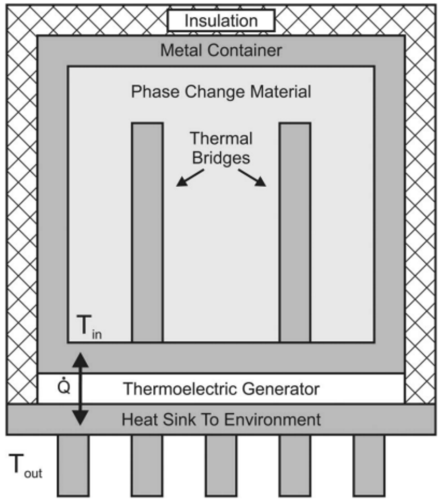
Micropelt
~4 x 3 X 1 mm
P < 15mW
@ ΔT=30K

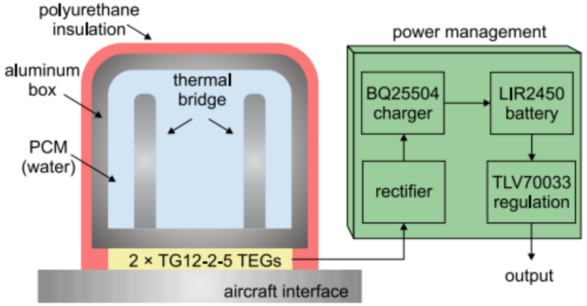
- ☐ Fast thermalization (need for a big heat sink)
- ☐ Non-flexible
- ☐ Bi_2Te_3 : Expensive/rare/toxic material/incompatible with CMOS
- ☐ Power proportional to available temperature gradient

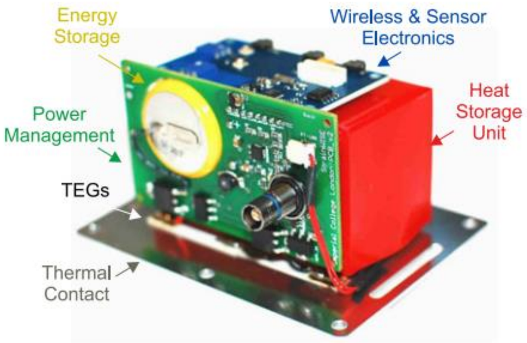
Nextreme
~ 11 x 10 x 1 mm
P < 130mW
@ ΔT=50K

Thermal EH

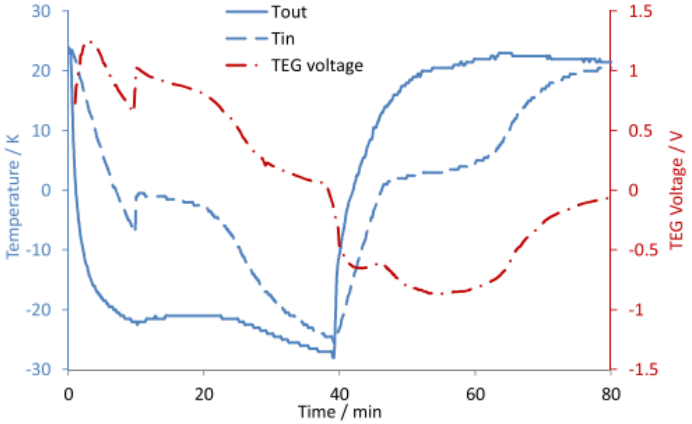
- Current trends:
- Enhancement of the coupling to environmental heat source at system level.
- Dynamic thermoelectric energy harvesting (heat storage)

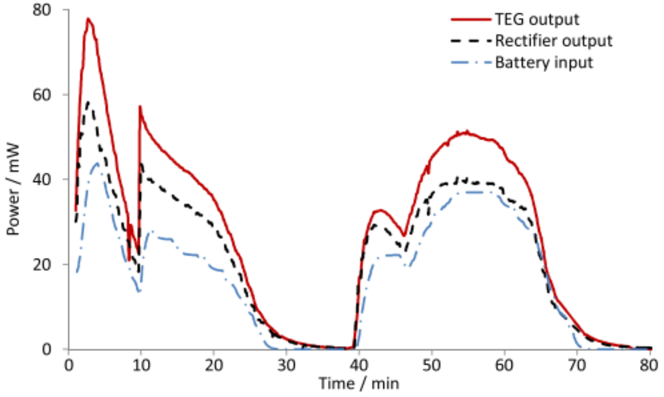






M. Kiziroglou et al., IEEE Trans. Indus. Elec. 2014



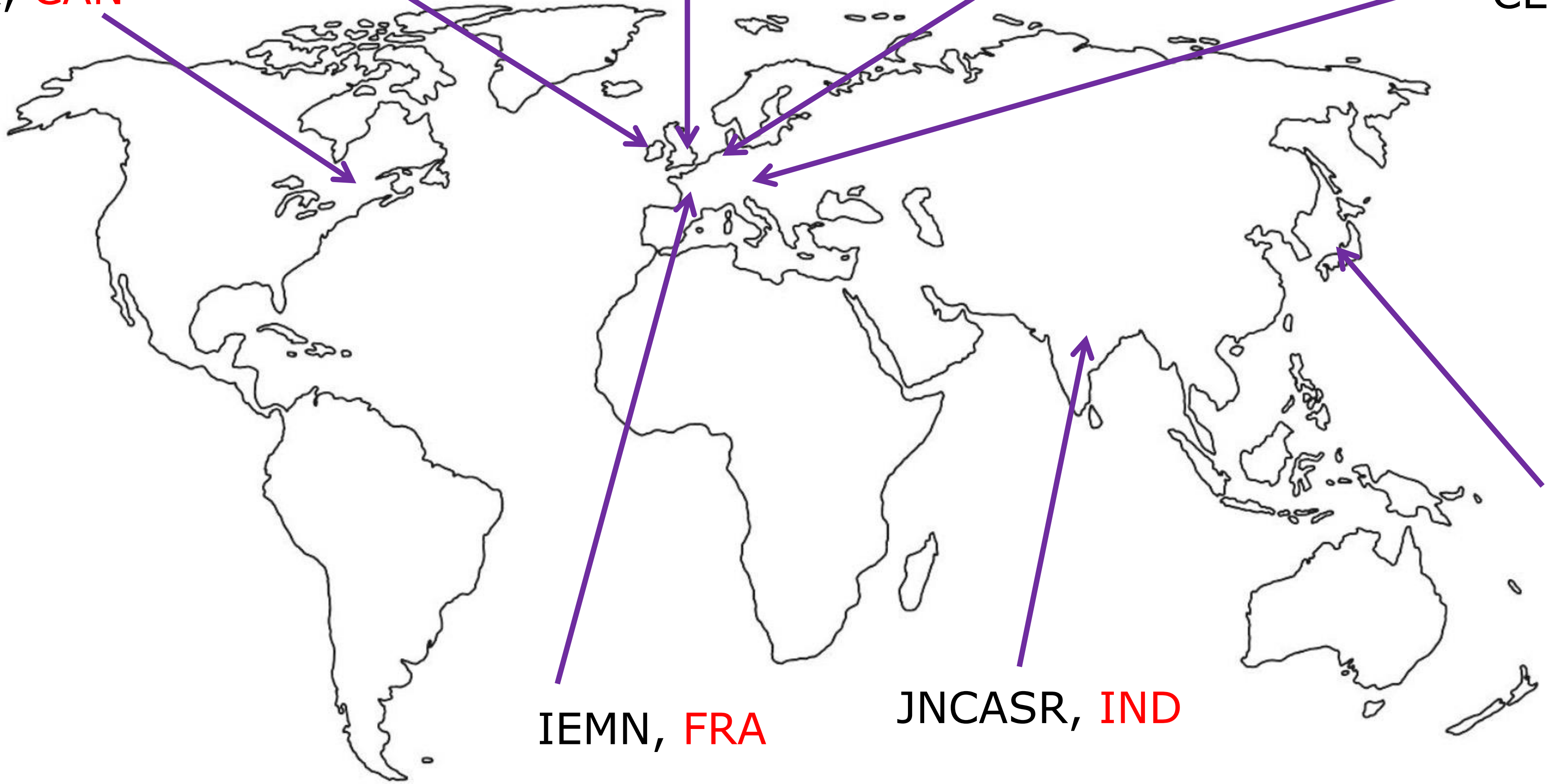


64 × 38 × 40 mm (141 g)
60 × 30 × 30 mm aluminum HSU

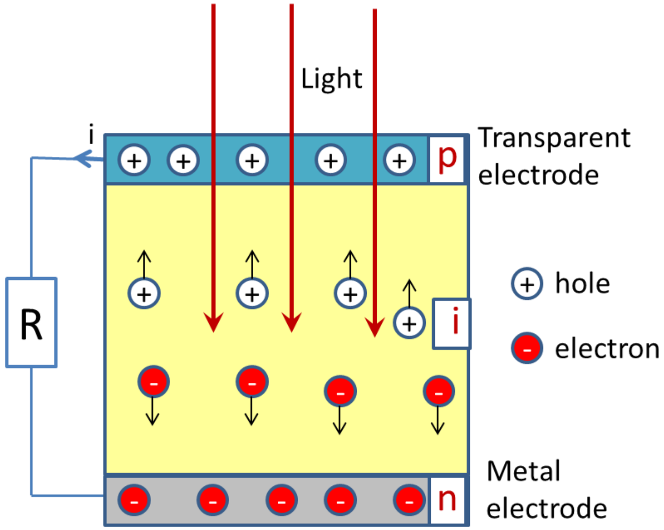
zT = 0.72, 126J, 1.62 J/cm^3

M. Kiziroglou et al., IEEE Trans. Indus. Elec. 2017

Thermal EH: Most active universities / RTO

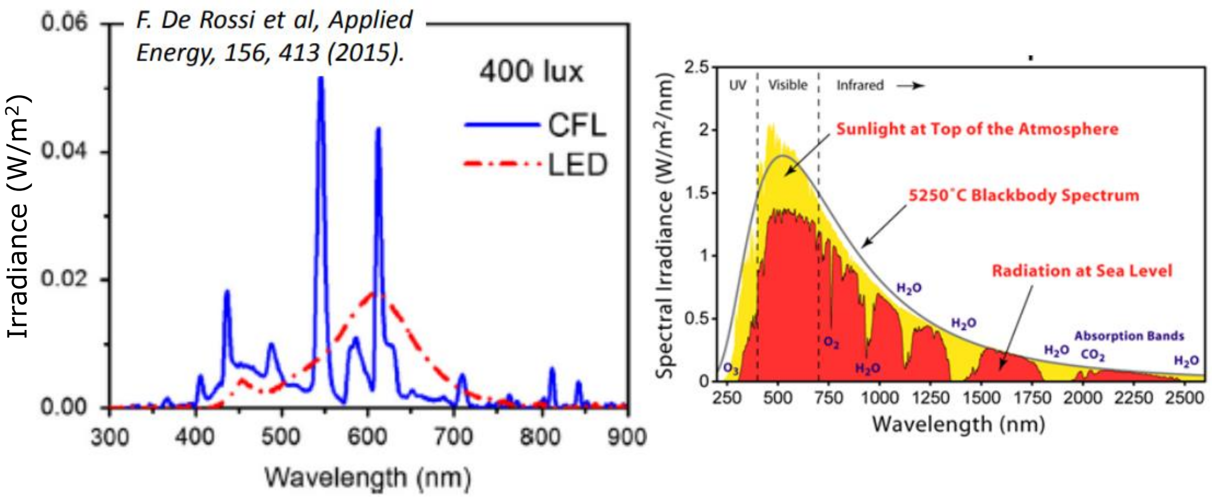


Photovoltaic EH



Principle : Photovoltaic effect:
- Absorption of light by the semiconductor - Electron-hole pair generation,
- separation and collection → Power delivered

Indoor and outdoor light level



- A market dominated by the Si (mature technology):
  - For outdoor applications, crystalline Si solar cells
  - For indoor applications, amorphous Si photovoltaic cells
- Solar cells spectral sensitivity and efficiency differ depending on the light spectrum which is very different for artificial and sun light

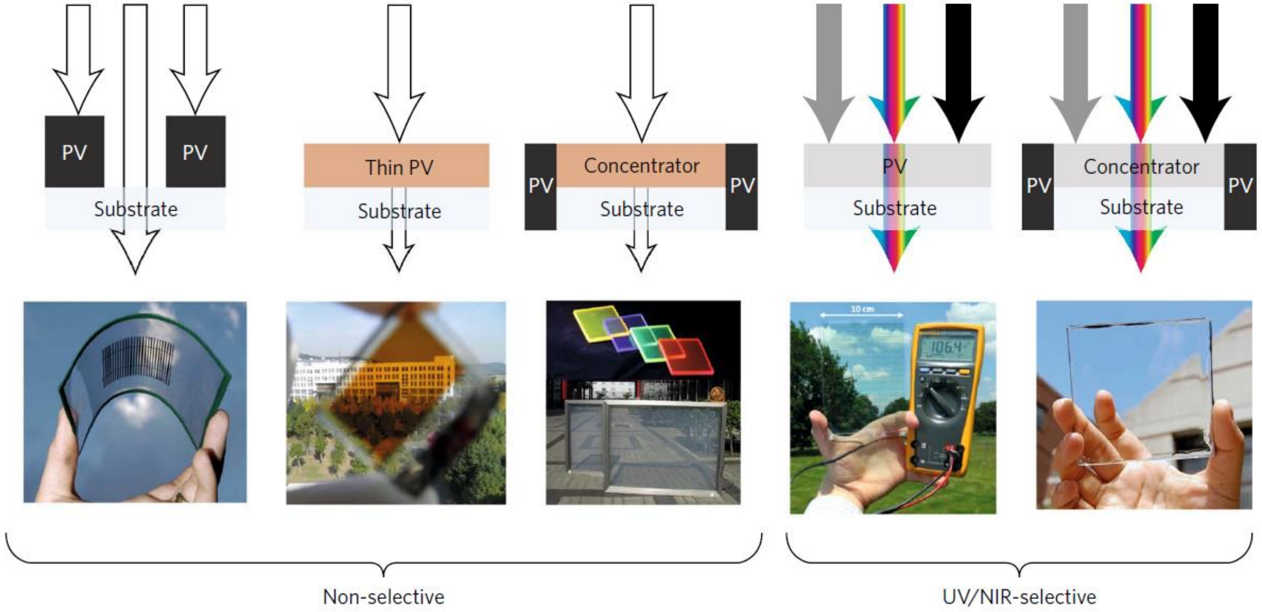
a-Si, organic, DSSC (dye sensitized solar cells), semiconductors compounds (III-V, CdTe,…), Perovskite

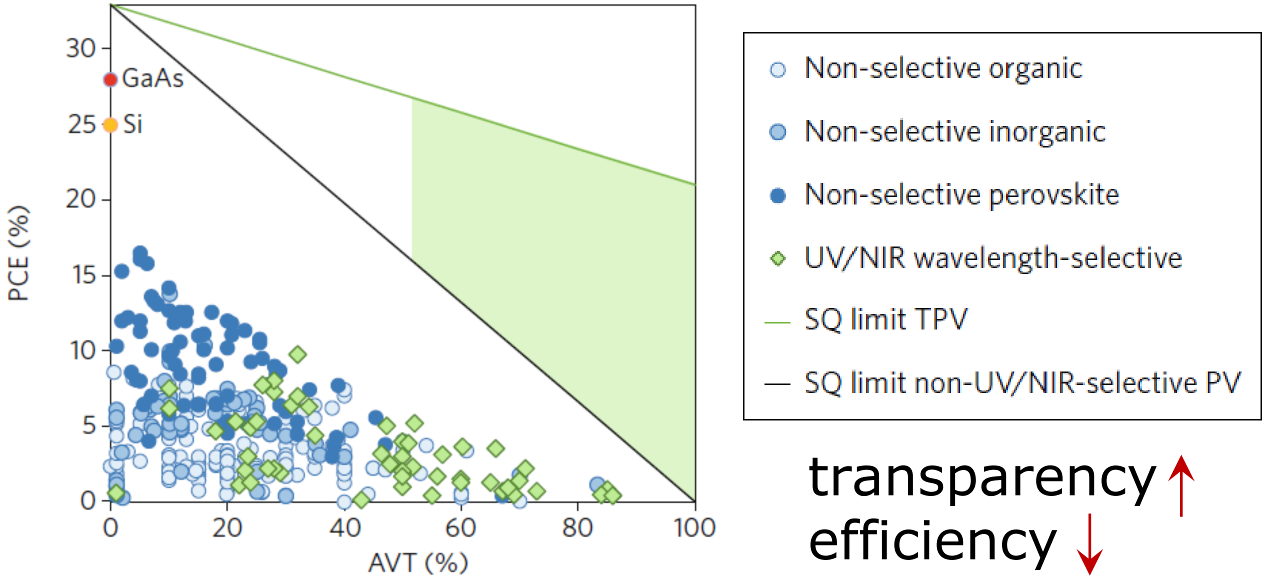
Si, tandem cells on Si, semiconductors compounds (CIGS…)

Courtesy of A. Kaminski, NEREID, 2016 .

Photovoltaic EH: current trends

- Develop high efficiency and low cost transparent PV (flexible, even better)
- PV covering other things other than roofs (e.g. windows, walls, e-devices …)
- Not all application need to be 100% transparent or highly efficient



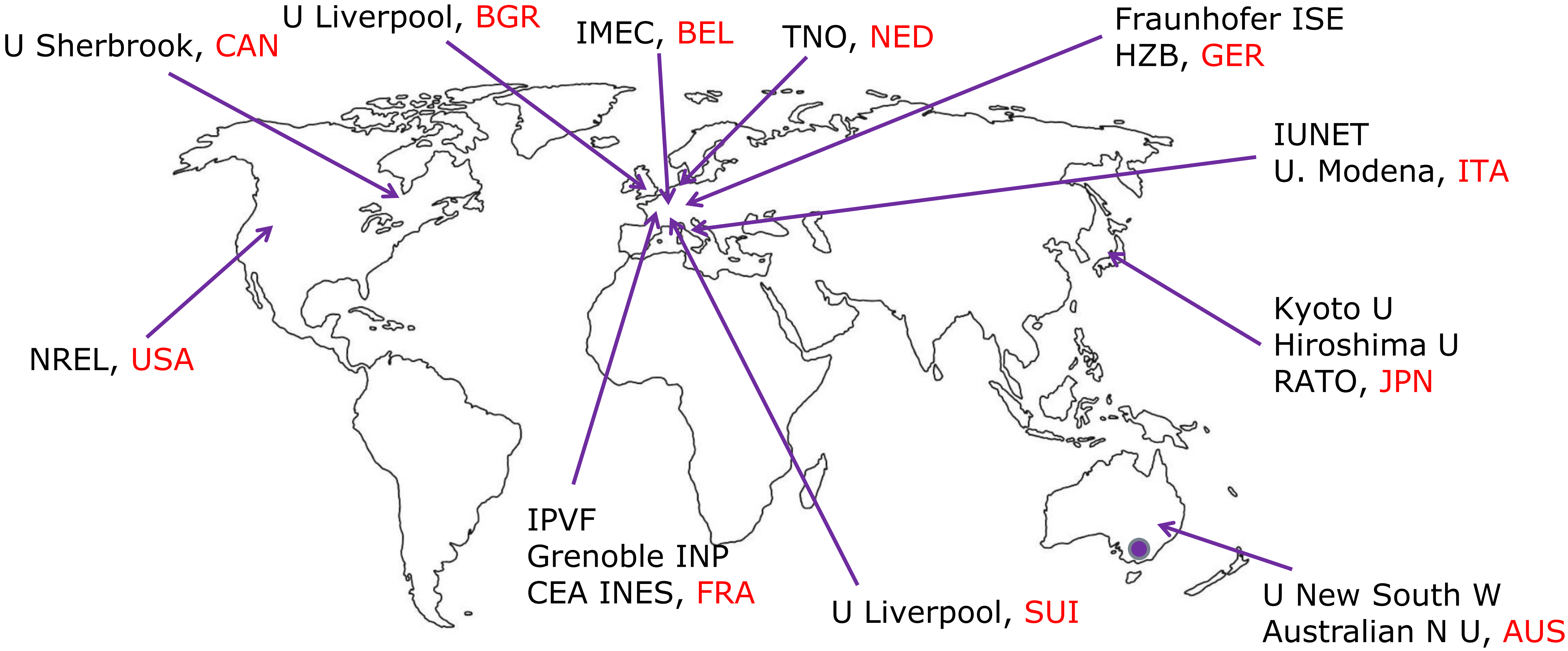


transparency ↑
efficiency ↓

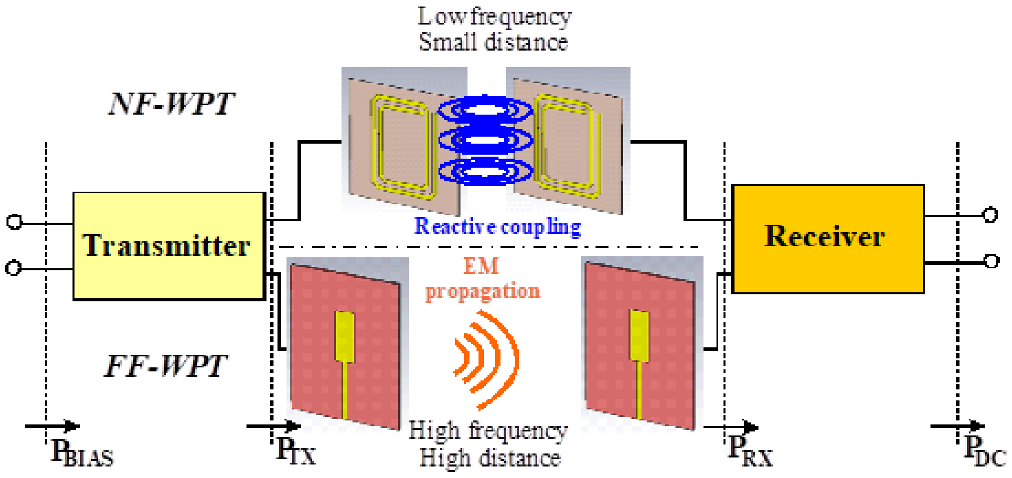
- Still work to be done before reachning large scale: reduce losses, increase lifetime…
- Low resistivity transparent electrodes (Nanowires, nanotubes, thin metallic films)

C. J. Traverse et al., Nature energy, 2017

Photovoltaic EH: Most active universities / RTO



RF EH /Wireless power transfer



2 Principles :

- Radiated far field RF source (High frequency 300MHz-GHz)
-> Antennas (no interaction)

Near EM field – Capacitive or inductive coupling
(low frequency 30kHz-MHz)
->coils, electrodes (strong interaction)

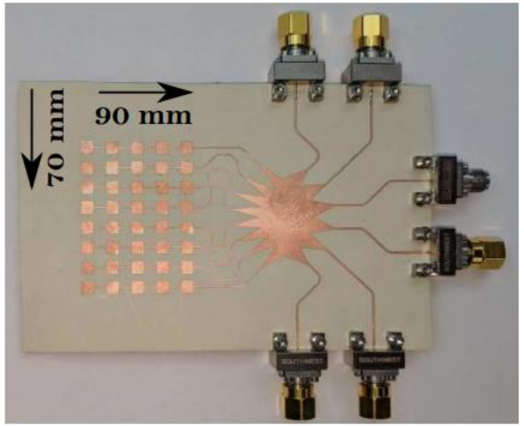
- Far field : Used for low/ultra low power (~µW-mW)
  - Applications (harvesting)
  - Low efficiency
  - No commercial applications
- Near Field : medium to high power app. (~mW-W-kW).
  - Medium to high efficiency
  - Commercial applications

RF EH/wireless power transfer: current trends

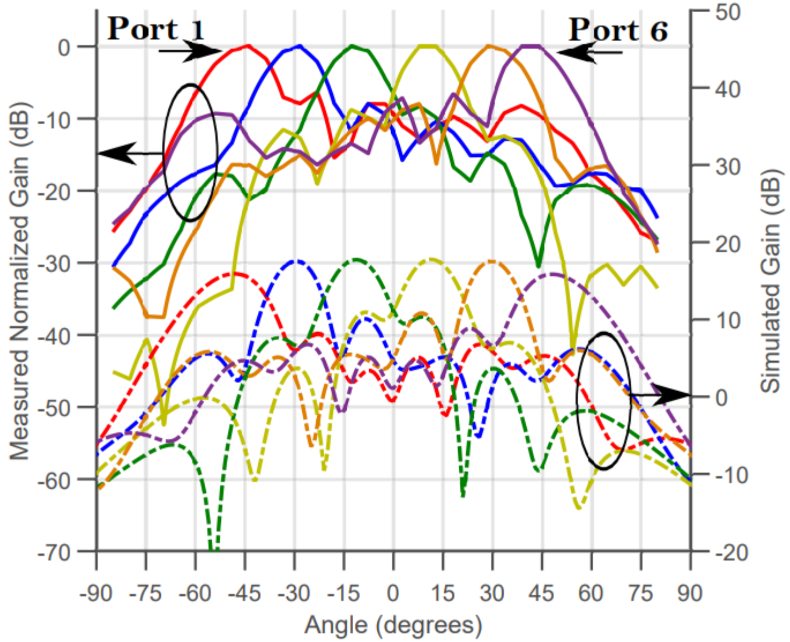
- EH at mm – wave : how to reach high gains + wide angular coverage (RF to DC)
- Typically Low power transmitted (regulations) → 5G (higher power)! > 24GHz

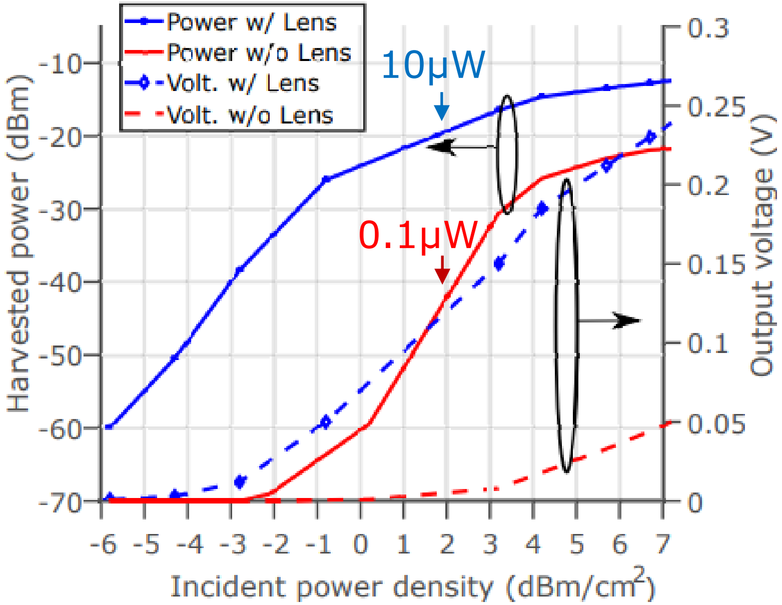
Beamforming networks (BFNs)
Rotman lens

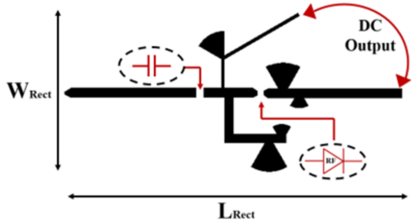
8 antenna ports



6 beam ports





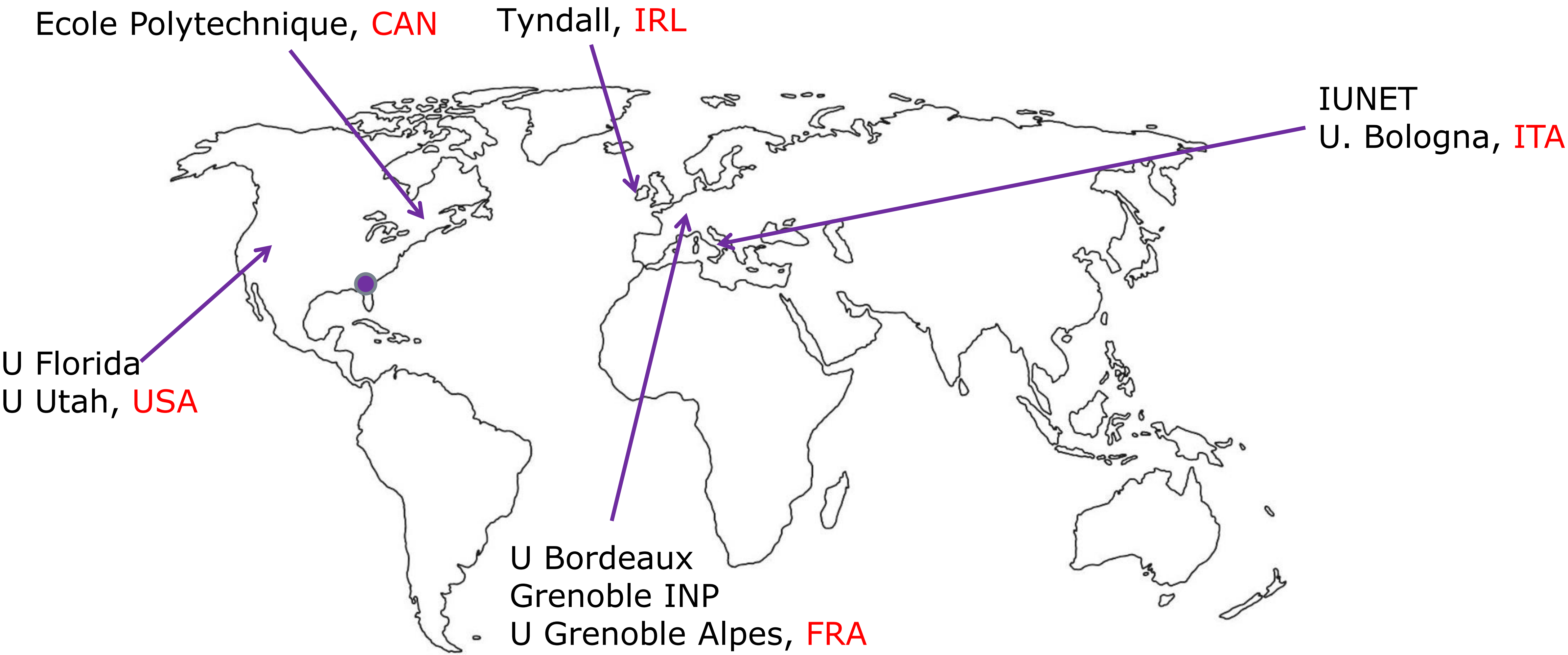


Rectifing circuits

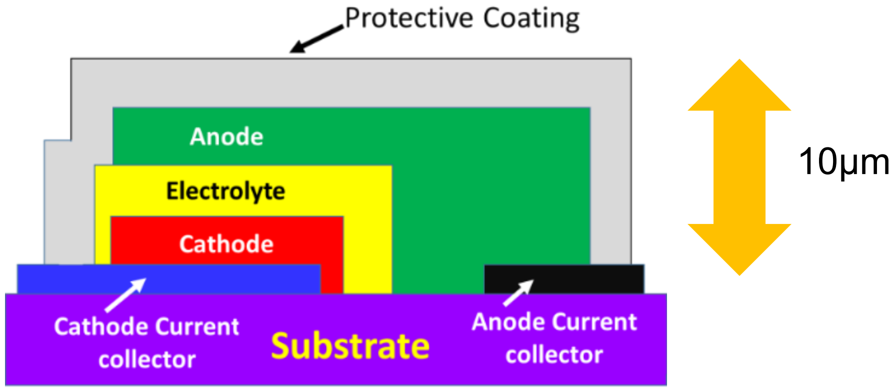
- It channels energy coming from any direction to one of the rectifiers.
- The DC outputs of the rectifiers are serially combined → power to the load
- Stable output regardless of the sources location (RF source location is unknown)
- Increase in power (same angular coverage w/o BF)

A. Eid et al., IEEE/MMT Symposium, 2019

RF EH/wireless power transfer : Most active universities / RTO



Energy storage: Micro-batteries



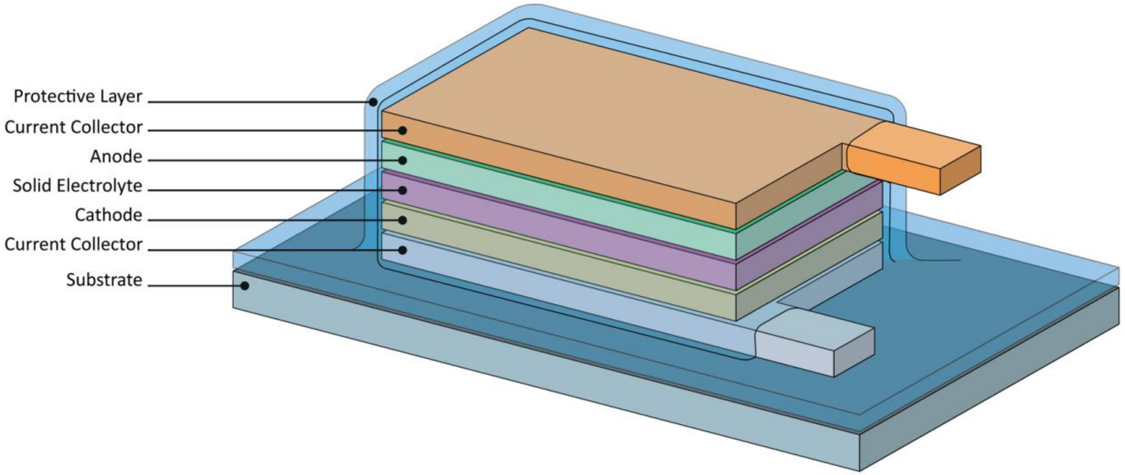
Principle :

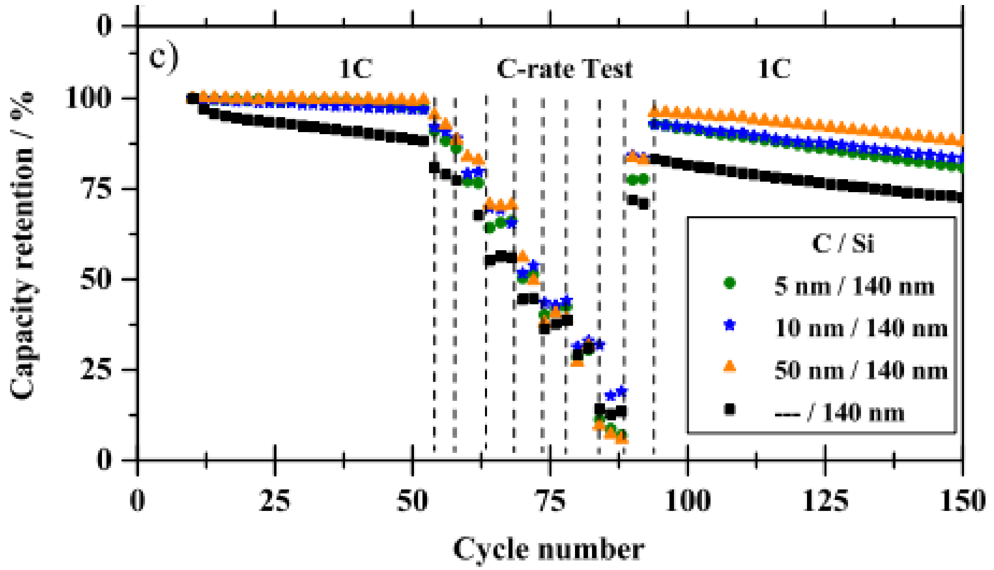
- Electrolyte : high ion conductivity, low electronic conductivity
- Replacement of the classical liquide electrolyte ⟶ thin film
- Si integrated
- Size reduction, safer

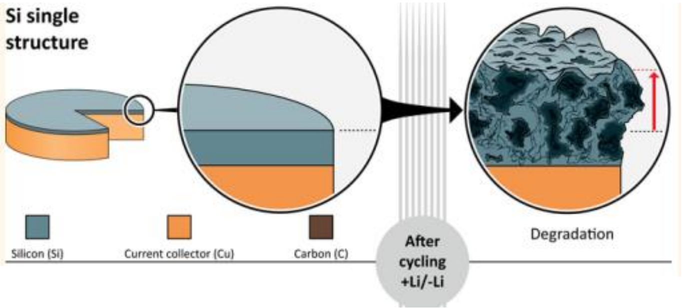
- ☐ Lithium based thin films: ~1 mWh/cm^2, capacity retention -> 1000 cycles
- ☐ Electrode thickness limit < ~µm
- ☐ Ionic conductivity of solid elecrolyte << liquid based (commercial)
- ☐ Thin film solid-state solutions for energy storage have existed for some years now but more energy density and higher power options at lower cost are required

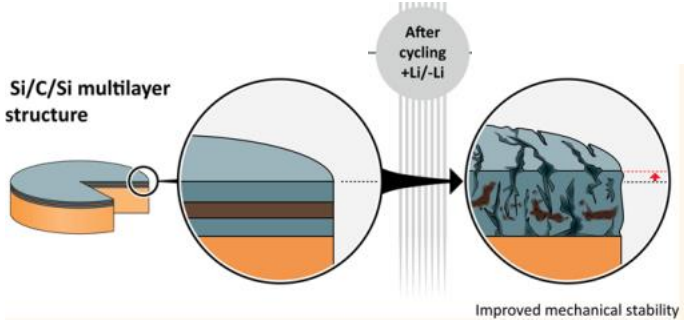
Energy storage: Micro-batteries – current trends

- Increase of performances : new materials for electrodes (quality), electrolyte
- Electrodes protective layers: Lithium cobalt oxide / Al_2O_3 , Si / C









- Increased electronic conductivity, mechanical stability
- Increased capacity retention

A. Reyes Jiménez et al., ACS Nano, 2017

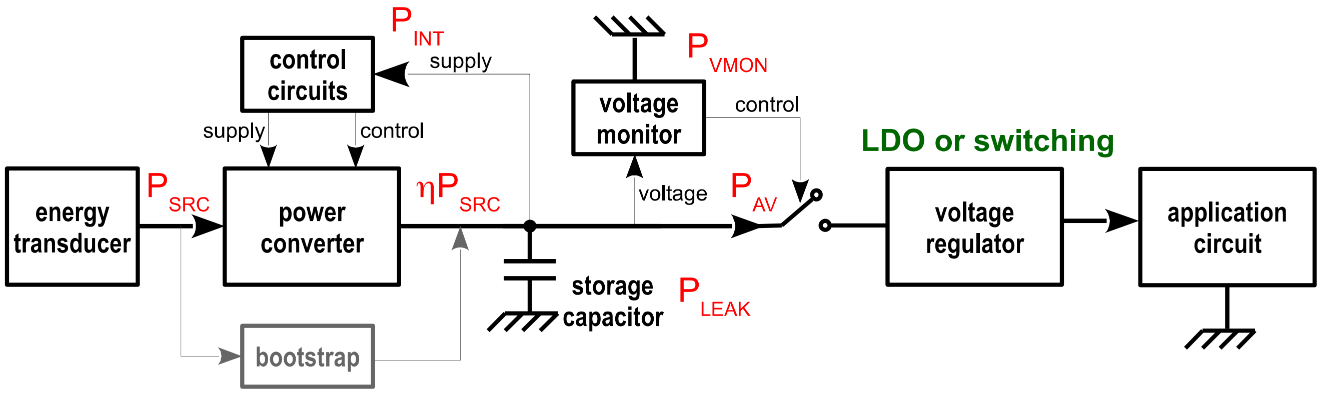
Energy storage: Micro-batteries - Most active universities / RTO

Tyndall
U. College Cork, IRL

U. Tsinghua, CHN

UC Berkeley, USA

Micro-power management



A. Romani et al., Computer, 2017

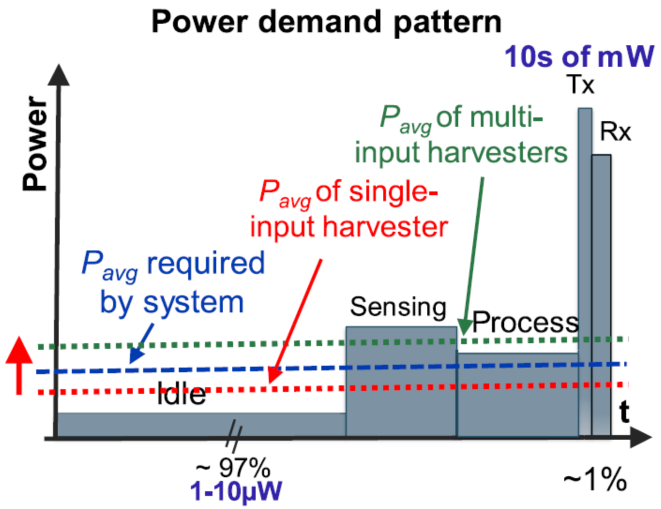
- Essential to store and deliver the harvested energy to circuits
- Must consume less than the input power
- Efficiency must be traded with self-consumption
- Should keep sources in the MPP

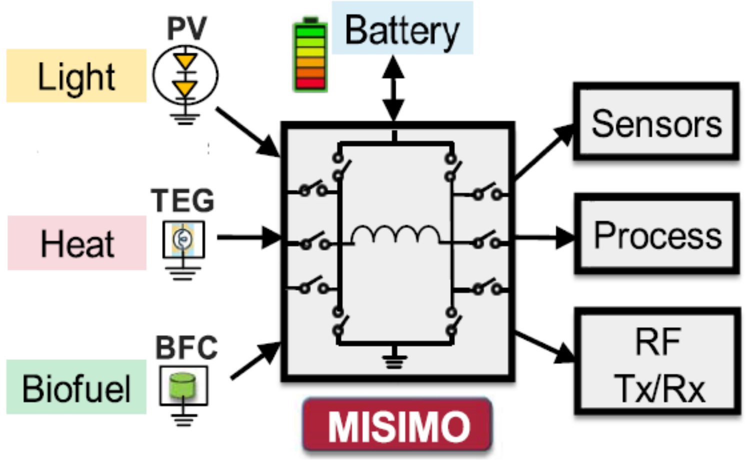
- It must be able to handle very low levels of ambient energies (1 µW).
- It must also be able to operate with near-0 voltages.

- Major silicon foundries have proposed in recent years dedicated products operating down to few µW and few hundreds mV, along with very tiny implementations requiring few components

Micro-power management: current trends

- Size reduction, increase efficiency, multiple harvesters...
- Multiple EH + Batteries, multiple out-puts
- Single inductor (DC-DC) → size reduction
- One stage → reduce losses

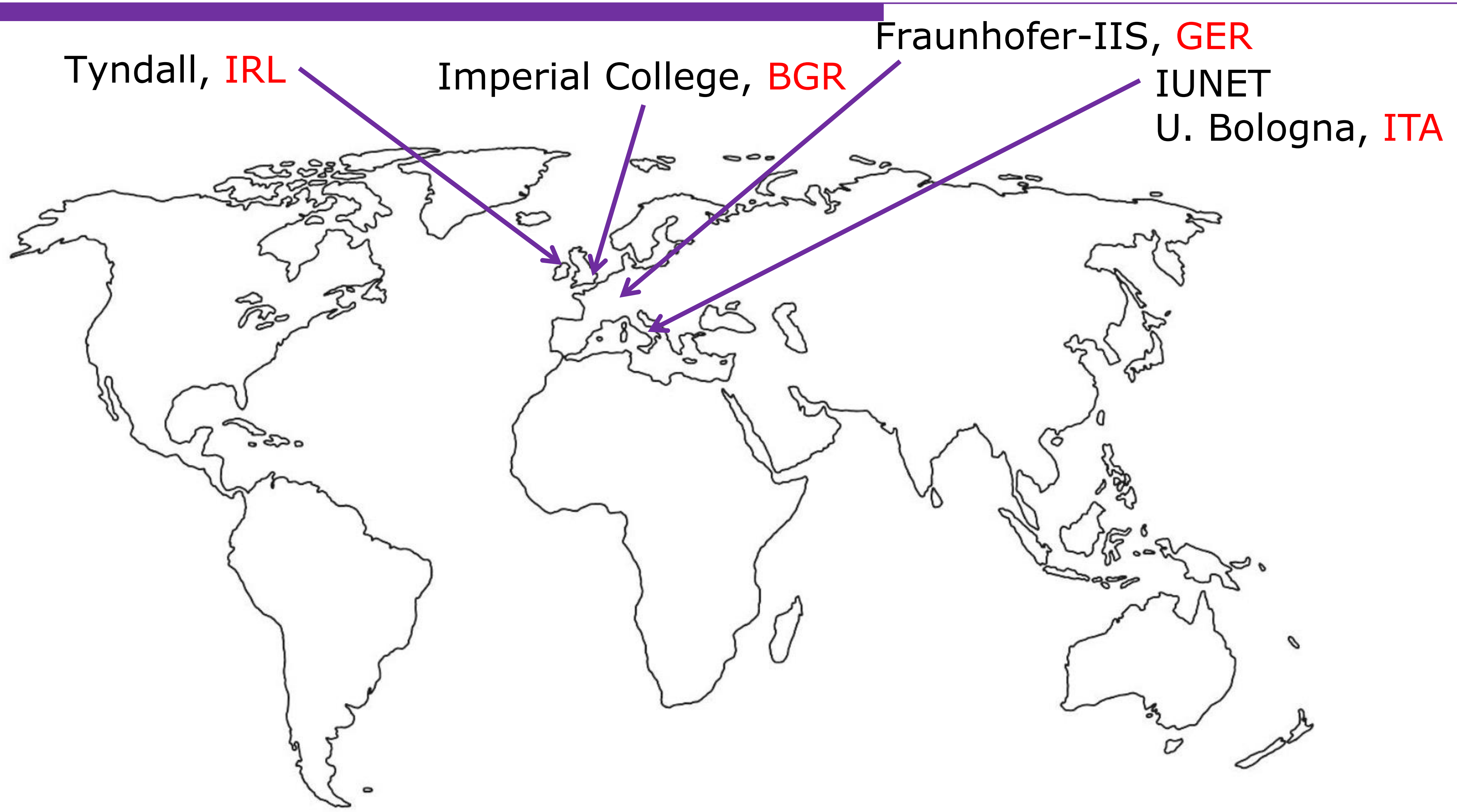




- 28-nm FDSOI
- Die area 0.5 mm²
- Output power 1µW - 60mW (efficiency >75%), Vout 1V
- Minimum input power 262nW

S. S. Amin et al., IEEE JSSC, 2018

Micro-power management : Most active universities / RTO



Conclusions and perspectives

- The improvement of the EH performance/efficiency is as important as the development of "green" materials. Replacing toxic/rare materials used nowadays (lead based piezoelectrics, Bi_2Te_3 for thermoelectrics, NdFeB - neodymium, for electromagnetic conversion).
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Flexible and low cost approaches for wearable applications (i.e. e-health) should be developed as well.
- The comprehensive system design combining all aspects of the fabrication process, harvester structure, power conversion circuits and storage will be the potential solution for increasing the power generation efficiency.

Acknowledgments

International Roadmap for Devices and Systems

MORE THAN MOORE WHITE PAPER

Energy Harvesting team

- **Gustavo Ardila**, Grenoble Alpes Univ./Grenoble INP (Team leader)
- **Aldo Romani**, IUNET/Univ. of Bologna (co-leader)
- **Hiro Akinaga**, National Institute of Advanced Industrial Science and Technology (AIST)
- **Philippe Basset**, Univ. Gustave Eiffel
- **Alessandro Bertacchini**, IUNET/Univ. of Modena and Reggio Emilia
- **Alessandra Costanzo**, Univ. of Bologna
- **Mike Hayes**, Tyndall
- **Maciej Haras**, Warsaw Univ. of Technology
- **Anne Kaminski**, Grenoble INP
- **Michail Kiziroglou**, Imperial College London
- **Ivona Mitrovic**, Univ. of Liverpool
- **Yoshiyuki Nonogushi**, Kyoto Institute of Technology
- **Alessandro Piovaccari**, Univ. of Bologna
- **Kafil M Razeeb**, Tyndall
- **James Rohan**, Tyndall
- **Saibal Roy**, Tyndall
- **Thomas Skotnicki**, Warsaw Univ. of Technology
- **Hiroshi Toshiyoshi**, Univ. of Tokyo
- **Eric Yeatman**, Imperial College London

Thank you for your attention !