Low-Power System Design

227-0781-00L

Fall Semester 2019

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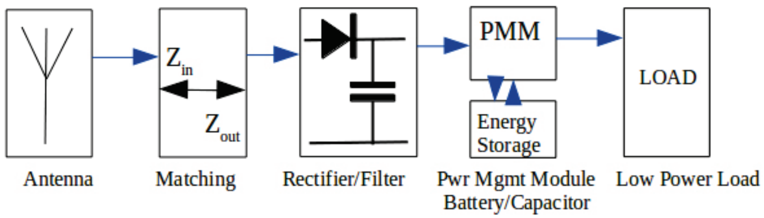
Plan for Today

- Renewable Energy
  - Energy Sources
  - Renewable Energy Sources – Harvesting Systems
- Energy Harvesting Systems Integration
  - Maximum Power Point Tracking
- TEG- based Energy Scavenging
- Slides contain material from J. Rabaey, D. Brunelli

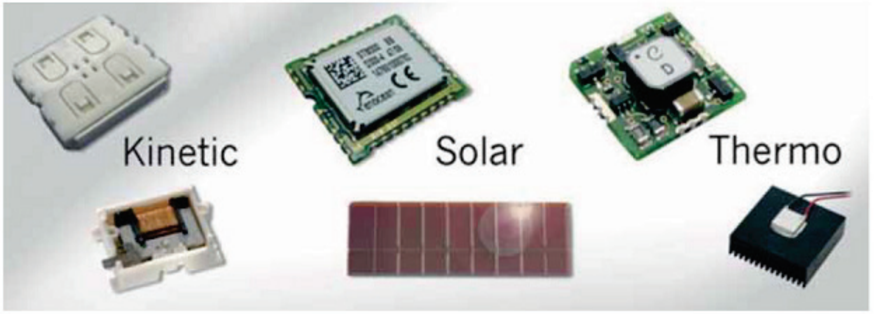
Reasons for Energy Harvesting

- Battery operation:
  - no continuous power source available
  - mobility

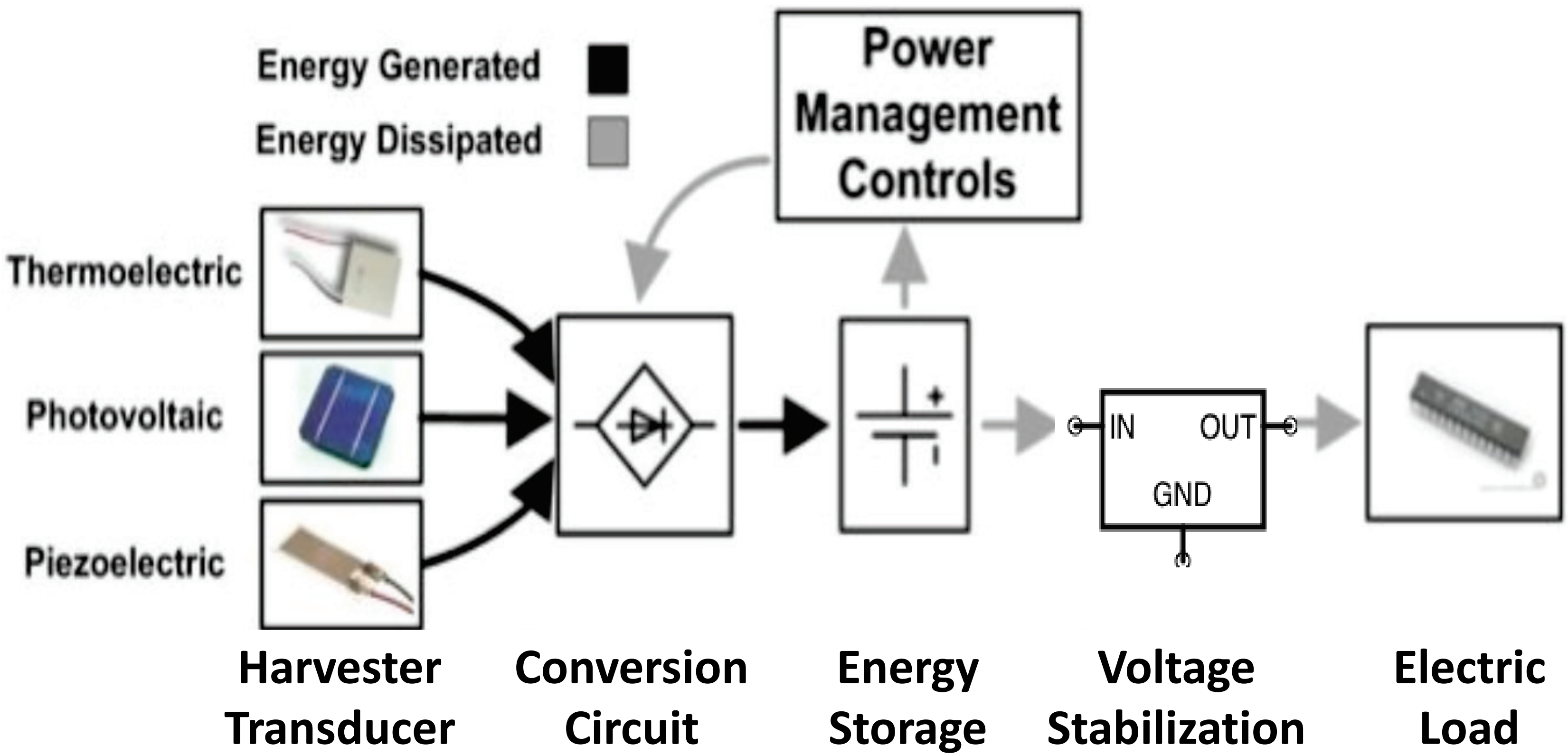
- Energy harvesting:
  - prolong lifetime of battery-operated devices
  - infinite lifetime using rechargeable batteries
  - autonomous operation



radio frequency (RF) harvesting



Typical Power Circuitry – Power Point Tracking



Low-Power System Design

FINITE ENERGY SOURCES
STORAGE

The Power Landscape

Do we want to exchange batteries in Billions of devices?

Or do you want to re-charge periodically?

What about our environment?

When should we use the energy?

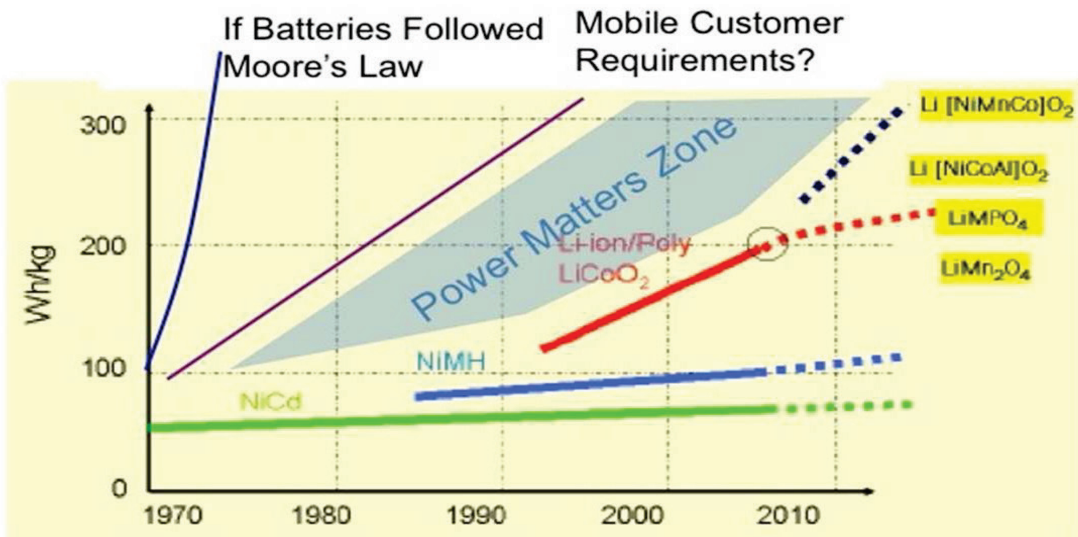
Can we guarantee long-term service?

Are ambient energy sources available?

How should we dimension the devices?

Nightmare: Power Availability

- Large gap between energy demand and supply possibilities



Source: Avicenne

- Battery technology cannot keep up the pace
  - Moore's law vs. 2-3%/year

Power Supply Problem Statement

- **Goal:** Provide as much energy as possible at smallest cost/volume/weight/recharge time/longevity
- Options
  - Primary batteries – not rechargeable
  - Secondary batteries – rechargeable
    - Only make sense for short term applications or in combination with some form of energy harvesting
- Requirements include
  - Low self-discharge
  - Long shelf live
  - Capacity under load
  - Efficient recharging at low current
  - Good relaxation properties (seeming self-recharging)
  - Voltage stability (to avoid excessive DC-DC conversion)

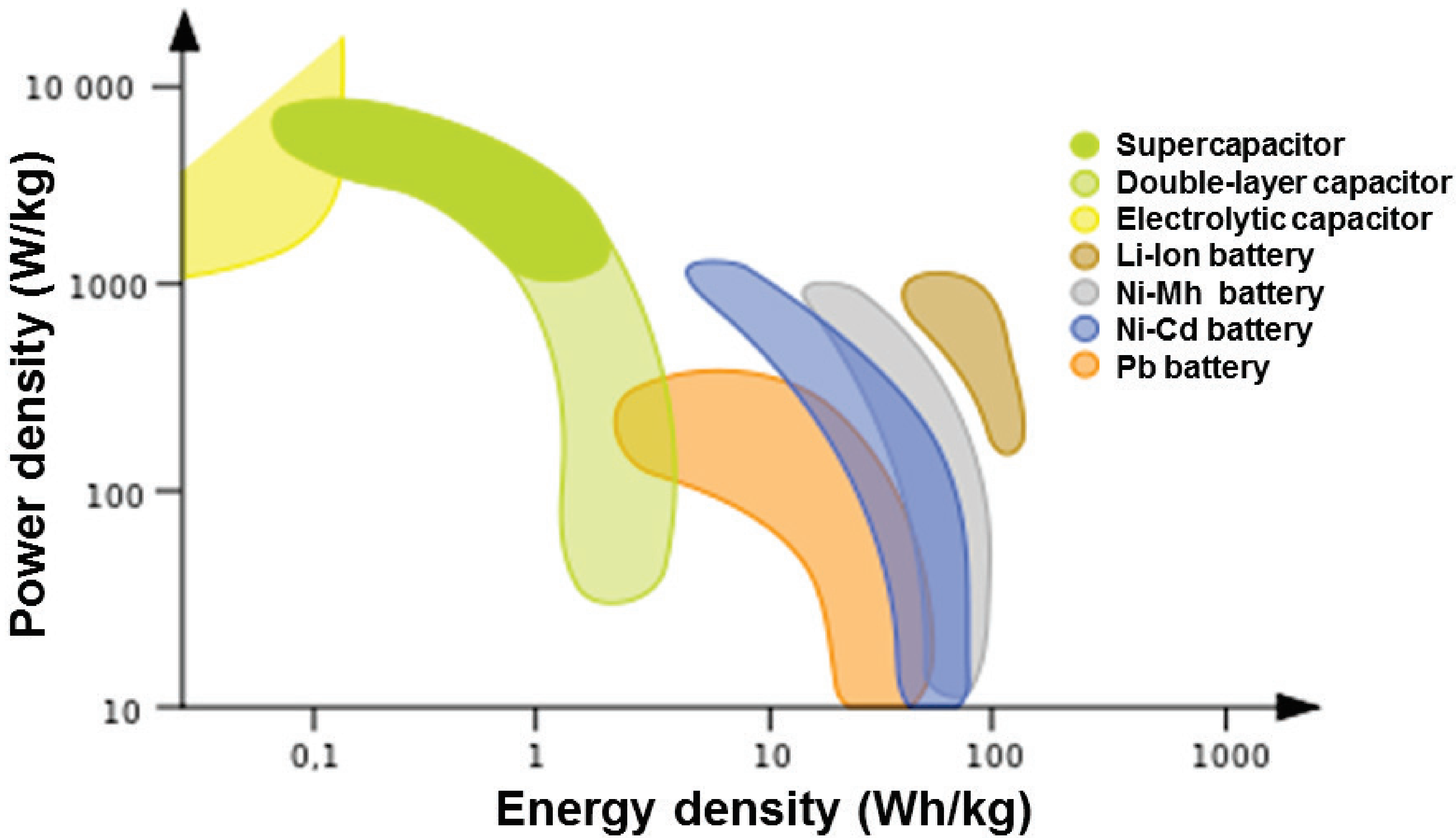
Definitions

- Energy Density
  - J/cm^3
    Energy per unit volume.

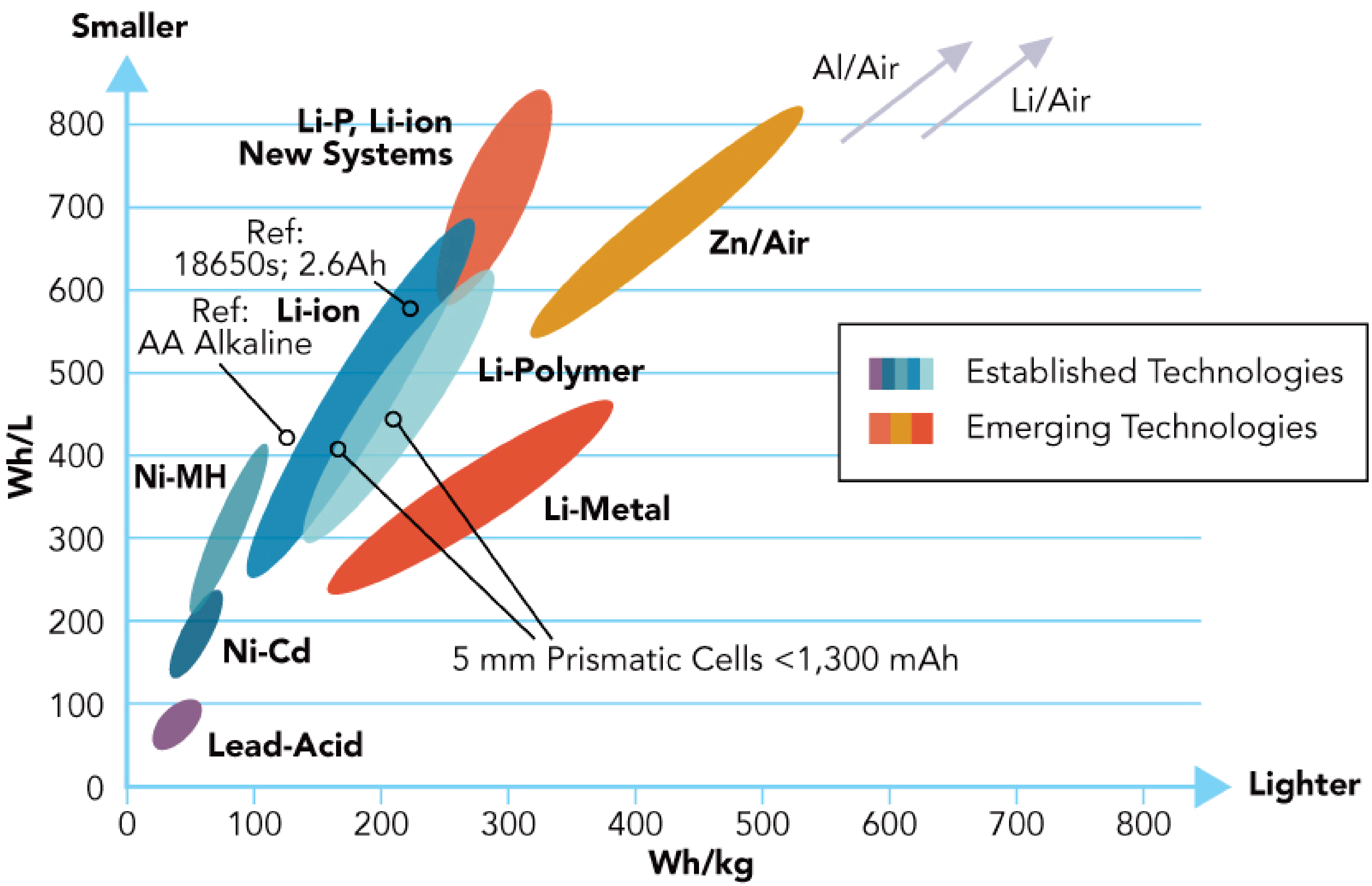
- Power Density
  - W/cm^3
    Maximum instantaneous power delivery per unit volume.
    For a battery this would be directly proportional to current density.

- Power Density per Year
  - $W/cm^3/year$
    Average power delivery per year of operation.

Energy Storage Characteristics

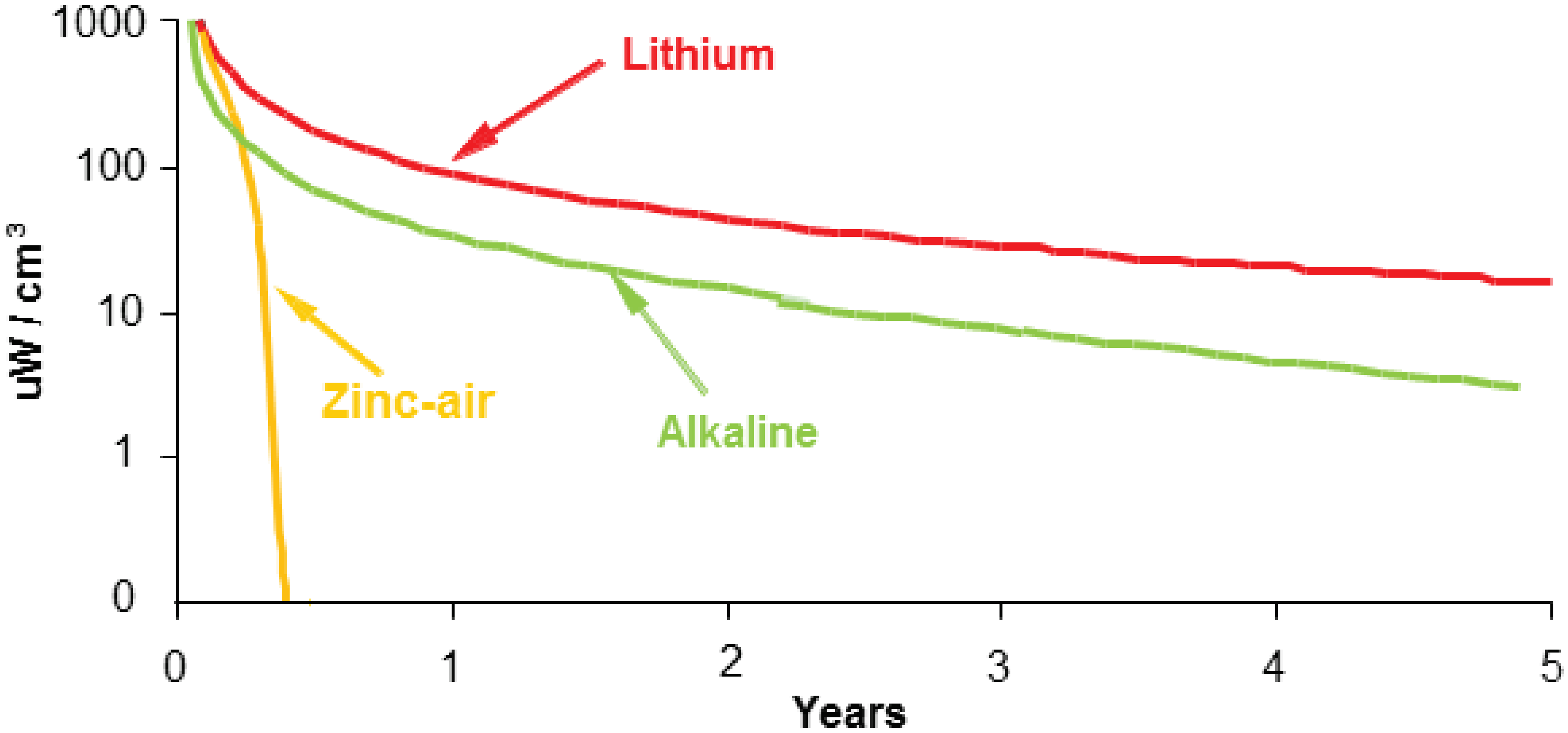


Energy Storage Volume vs. Weight



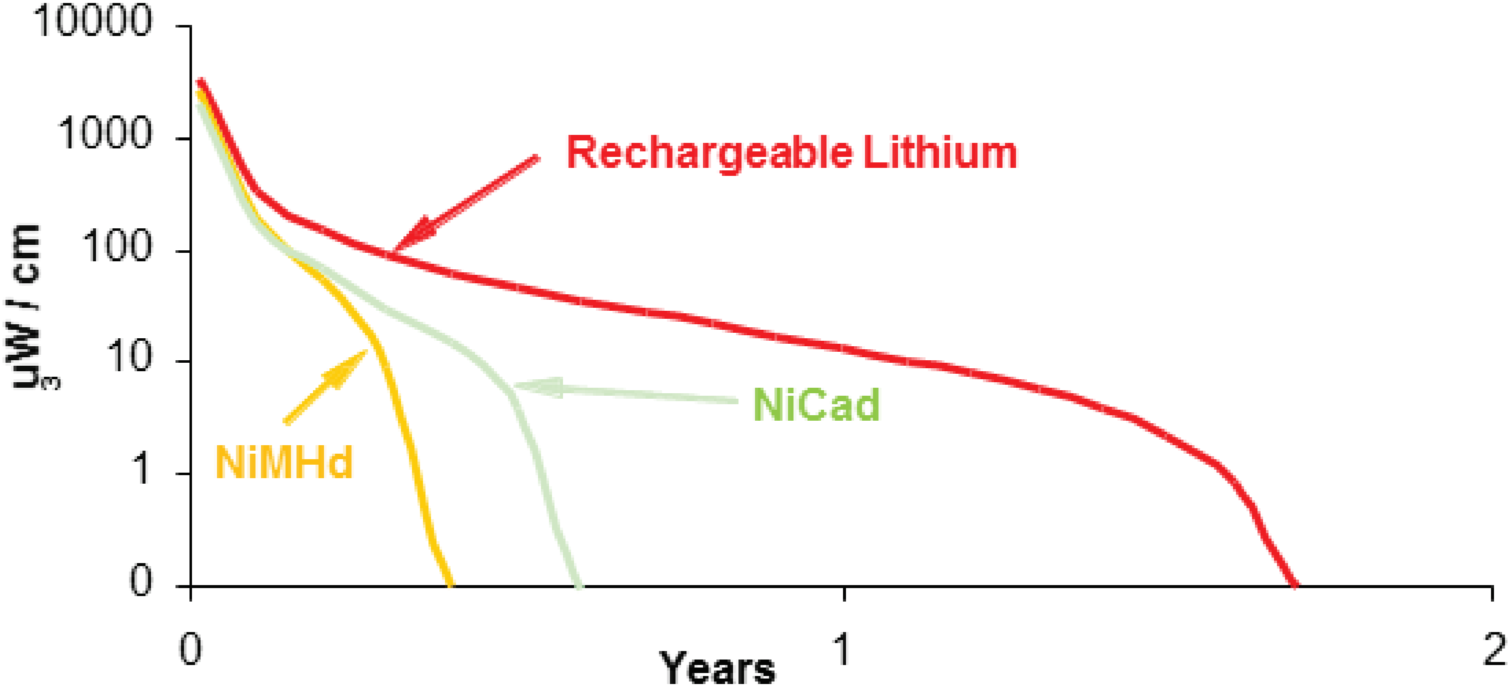
[Nexergy]

Primary Batteries Lifetime



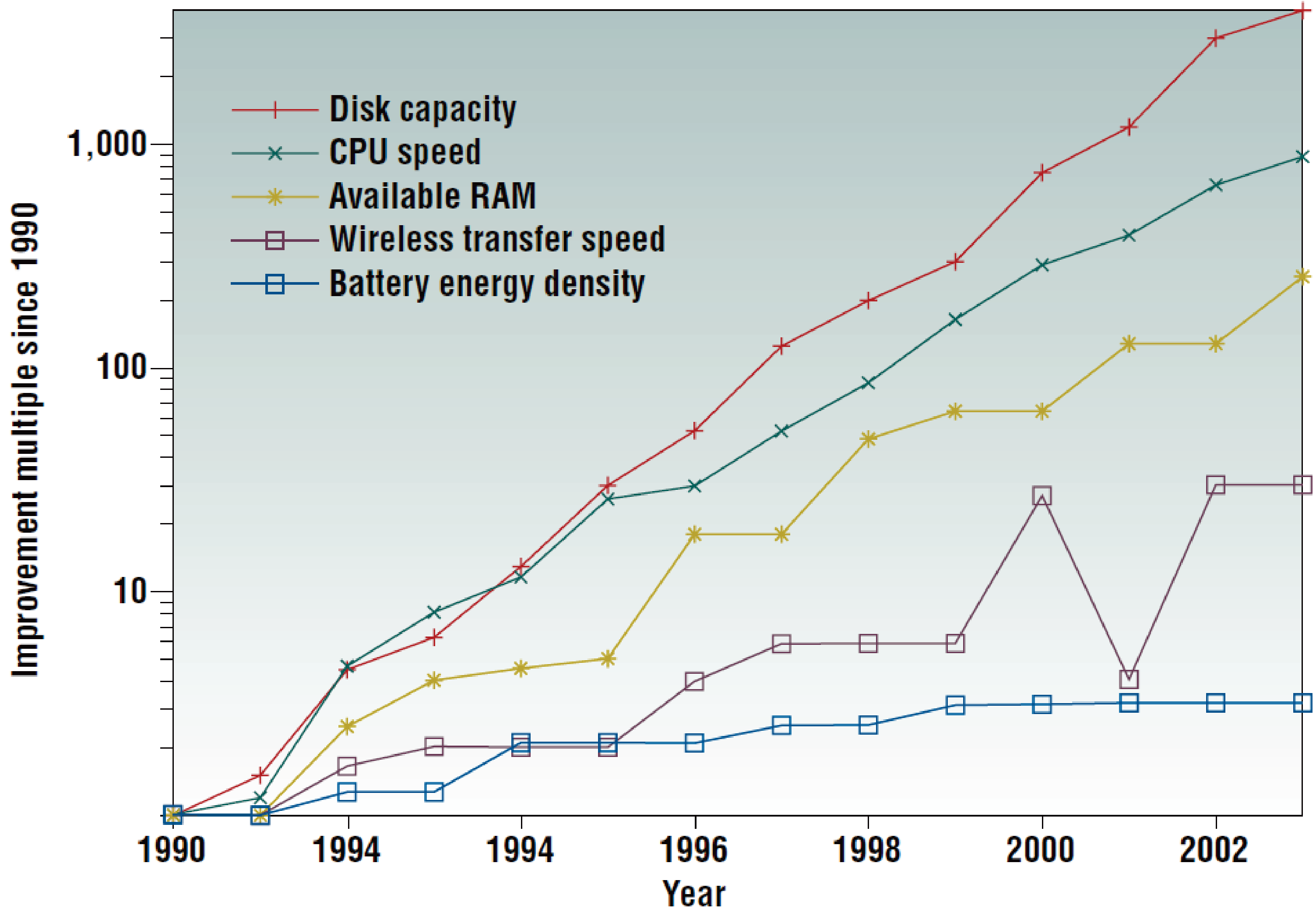
Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm³)	3780	2880	1200

Secondary Batteries Lifetime



Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm³)	1080	860	650

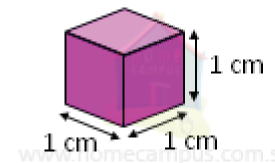
Progress in Energy Storage is Slow



[Paradiso, IEEE Pervasive Computing 2005]

A Simple Power Example

- At an average power consumption of 100uW, you need slightly more than 1 cm^3 of lithium battery volume for 1 year of operation, assuming you can use 100% of the charge in the battery.

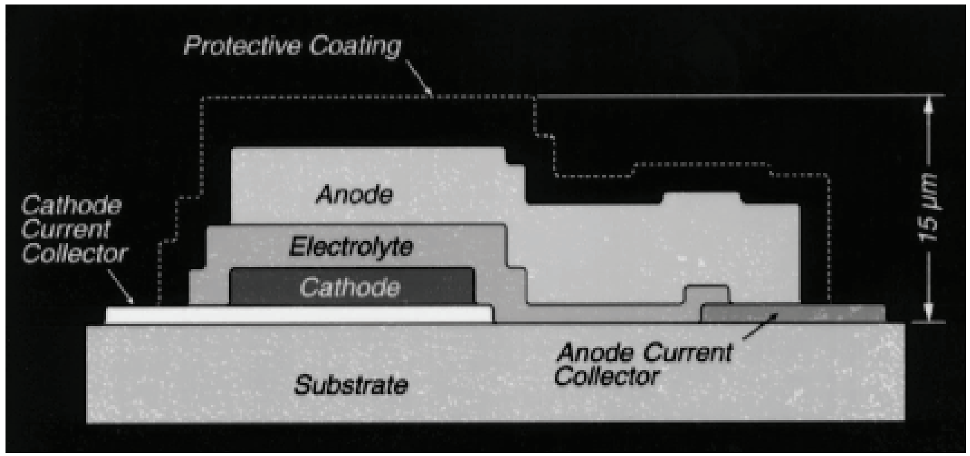


- Energy density of rechargeable batteries is less than half that of primary batteries.

- In reality 100% is not realistic: So, someone needs to either replace batteries in every system every ~9 months, or recharge every battery every ~3 to 4 months.

Technology: Micro On-chip Batteries

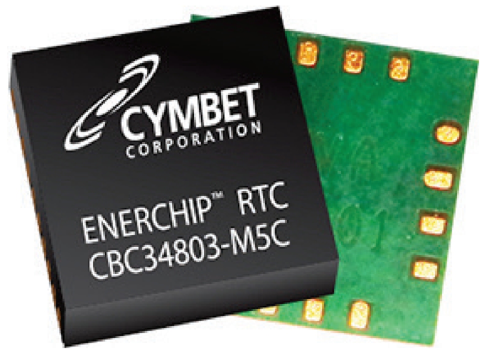
- Primary Lithium on-chip battery proposed by Bates et al. 2000



- Most research in this area is on secondary batteries
  - Current output is a limiting factor due to very small surface area
  - Depending on chemistry and researcher, outputs range from 1 to 10 mA/cm^2 at 1.5 to 4.2 volts
  - Most likely used as small capacity storage in conjunction with another (primary) power source

Technolgy: Integrated Chip-Size Batteries

- **EnerChip RTC Family: RTC + EnerChip + PMIC in Single Package**



- The EnerChip RTC product family combines an ultra low power Real Time Clock with an integrated EnerChip 5uAh battery and Power Management IC integrated into a small 5mm x 5mm plastic QFN package
- 120 hours of power holdover/charge in lowest power clock mode

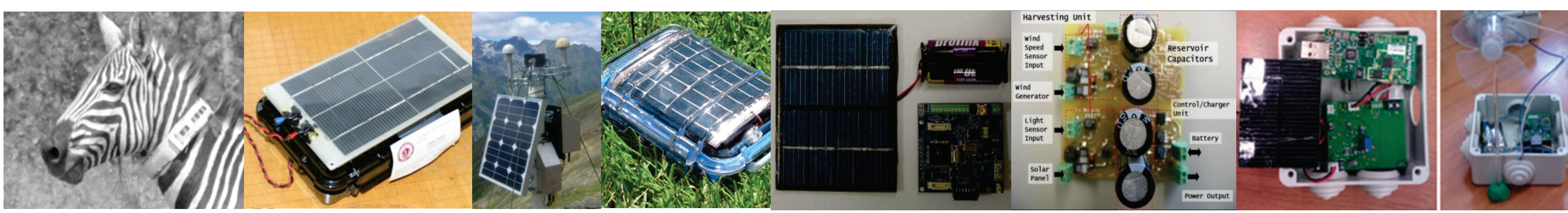
[EnerChip]

Towards Perpetual Operation

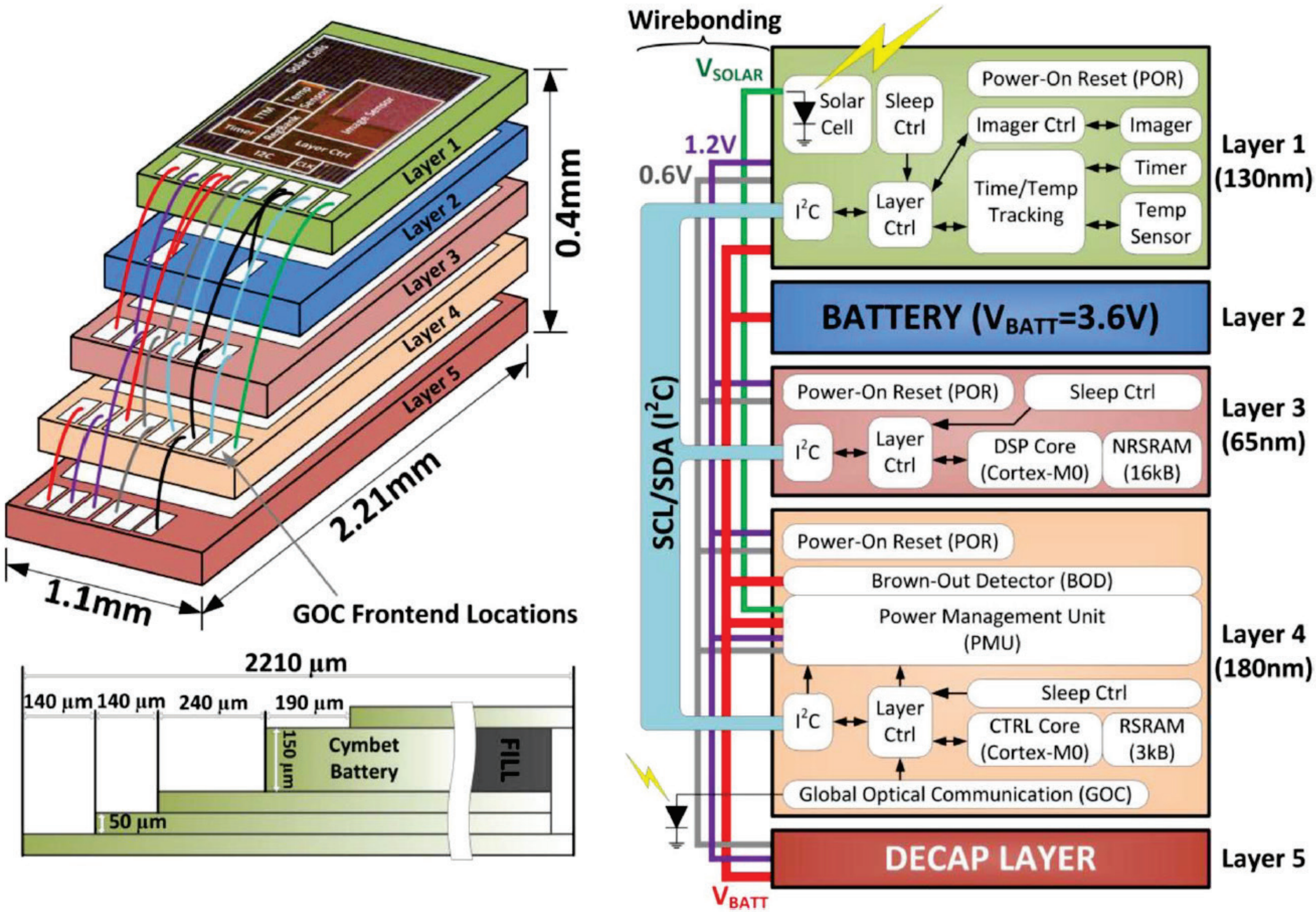
- "Indefinite" operation
  - Effective, long term, power supplies are limited and/or expensive
  - We cannot always recharge and we cannot carry enough energy using primary technologies

Solution

- Design systems that harvest limited energy from ambient (heat, light, radiation, vibrations…) or scavenge power from human activity



System Integration: Zero-Power Systems



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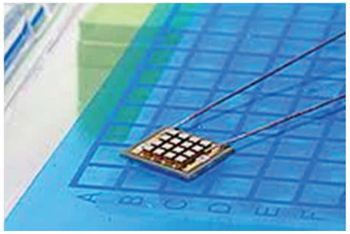
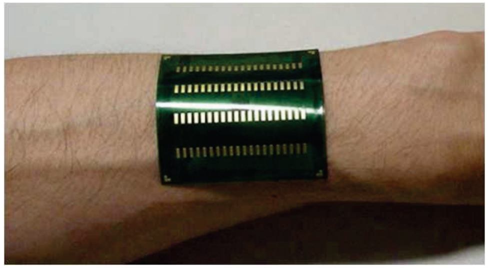
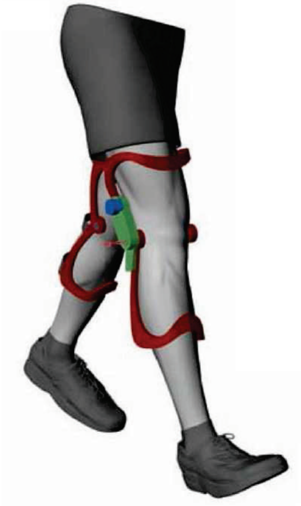
RENEWABLE ENERGY SOURCES – HARVESTING SYSTEMS

Energy Harvesting Basics

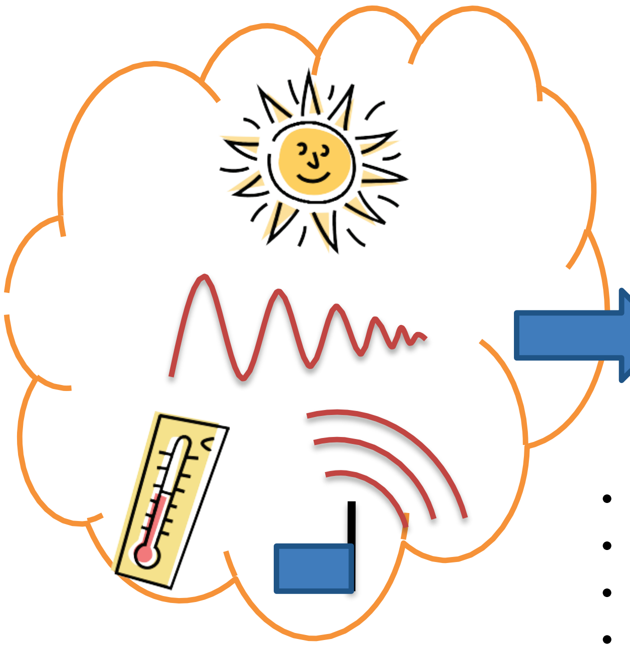
- **Energy harvesting** is the process by which energy is **captured** and **stored**
- This term often refers to small, autonomous devices: **micro energy harvesting**
  - Energy harvesting shrinks or replaces batteries or extends recharge periods
  - Power output of energy harvesting transducers is linked to their size (area, volume) and thus to their price
  - Power addresses matching of loads and supplies aiming at the maximum energy output

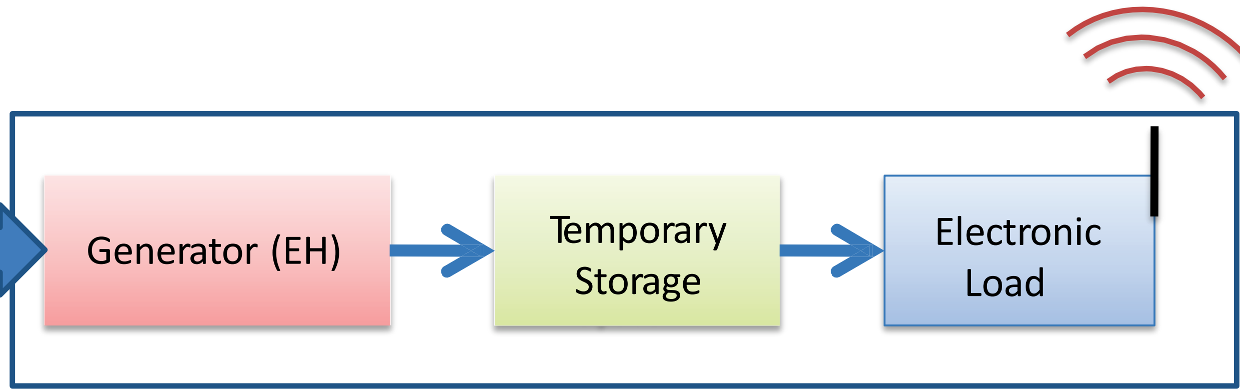






Energy Harvesting Principle





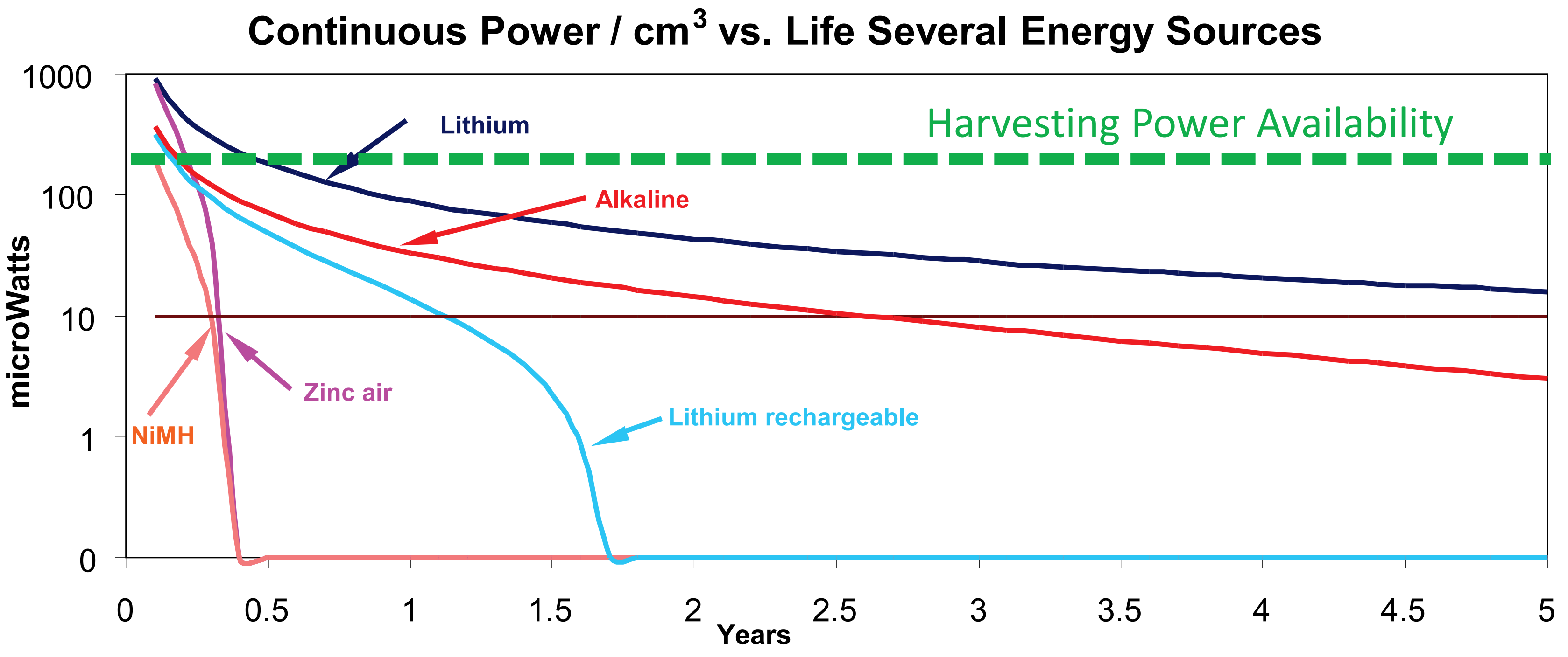
- Piezoelectric
- Electrodynamics
- Photovoltaic
- Thermoelectric

- Ultra capacitors
- Rechargeable Batteries

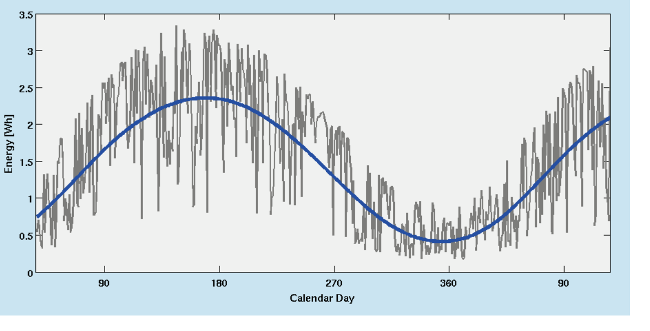
- Low power devices
- Wireless sensors
- MEMS actuators
- Consumer electronics

- Benefits
  - Long lasting operability
  - No chemical disposal
  - Cost saving
  - Safety
  - Maintenance free
  - No charging points
  - Inaccessible sites operability
  - Flexibility
  - Applications otherwise impossible

Extending the Lifetime



- Of course life is not quite so easy: The energy harvesting (input) exhibits fluctuations



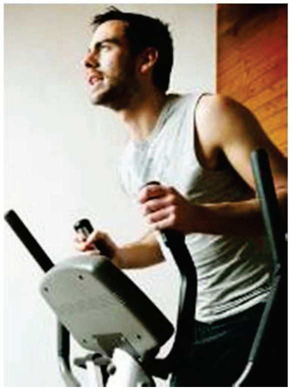
Available Energy is All Around

Light

EM waves

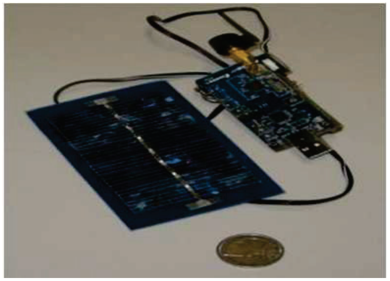
Motion and vibration

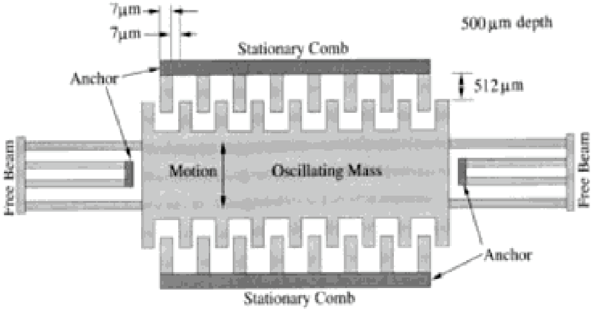
Heat

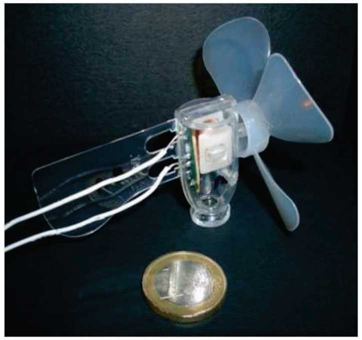


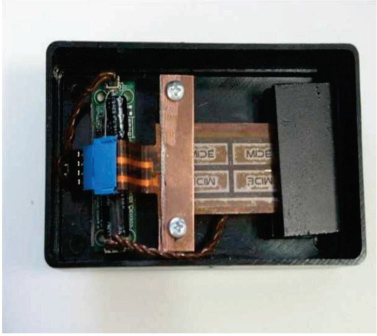
Ambient Energy Sources

- Light
  - Photovoltaic cells 10 uW/cm^2 to 15 mW/cm^2
- Temperature gradients
  - 80 uW/cm^2 @ 1V from 5K difference
- Mechanical sources
  - Vibrations 0.1 to 10000 uW/cm^2
  - Pressure variation
  - Acceleration
  - Air/liquid flow
- Radiation
  - RF sources
  - Nuclear radiation







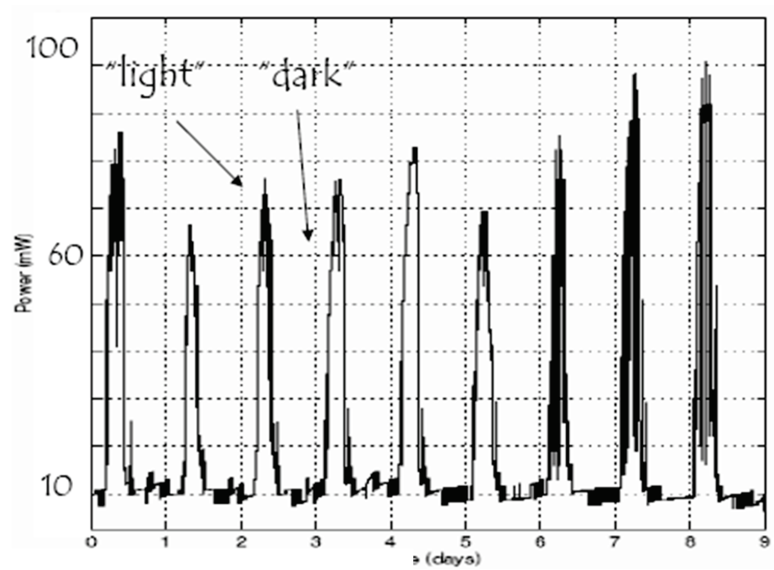


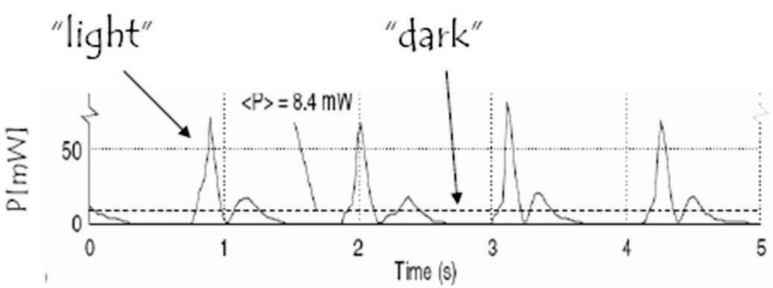
Energy Harvesting Sources

Energy Source	Source Polarity	Efficiency	Harvested Power	Characteristics
Light	DC	10~24%	100 mW/cm^2 (Outdoor) 100 μW/cm^2 (illuminated office)	Operating conditions vary widely with environment light level. MPPT algorithms needed to achieve maximum power transfer
Thermal	DC	~0.1% ~3%	60 μW/cm^2 (Human) ~1-10 mW/cm^2 (Industrial)	Low output voltage. Step-up circuit needed. Impedance matching to achieve maximum power transfer
Vibration	AC	25~50%	~4 μW/cm^3 (Human motion - Hz) ~800 μW/cm^3 (Machines - KHz)	High AC output voltage with positive and negative fluctuations (spikes). Rectifier & Step-down circuits are needed.
Ambient Air flow	AC	~39% (Dynamic) ~41% (Generator)	35 μW/cm^2 (@ <1 m/s) 3.5 mW/cm^2 (@ 8.4 m/s)	Dual or 3-phase output. Rectifier is needed. MPP varies slightly with wind speed. Impedance matching is sufficient to achieve maximum power transfer in many applications
RF	AC	~50%	0.1 μW/cm^2 (GSM 900 MHz) 0.001 mW/cm^2 (WiFi)	Impedance matching to achieve maximum power transfer

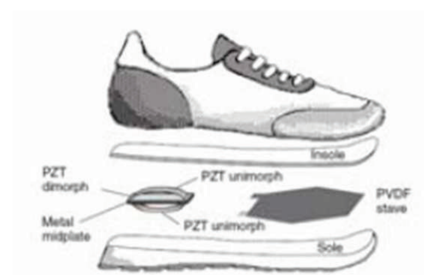
Ambient Energy
Non-monotone, Unpredictable

- Example: Solar power (PV-cells)
- Example: Power waveform from human walk (piezo-scavengers)

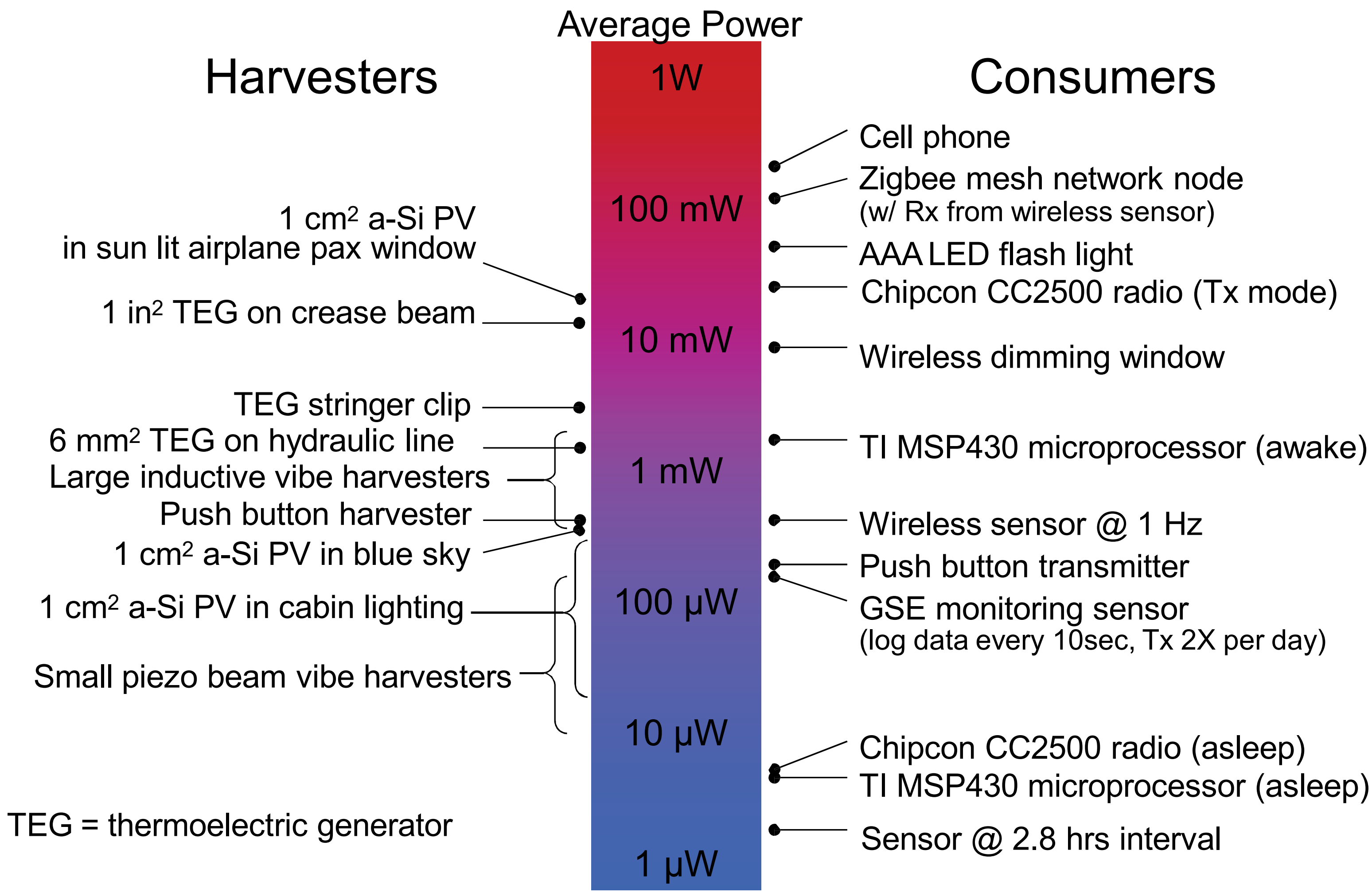




[Paradiso05]



Power Generation & Utilization



Technology: Solar Power

- Max. power density for outdoor solar is 1000 W/m^2 or 100 mW/cm^2
  - At midday, summer, no clouds, right angle reception
  - A night with full moon yields only 1 mW/m^2
  - Winter solar energy (in Europe) is about $1/10^{th}$ of summer
  - Indoors 500-1000 mW/m^2
  - Attenuation over distance is very strong

Distance	20cm	30cm	45 cm	Office Light
uW/cm^2	503	236	111	7.2

Power densities measured indoors from a 60 Watt incandescent light bulb

- Typical solar cell efficiencies: 10-20%
  - 2-5% for very cheap/small cells

Technology: Solar Panel Characteristics

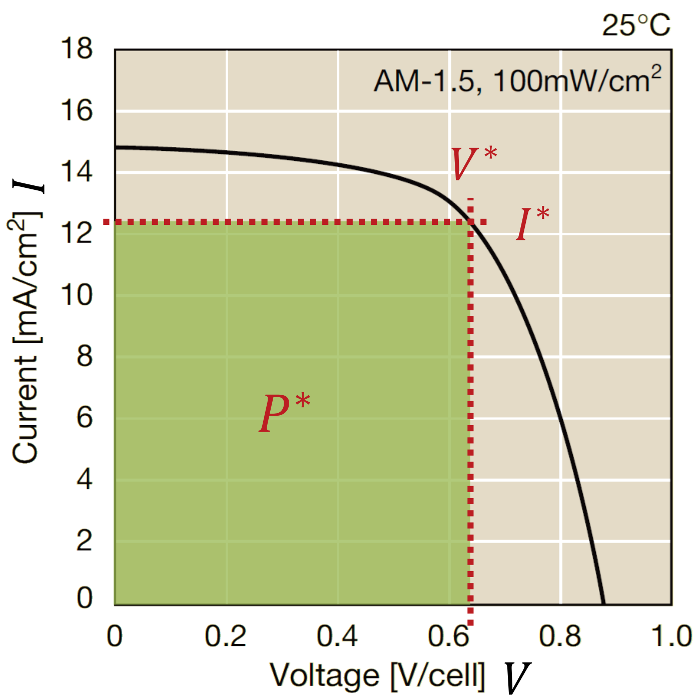
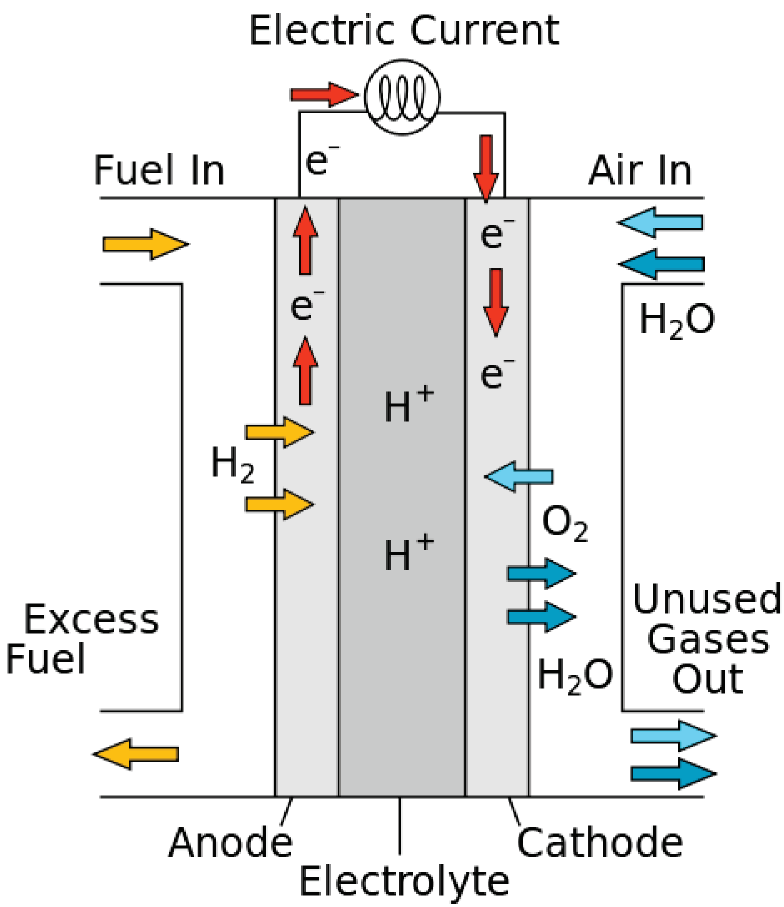


Diagram: *Amorton Amorphous Silicon Solar Cells Datasheet,* © Panasonic

- Variable output power
  - Illuminance level
  - Electrical operation point
  - (Temperature, age, …)
- I-V-Characteristics
  - Non-linear
- Maximum Power Point Tracking
  - Dynamic algorithm to find P^*

Technology: Micro-Fuel Cells

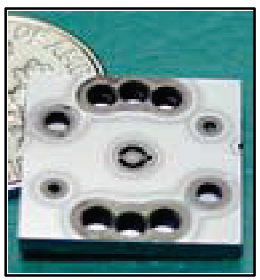


- Max current is a limiting factor due to surface area constraints (as with micro-batteries).
- Methanol energy density is 17.6 kJ/cm3. (6 X lithium and 15 X rechargeable lithium).
- Efficiencies of large fuel cells is about 45% (up to almost 90% if cogeneration is employed.)
- Efficiencies of demonstrated micro-fuel cells are on the order of 1% (Holladay et al. 2002).
- Products are not really micro

Technology: Micro-Heat Engines

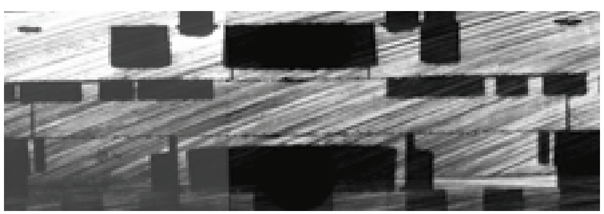
4 mm Turbine – top view

15 mm



ROTOR

Microturbine bearing rig



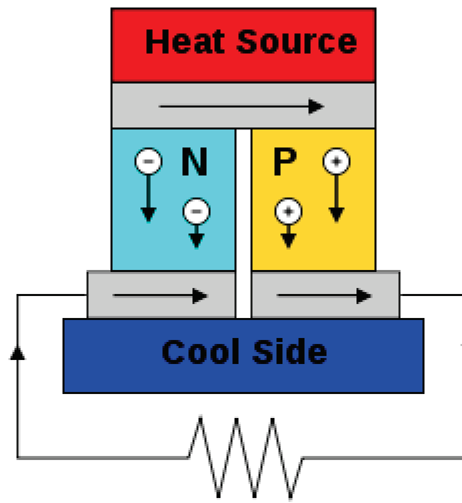
4 mm dia

- Research started by Epstein et al. 1997. Many types of engines are now being developed
- Petrol (gasoline) energy density is 30 kJ/cm^3
  - 10 X lithium and 25 X rechargeable lithium
- Expected efficiencies range from 5% to 20%
- 0.1 to 10 W output
- Size ~ 1cm^3

[L. Frechette, Columbia University]

Technology: Thermal Gradients

- **Seebeck effect** is the conversion of temperature differences (heat flux) directly into electricity



- Efficiency is given by:

$$\eta = \frac{\Delta T}{T}$$

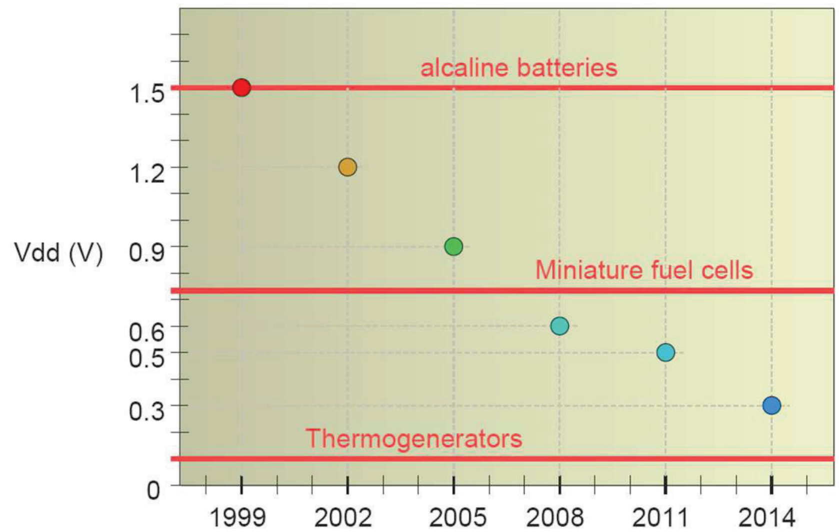
  - At T = 20°C and ΔT = 5°C, η = 1.6%
  - However, demonstrated efficiencies are far lower.

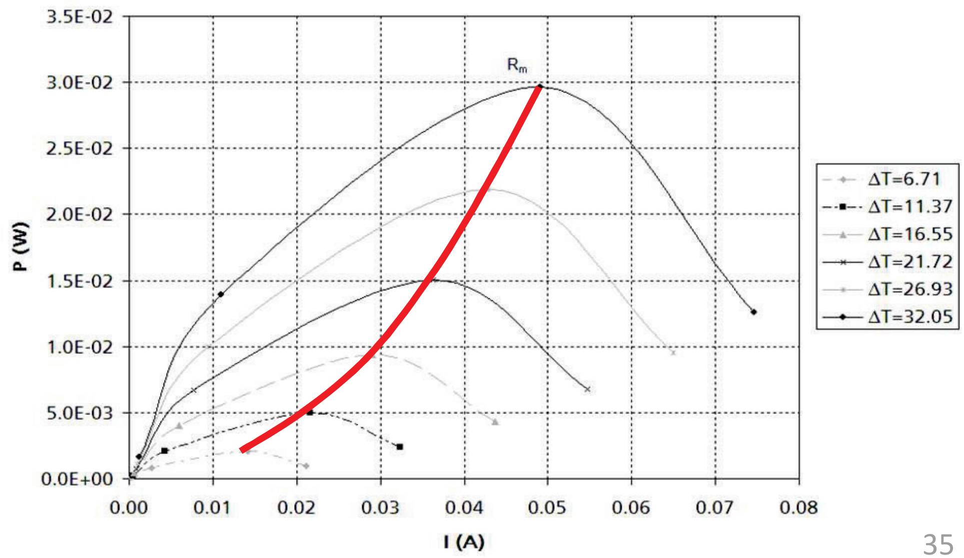
- Power is proportional to ΔT^2

$$P_{out} \propto \frac{\Delta T^2}{T}$$

TEG Characteristics

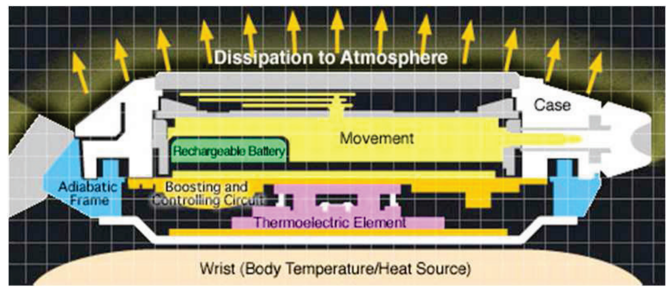
- TEGs output voltage is very low
- TEGs have a maximum power point (MPP) which changes with ΔT
- MPP is usually the half of the open circuit voltage (V_{teg} - V_{oc})
- Problem
  - Internal resistance of TEG depends on temperature and aging

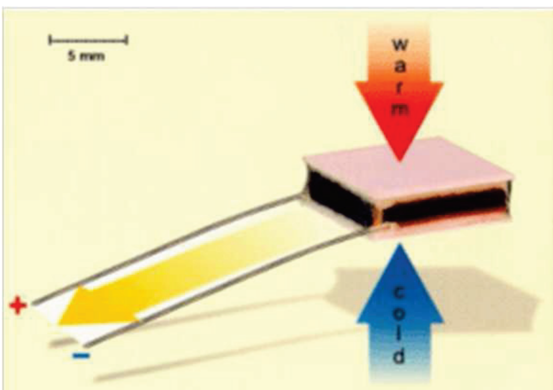


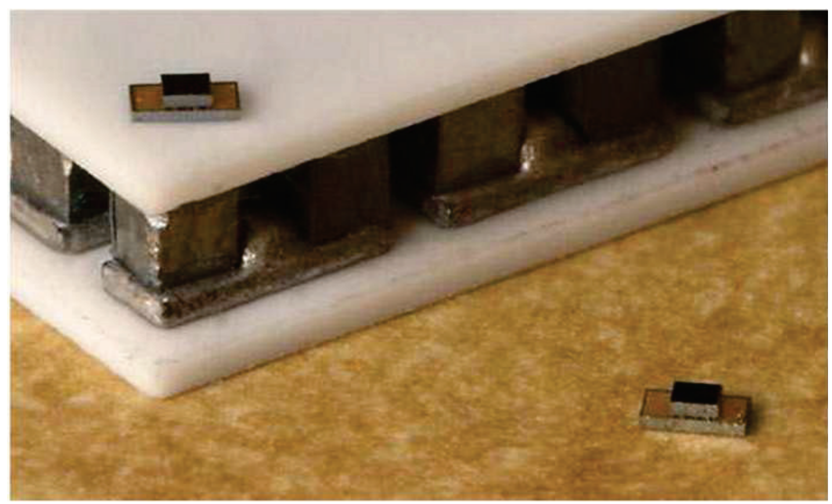


Example: Thermo Electric Generator

Seiko Thermic wristwatch, convert heat from the wrist (body heat) into electricity.

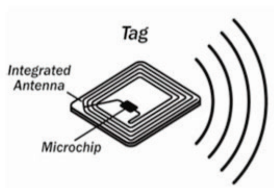


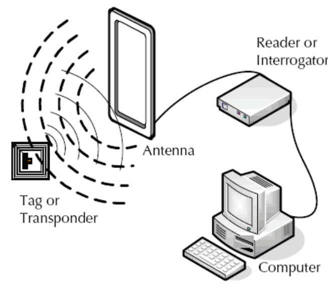




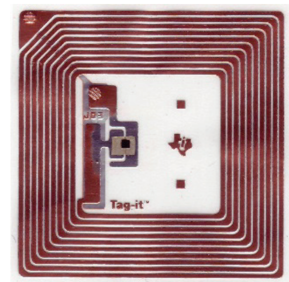
Technology: RF Radiation Sources

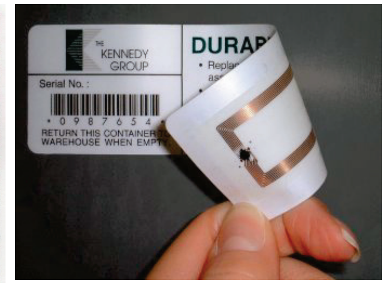
- Remote powering of systems from RF sources

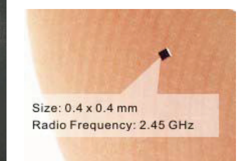




- Inductive coupling using a large excitation coil and a small pickup coil
  - Medical Implants
  - RFID Tags
  - Smart Cards
  - Wristwatches
  - Badges
- Experimental systems with higher power capabilities are explored







- Issue: Attenuation

$$P_r = \frac{P_o \lambda^2}{4\pi R^2}$$

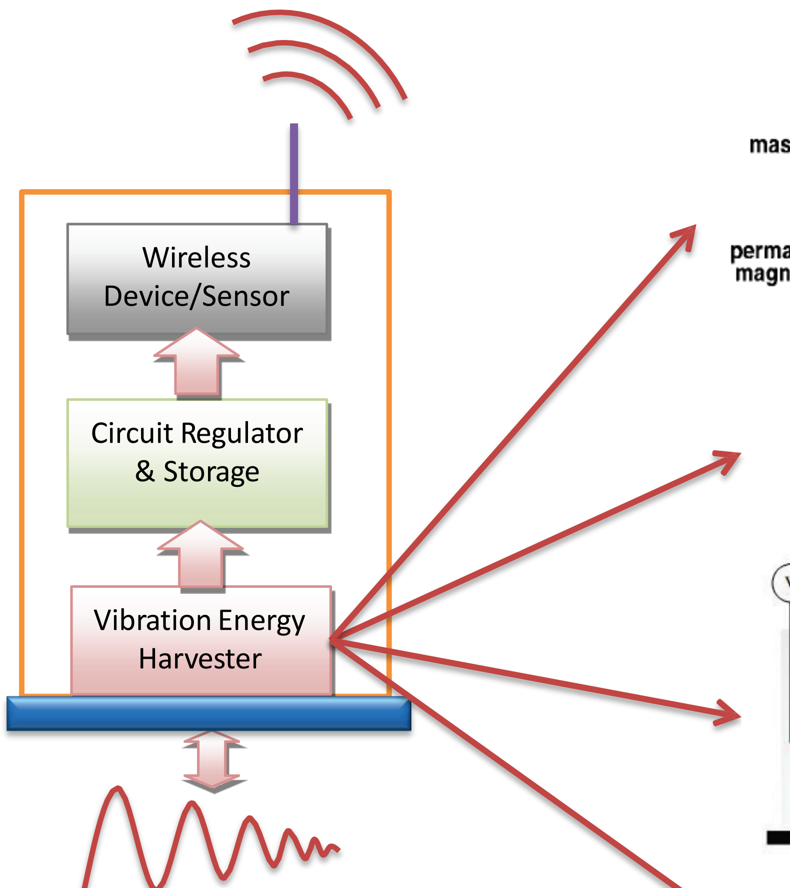
P_0 = transmit power
P_r = power received
λ = wavelength
R = transmit distance

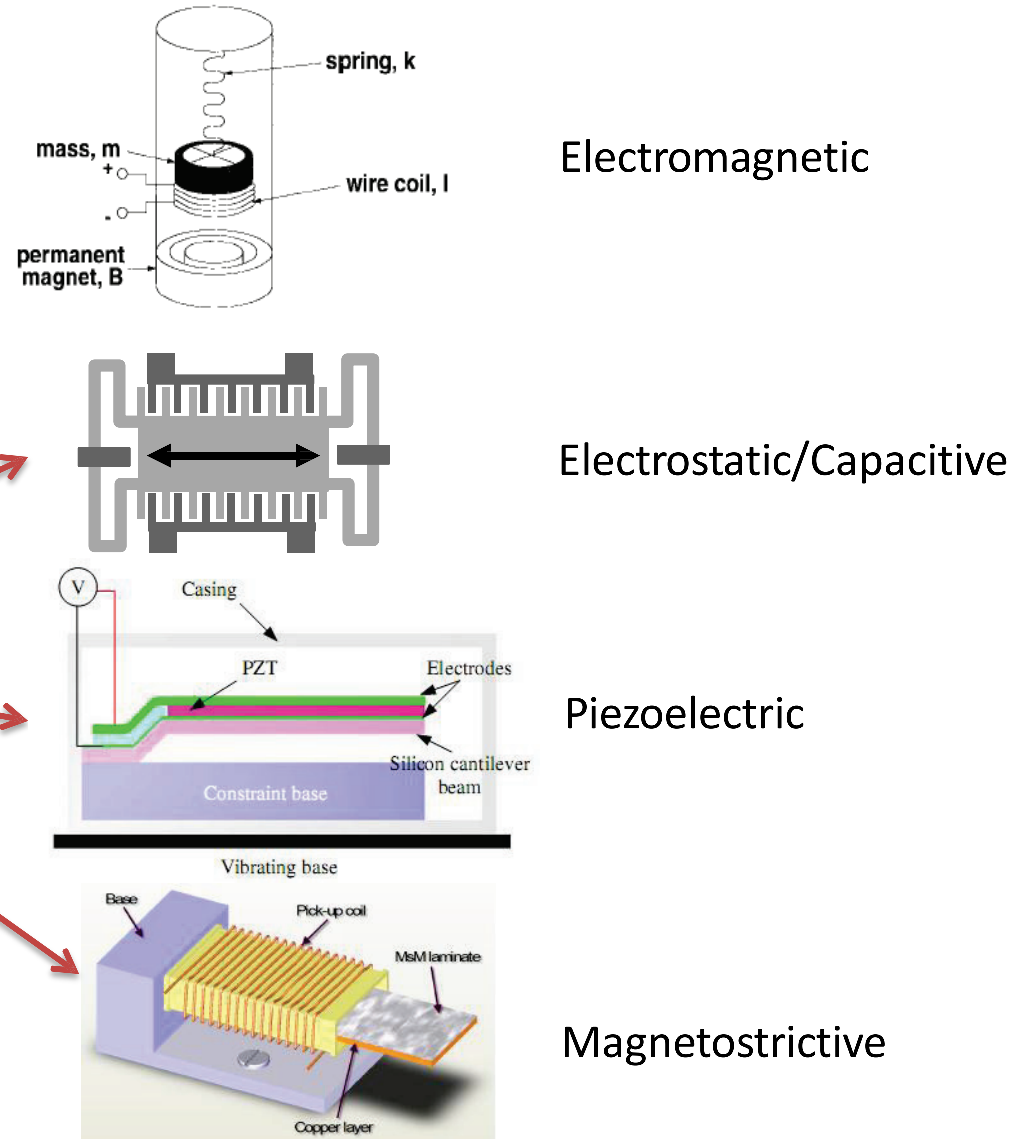
- Example

2.4 GHz, 5 meters, P_0 = 1 watt, P_r = 50 uW

- Probably not useful for a dense sensor networks, but useful in many applications

Technology: Vibration Energy Harvesting





- Ambient vibrations
- Human motion
- Wind, Hydro

Vibrations

- Generic vibration power conversion model (adapted from William et al. 1995)

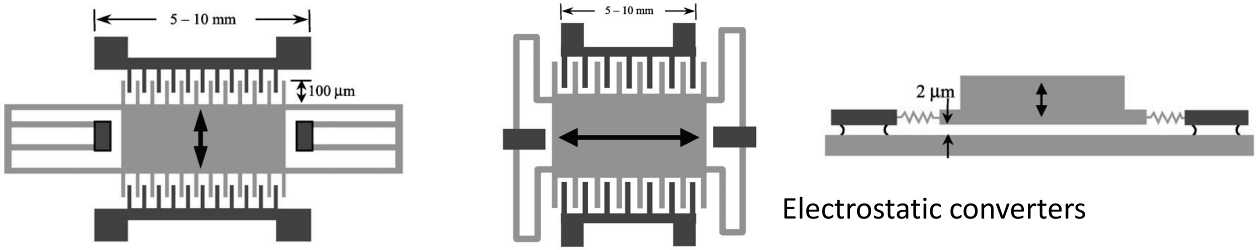
$$P = \frac{m \zeta_e^2 A^2}{4\omega(\zeta_e + \zeta_m)^2}$$

m is the proof mass
ζ_e is the electically induced damping ratio
ζ_m is the mechanical damping ratio
A is the acc. amplitude of the vibrations
ω is the resonant freq. and input freq.

Vibration Source	Peak Acc. (m/s^2)	Freq. (Hz)
Base of 3-axis machine tool	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just as door closes	3	125
Small microwave oven HVAC	2.25	121
vents in office building	0.2 – 1.5	60
Wooden deck with foot traffic	1.3	385
Breadmaker	1.03	121
External windows next to street	0.7	100
Notebook computer w/ CD.	0.6	75
Washing machine	0.5	109
Second story floor of a wood frame office building	0.2	100
Refrigerator	0.1	240

Acceleration magnitudes range from 0.1 to 10 m/s^2.
Frequencies range from 60 to 200 Hz.

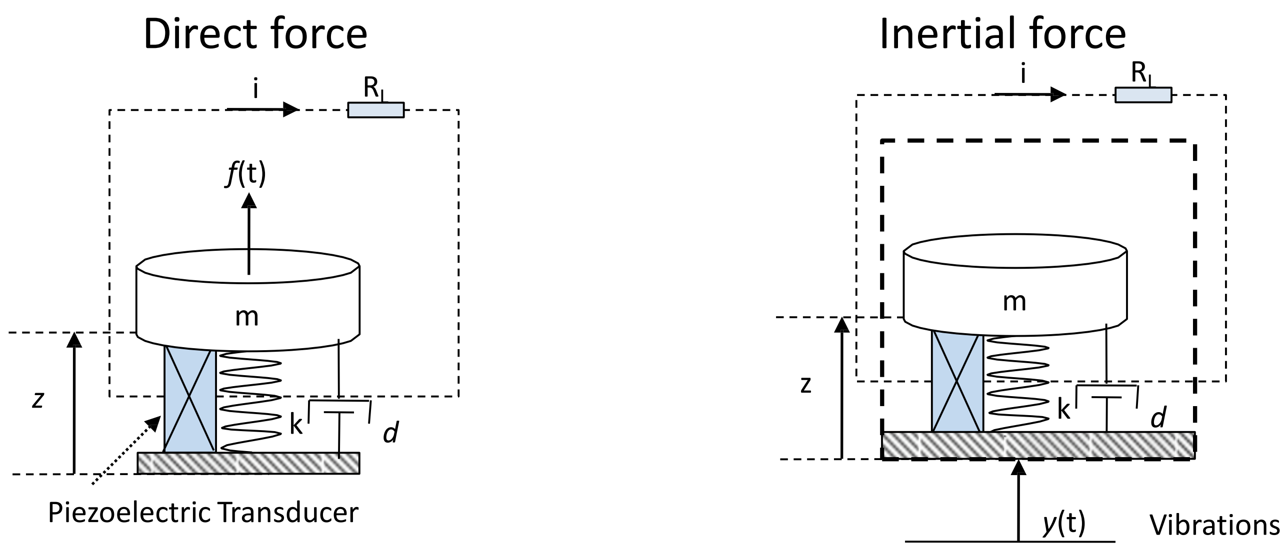
- Three things to notice from the model:
  - Power output is proportional to the mass of the device
  - Power is proportional to the square of the acceleration amplitude
  - Power output is inversely proportional to frequency



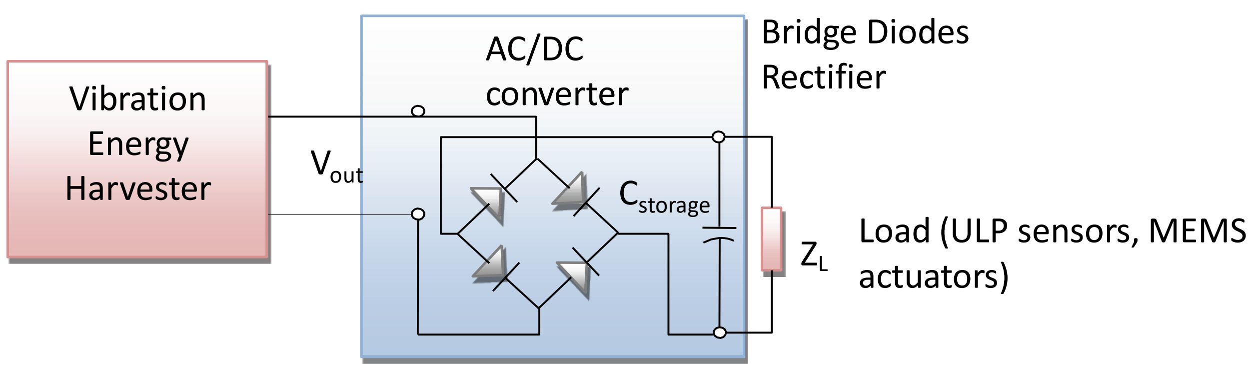
Electrostatic converters

[S. Roundy, UC Berkeley]

Vibration – Basic Operating Principles

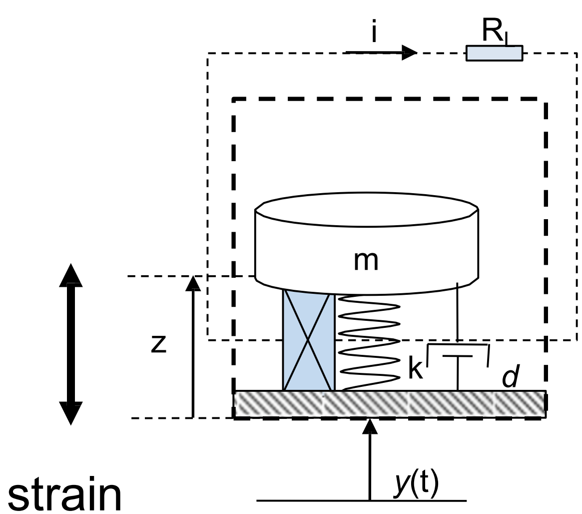


Inertial generators are more flexible than direct-force devices because they require only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

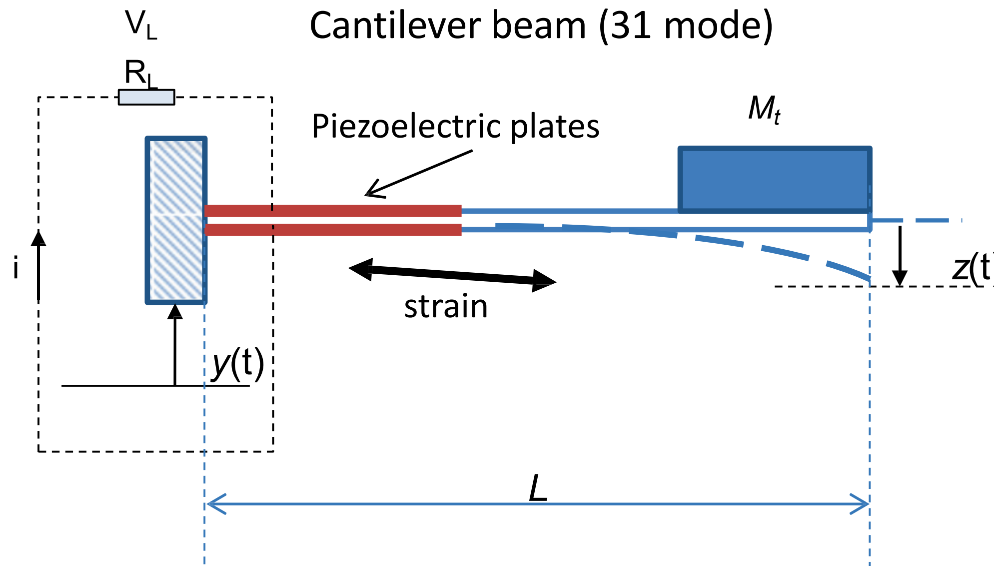


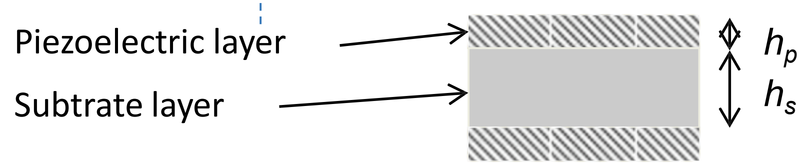
Piezoelectric Mechanical-to-electrical Conversion

Piezoelctric bulk (33 mode)

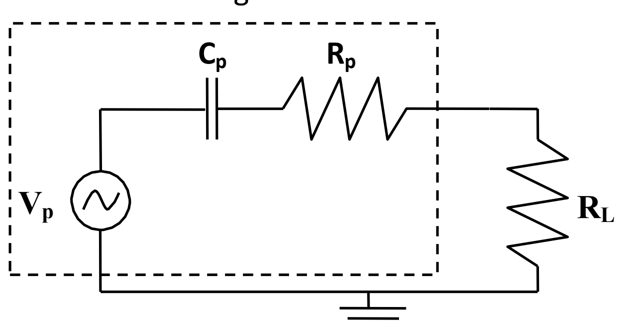


Cantilever beam (31 mode)





Piezoelectric generator



At open circuit

$$V_{oc} = -\frac{d_{31}h}{\varepsilon^S}T_1$$

The power delivered to the load is simply

$$P = \frac{V_L^2}{R_L}$$

[S. Roundy, Energy scavenging for wireless sensor networks, Kluwer]

Energy Harvesting Methods - Overview

Power Source	P/cm³ (uW/cm³)	E/cm³ (J/cm³)	P/cm³/Yr (uW/cm³/Yr)	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	2880	90	No	No	Yes
Secondary Battery	-	1080	34	-	No	Yes
Micro-Fuel Cell	-	3500	110	Maybe	Maybe	No
Ultra-capacitor	-	50-100	1.6-3.2	No	Yes	Yes
Heat engine	-	3346	106	Yes	Yes	No
Radioactive(^{63}Ni)	0.52	1640	0.52	Yes	Yes	No
Solar (outside)	15000	-	-	Usually	Maybe	Yes
Solar (inside)	10	-	-	Usually	Maybe	Yes
Temperature	40	-	-	Usually	Maybe	Upcoming
Human Power	330	-	-	Yes	Yes	No
Air flow	380	-	-	Yes	Yes	No
Pressure Variation	17	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	No

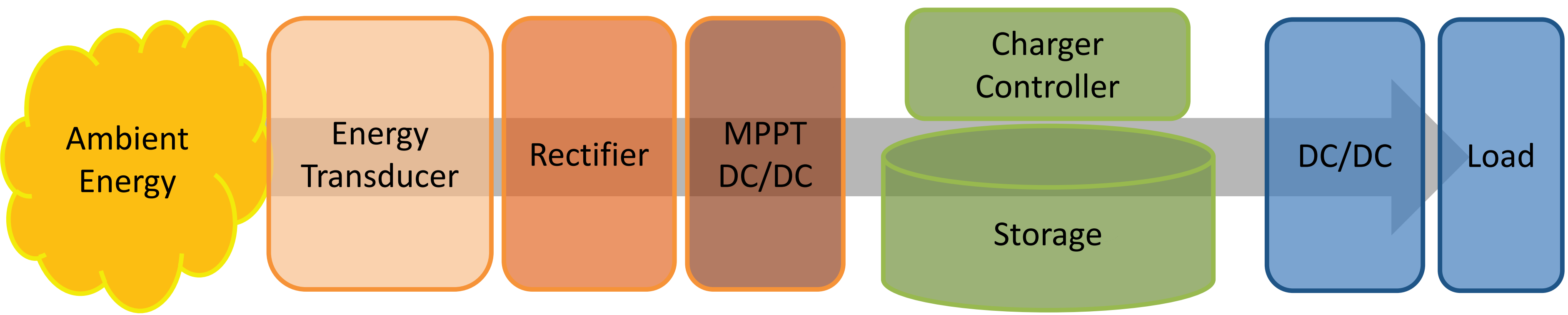
[S. Roundy, UC Berkeley]

Low-Power System Design

ENERGY HARVESTING – SYSTEMS INTEGRATION

Generic Energy Harvesting Design

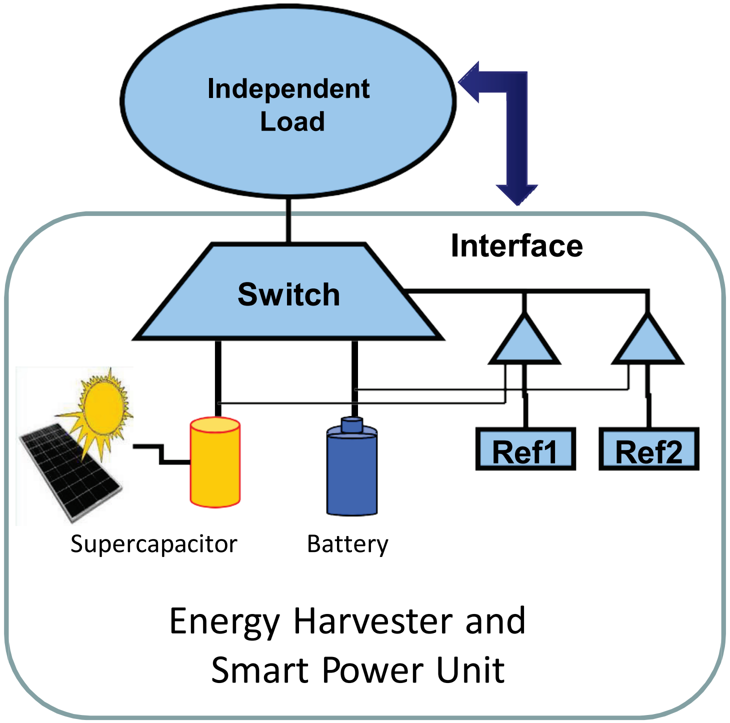
- **Dedicated blocks**, depending on energy source, ambient conditions and application
- **Not always all are required** in a given application/source
- Design process of rectifier, DC-DC converter and MPPT is **challenging**
- Charger/limiter/protection consumes additional power and are often to some extent redundant

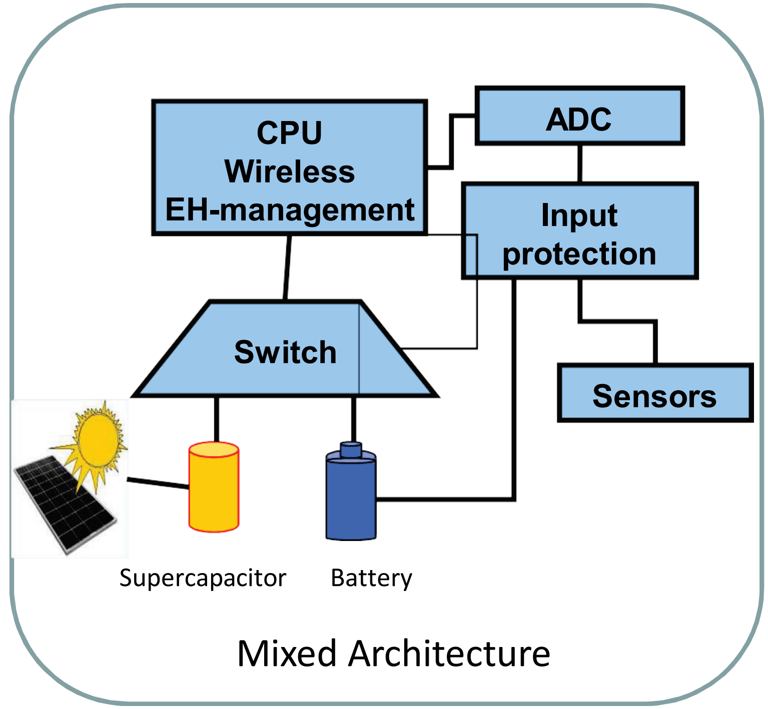


Opens up significant control-space issues w.r.t. energy usage

This needs software support!

Integration Into Mixed Architectures





- General purpose
- Optimized from Ambient Source and storage, but not for a specific application
- Plug-&-play
- Analog or with digital Interface for external power management

- Usually more efficient
- Tailored on a specific application
- HW /SW dependent

Electric Power – Source and Sink

- The instantaneous electric power delivered to a load is given by:

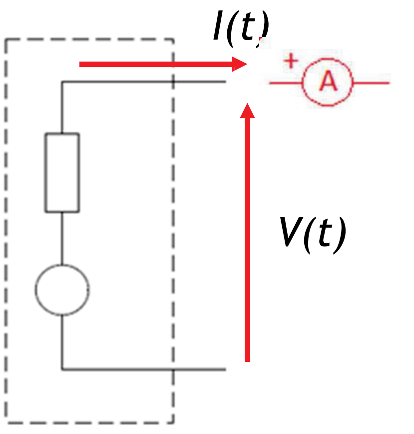
$$P(t) = I(t)\,V(t)$$

- In case of resistive loads, then

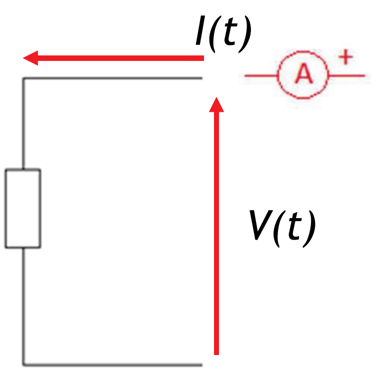
$$P(t) = R\,I(t)^2 = \frac{V(t)^2}{R}$$

- P(t) is the **instantaneous power**, measured in Watts [W]
- V(t) is the **voltage difference** across the load, measured in Volts [V]
- I(t) is the **current** through it, measured in Amperes [A]
- R is the **resistance**, measured in Ohms [Ω]

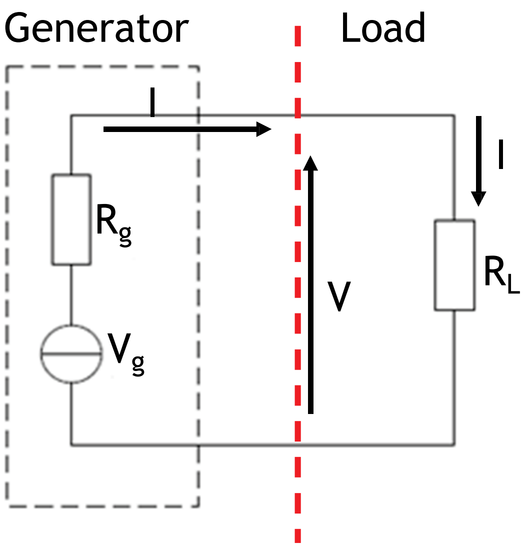
GENERATOR (delivered power >0)



USER (incoming power >0)



Maximum Power Transfer



$$V_g - R_g\, I - R_L\, I = 0$$

$$I = \frac{V_g}{R_g + R_L}$$

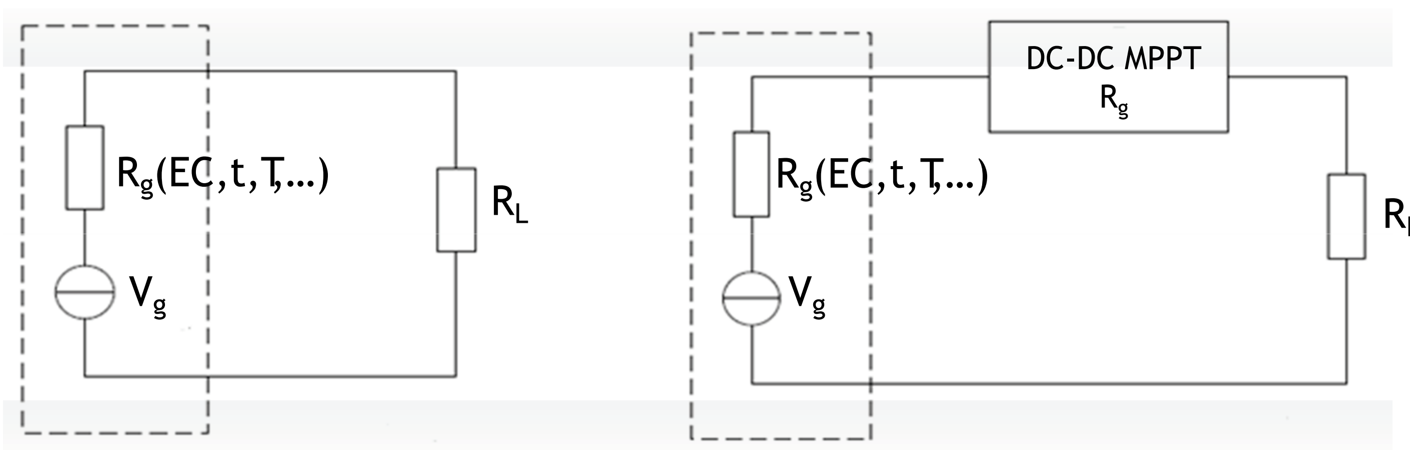
$$P = R_L\, I^2 = V_g^2 \frac{R_L}{(R_g + R_L)^2}$$

$$\max_{R_L}(P) \Rightarrow \max_{R_L}\left(\frac{R_L}{R_g + R_L}\right) \xrightarrow{\frac{dP}{R_L} = 0} \frac{(R_g + R_L)^2 - 2(R_g + R_L)^2 R_L}{(R_g + R_L)^4} = 0$$

$R_L = R_g$ Resistance Matching

Maximum Power Point Tracking

- Maximum power from source to load when internal resistances are matched
- Input resistance of a DC-DC converter is influenced with its duty cycle
- R_g depends on several factors → R_g (Environmental condition, time, temperature, …)



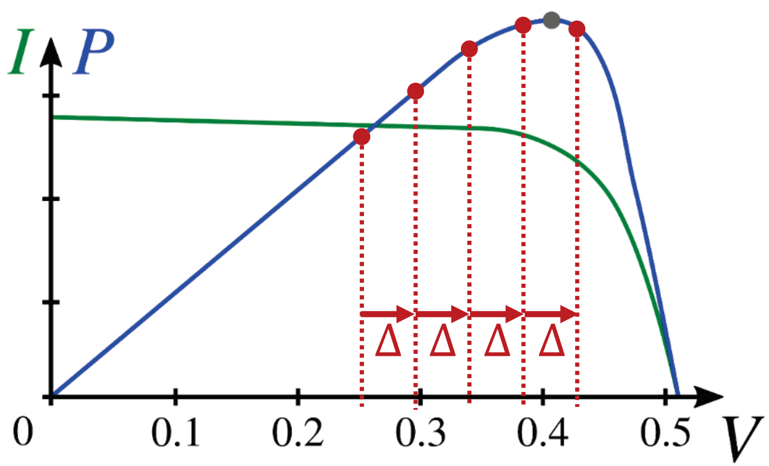
Ideal situation:

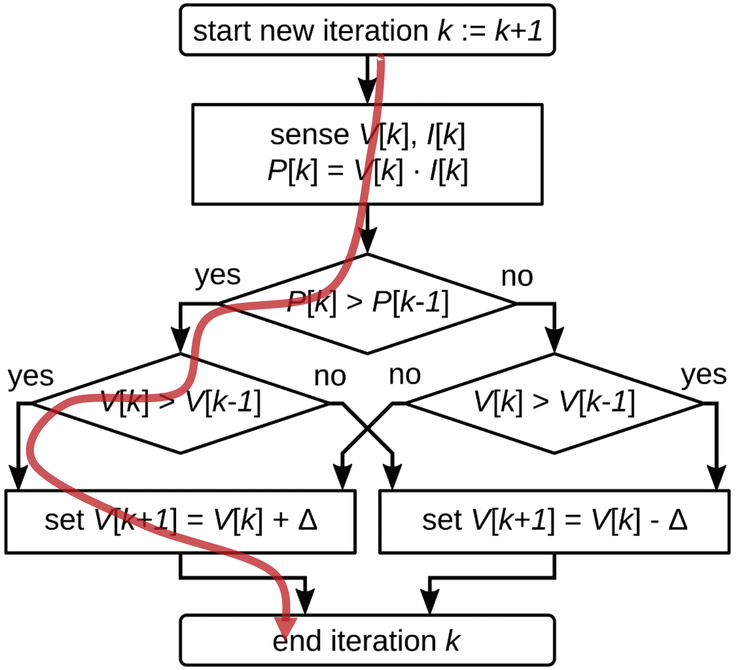
- *Load R_L and internal resistance R_g are naturally matched*
- *V_g in the correct range*

Typical situation:

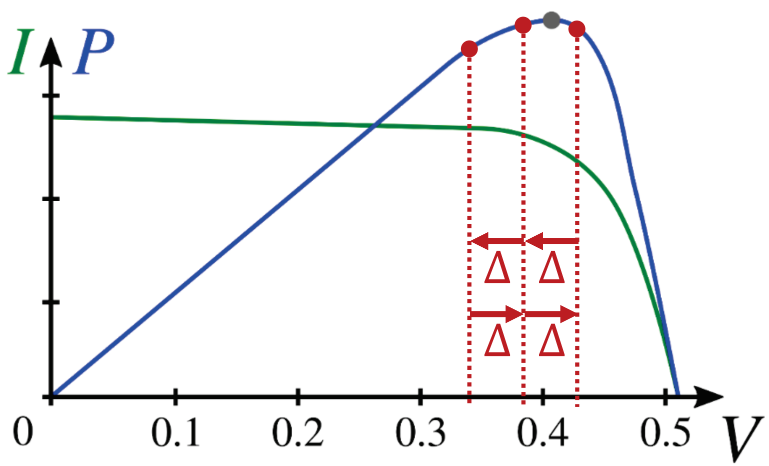
- *DC/DC with MPPT to match R_L and R_g and /or to adjust V_g*
- ***MPPT adjusts resistance matching over time***

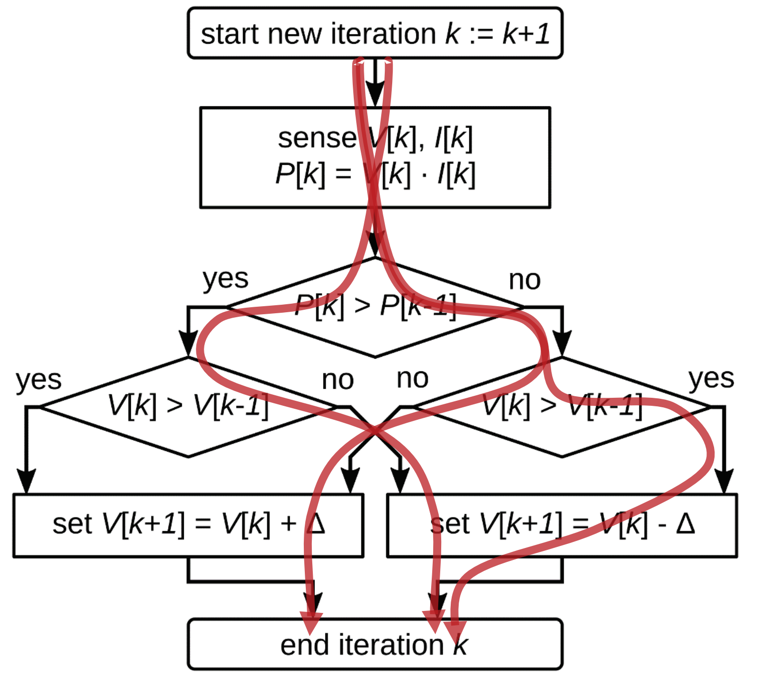
Maximum Power Point Tracking



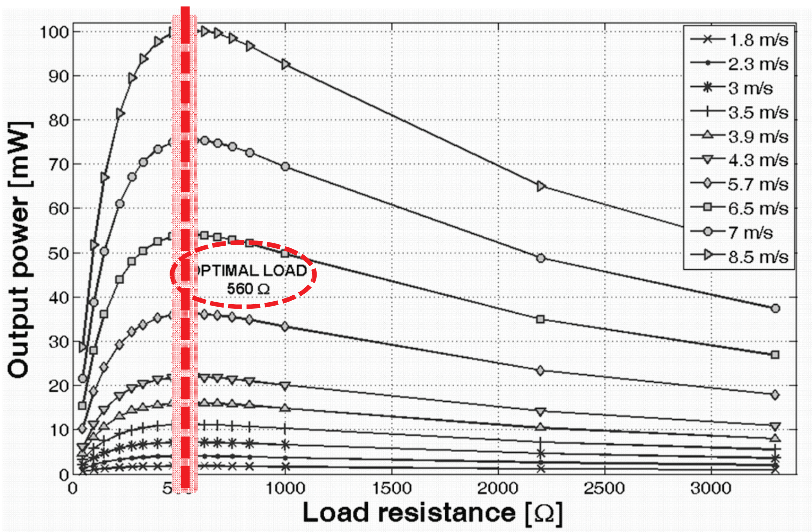


Maximum Power Point Tracking

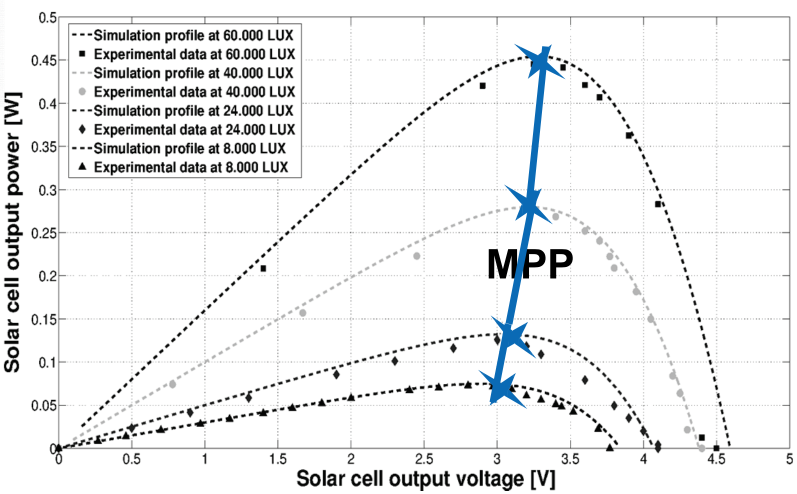




Maximum Power Point Under Ambient Conditions



- Two main cases:
  - MPP varies slightly with ambient conditions (e.g. wind generators)
  - Wide variations of the MPP (e.g. solar cells)



- Two main solutions:
  - Static impedance matching
  - Dynamic Maximum Power Point Tracking (MPPT)

Low-Power System Design

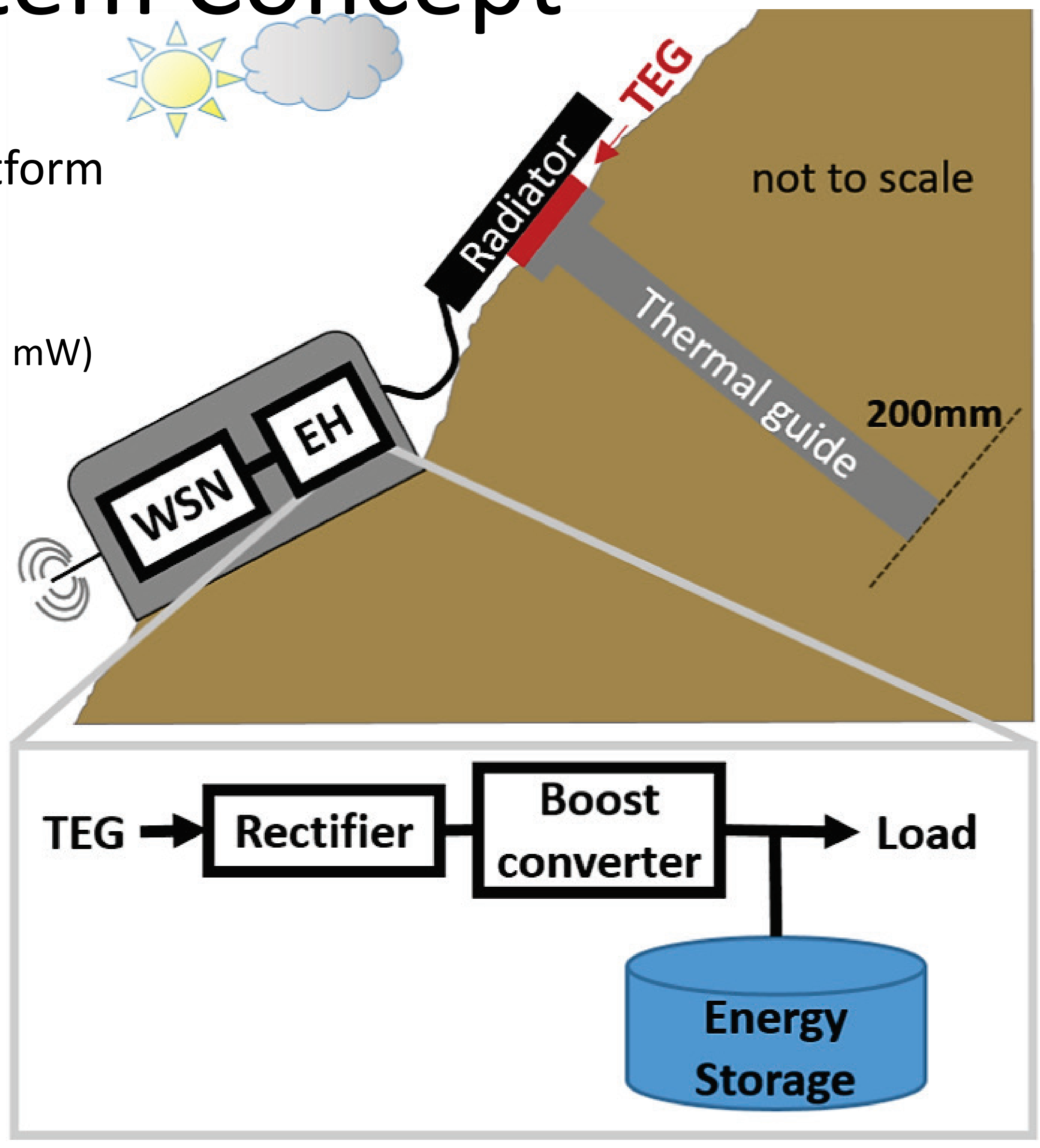
TEG-BASED ENERGY HARVESTING FOR THE PERMASENSE WSN

[Master Thesis by D. Bernath, 2016]

System Concept

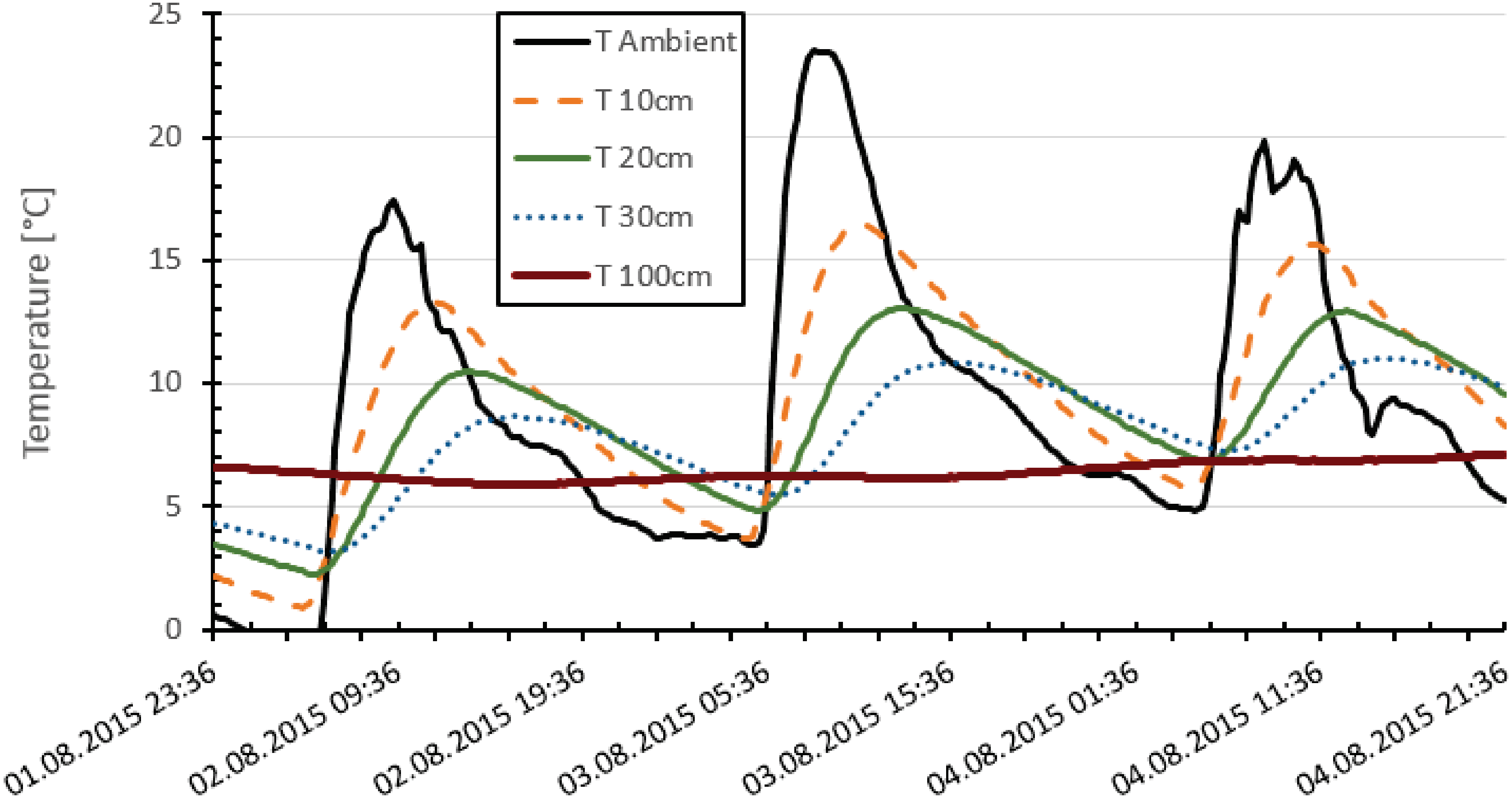
- Universal TEG Harvesting Platform
  - Ground to atmosphere
  - Generic ~1mW class load
  - Example: PermaSense WSN (0.5 mW)

- Optimization areas
  - Thermal guide
  - Radiator
  - TEG
  - Rectifier
  - Boost converter



[L. Sigrist, N. Stricker, D. Bernath, J. Beutel and L. Thiele, "Thermoelectric Energy Harvesting from Gradients in the Earth Surface," in IEEE Transactions on Industrial Electronics, 2019.]

Diurnal Temperature Difference in Rock Wall



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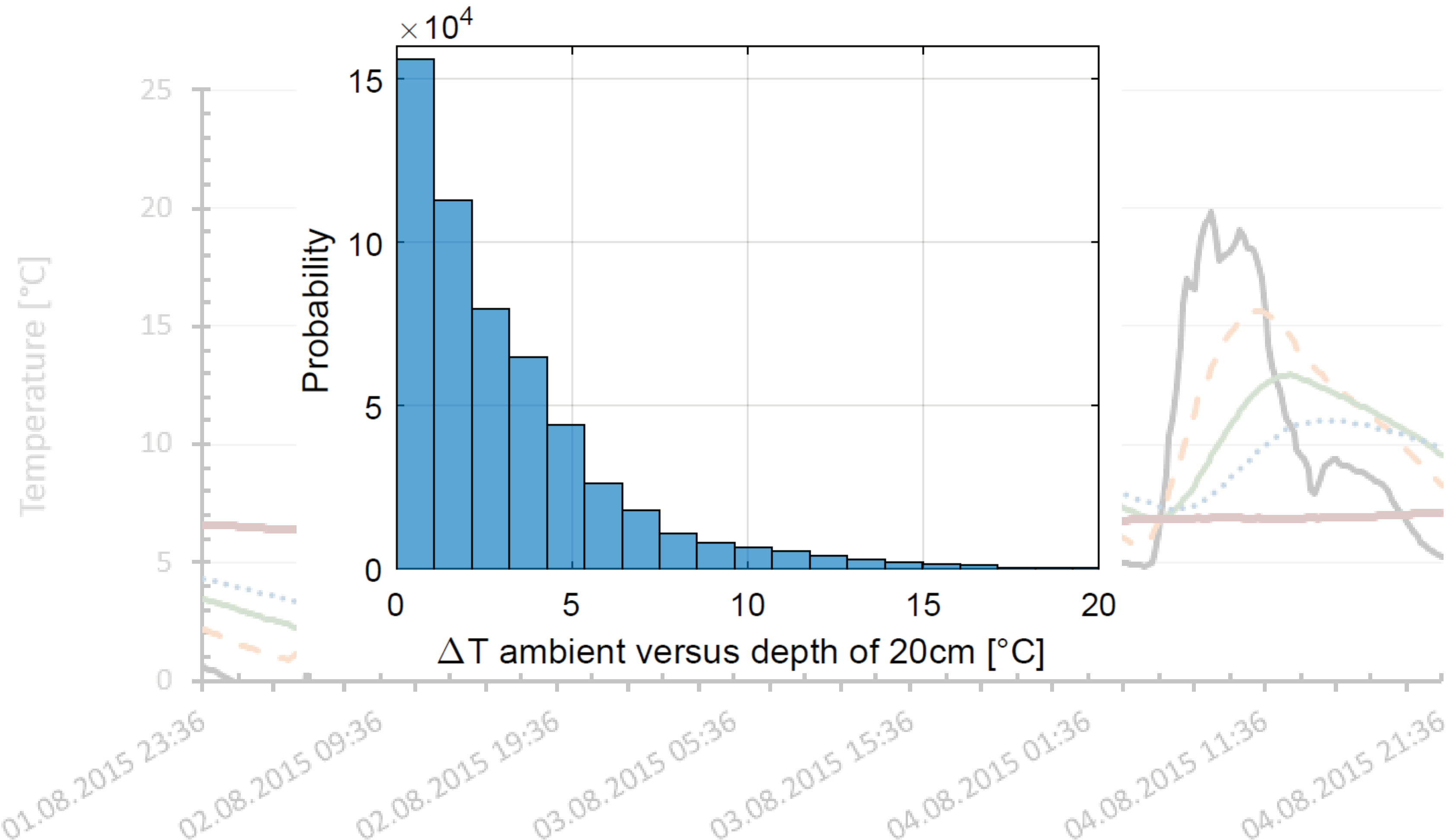
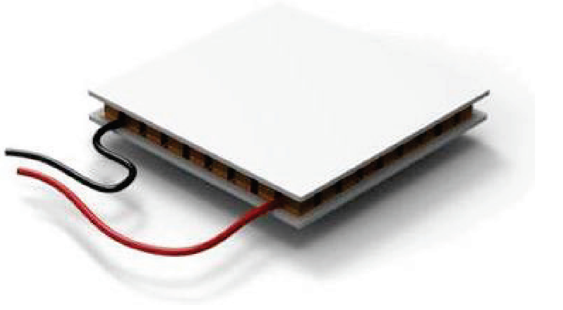
Diurnal Temperature Difference in Rock Wall



Thermoelectric Generat

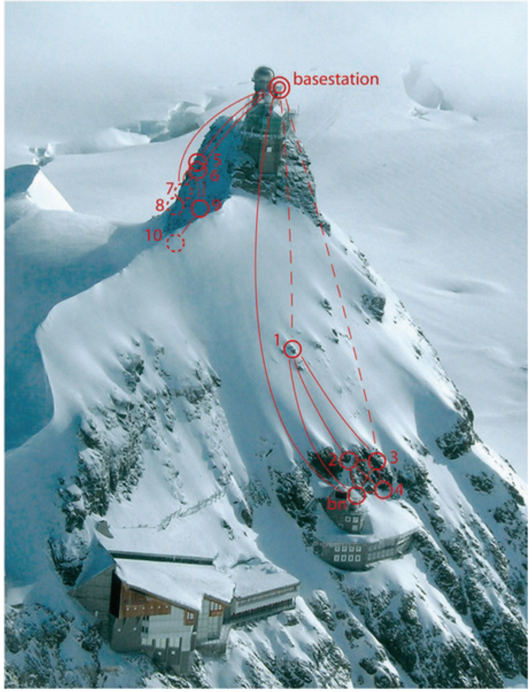


$$V_{oc} = \alpha \cdot \Delta T_{TEG}$$

0-300 mV

$$P_{max} = \frac{\alpha^2}{4 \cdot R_{el\,TEG}} \cdot \left[\Delta T_{TEG}\right]^2 \; [W]$$

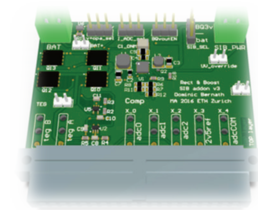
Design Constraints



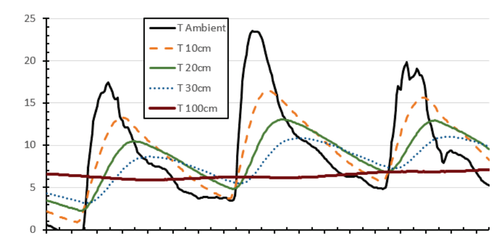
- Environmental influences
  - -30°C to +30°C
  - Snow & ice
  - Shock proof in case of rock fall
- Feasibility
  - Max 20mm diameter and 200mm deep holes for practical installation
    - Limits rock side heat flow
  - Simple installation procedure

Challenges

- Electrical Circuit Design
  - Rectification of ultra low voltage DC TEG signals
  - System integration with rectification, boost converter and storage



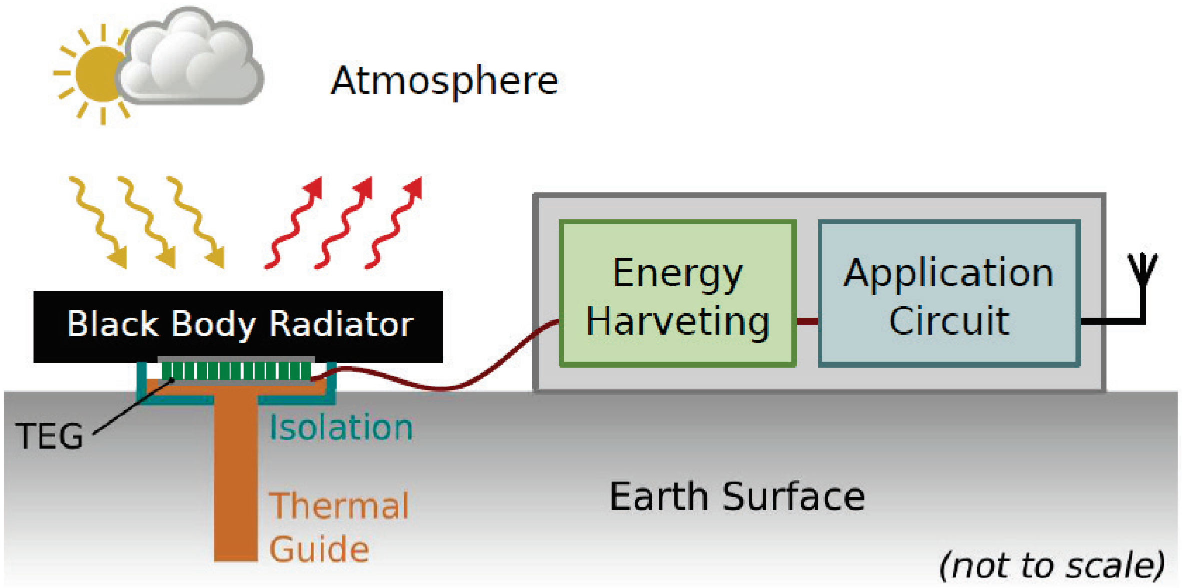
- Thermal Coupling
  - Testbed evaluation, measurements
  - Thermal lumped parameter model
  - Augmentation of thermal model with meteorological input data



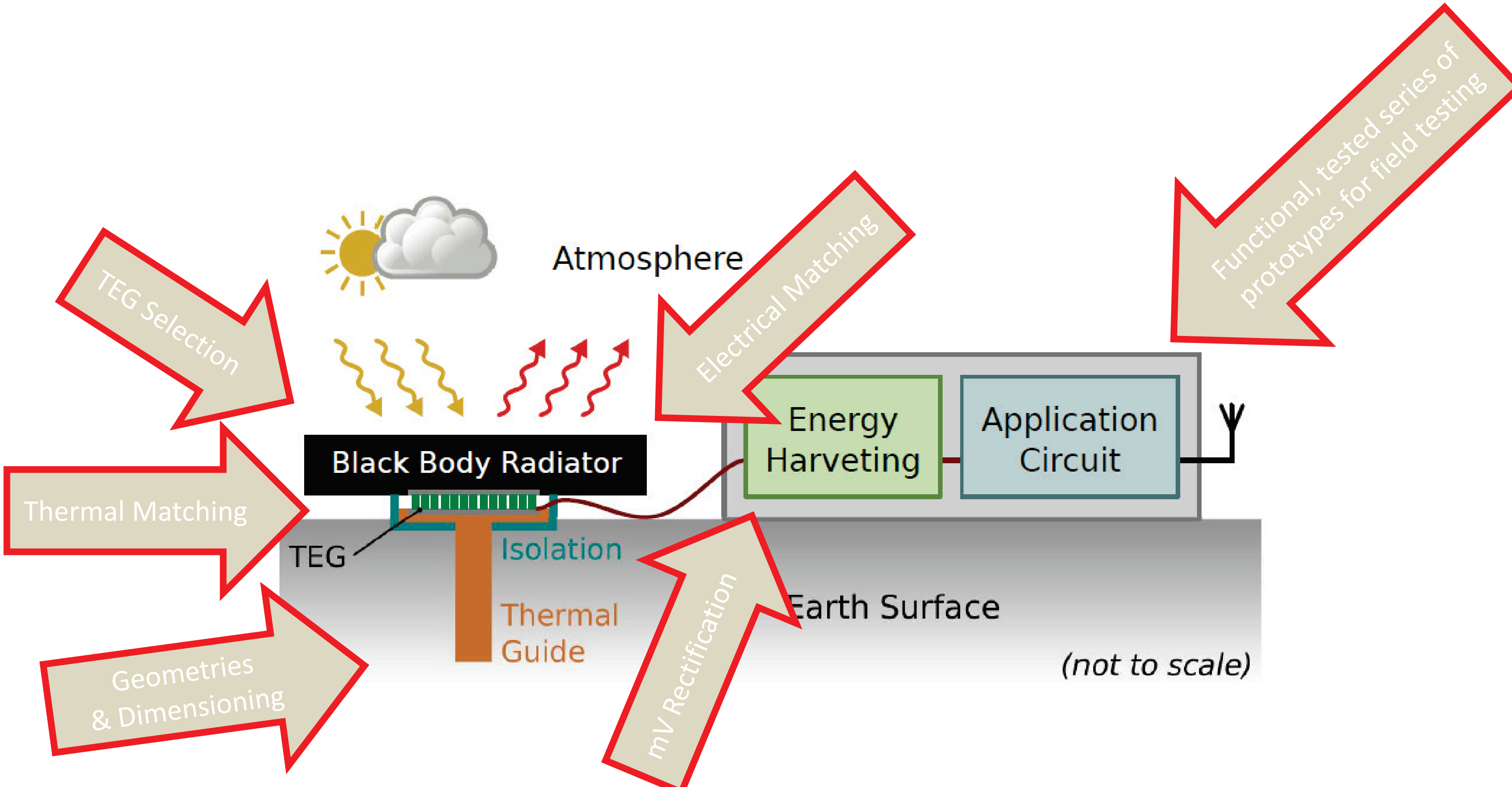
- Mechanical Design
  - Thermal guide, radiator, insulators

- Experimental Field Testing

System Design



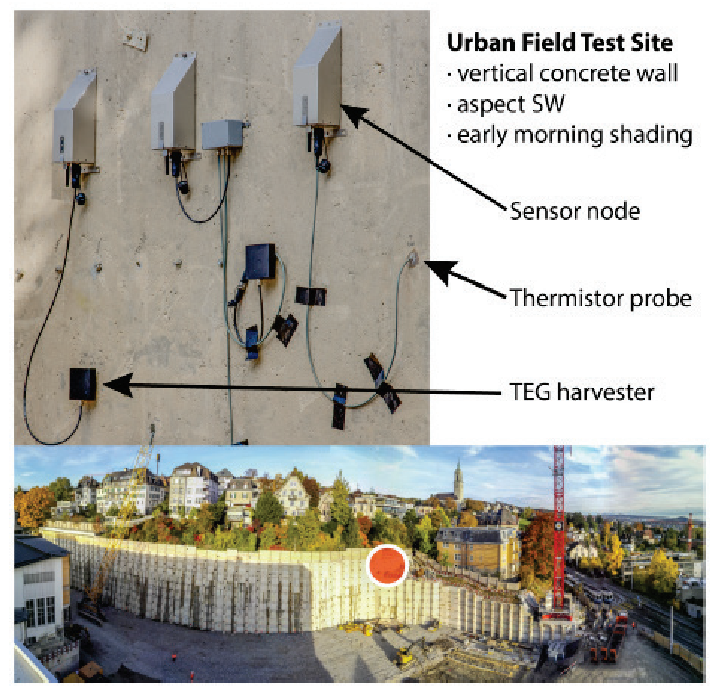
Challenges



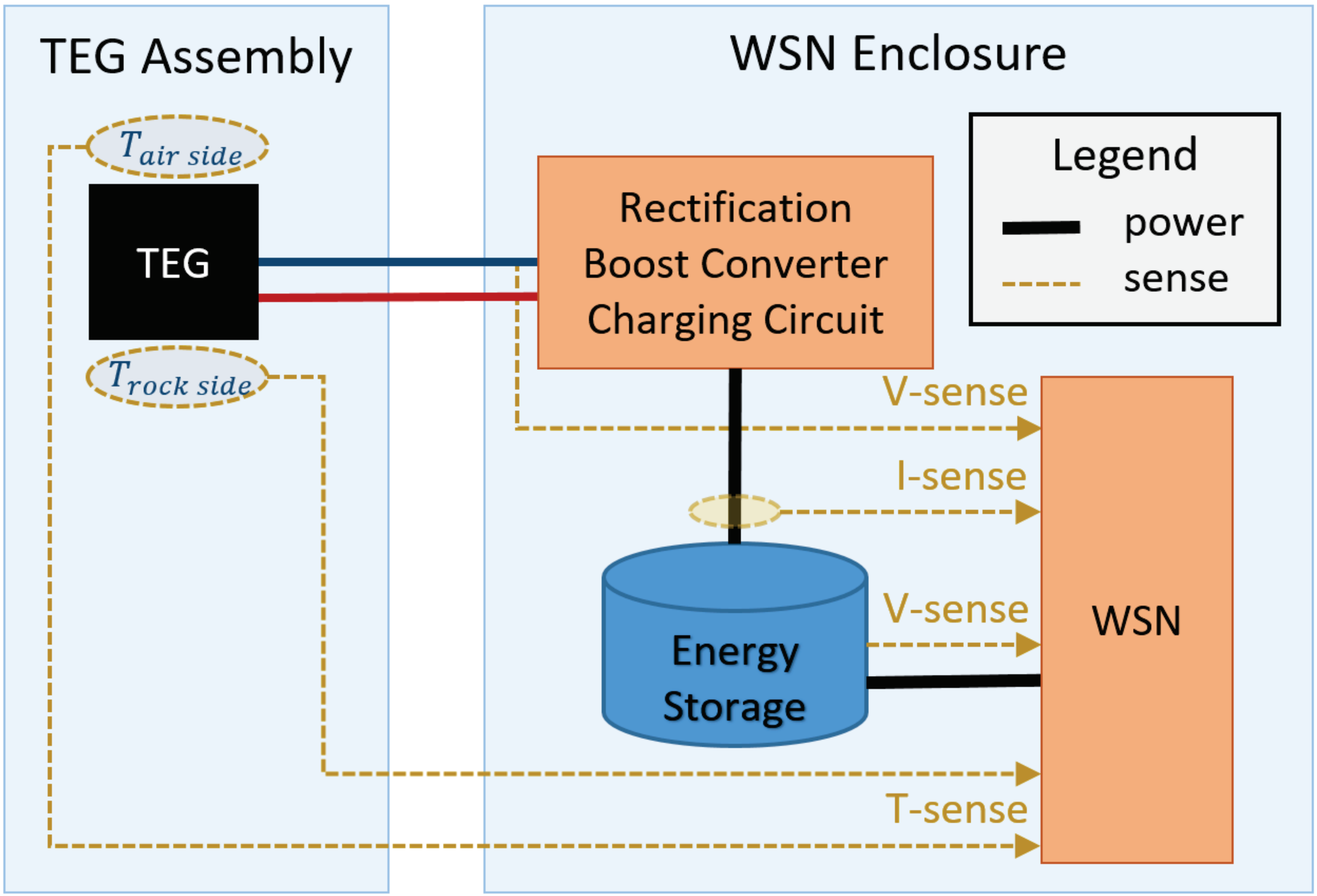
Atmosphere
Black Body Radiator
TEG
Isolation
Thermal
Guide
Energy
Harveting
Application
Circuit
Earth Surface
(not to scale)
TEG Selection
Thermal Matching
Geometries
& Dimensioning
Electrical Matching
mV Rectification
Functional, tested series of
prototypes for field testing

4-Phase Approach

- Analysis/Modeling
  - Active rectification
  - Thermal model; matching
  - Irradiation model; estimation of harvested energy output based on meteorology
- System design
- Testbed characterization, design validation
- Field experiments
  - Urban concrete wall
  - High-Alpine rock wall

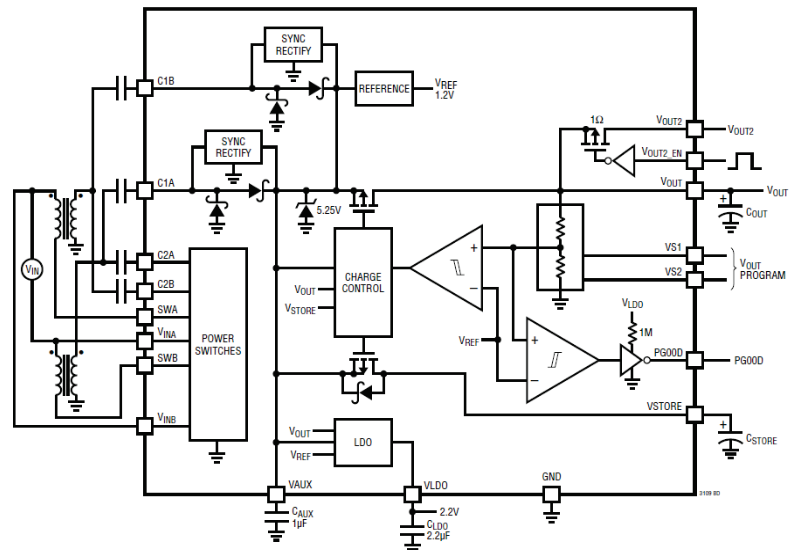


Electrical Overview



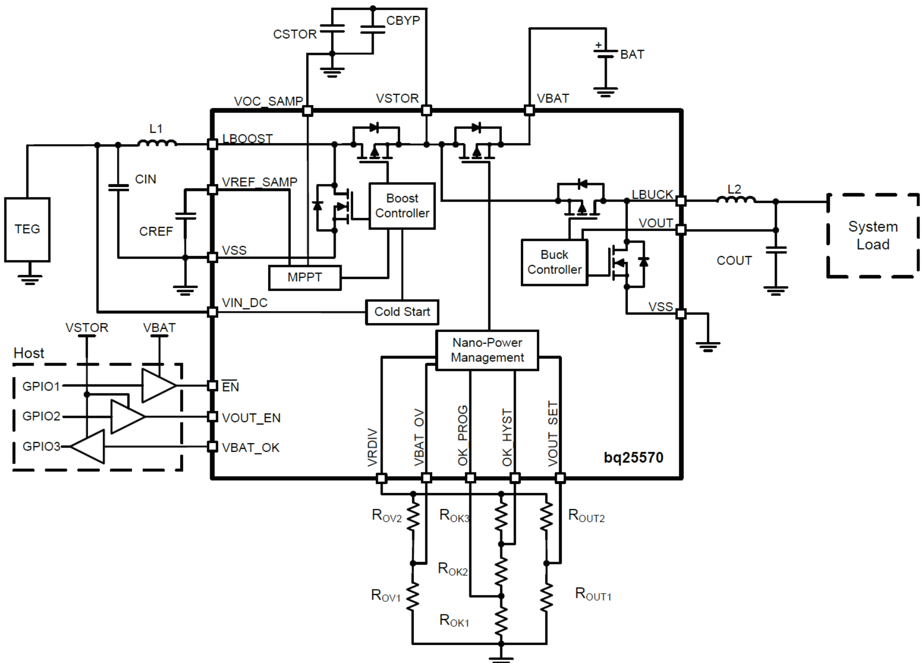
Harvesting Charge Controller Options

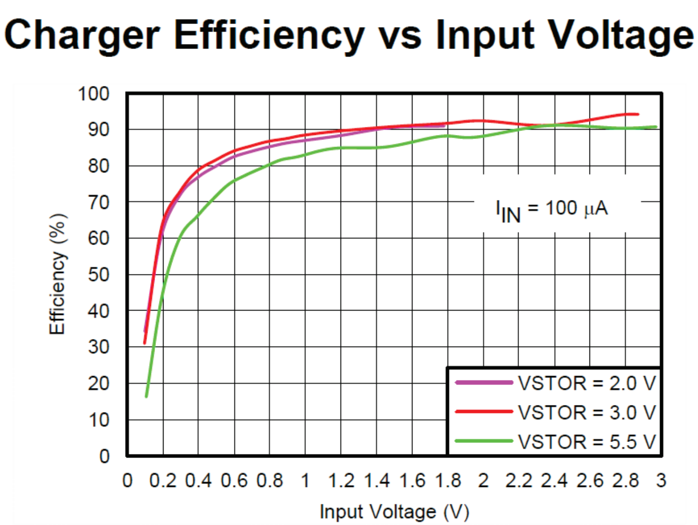
	TI BQM255xx	Analog LTC3109
Regulator design	MPPT	Sync. Regulator
Input polarity	Unipolar	Bipolar
Min. harvesting voltage	100 mV	30 mV
Efficiency	0.6	0.3
Output	Unregulated	Regulated
Storage management	Yes	Partly
Power good output	Yes	Yes



LTC 3109 Block Diagram

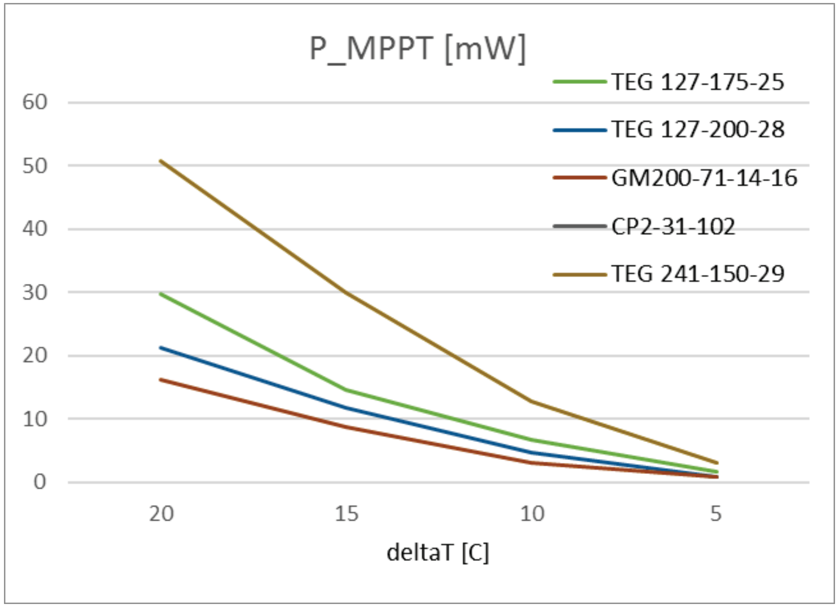
BQ25570 MPPT Charge Controller

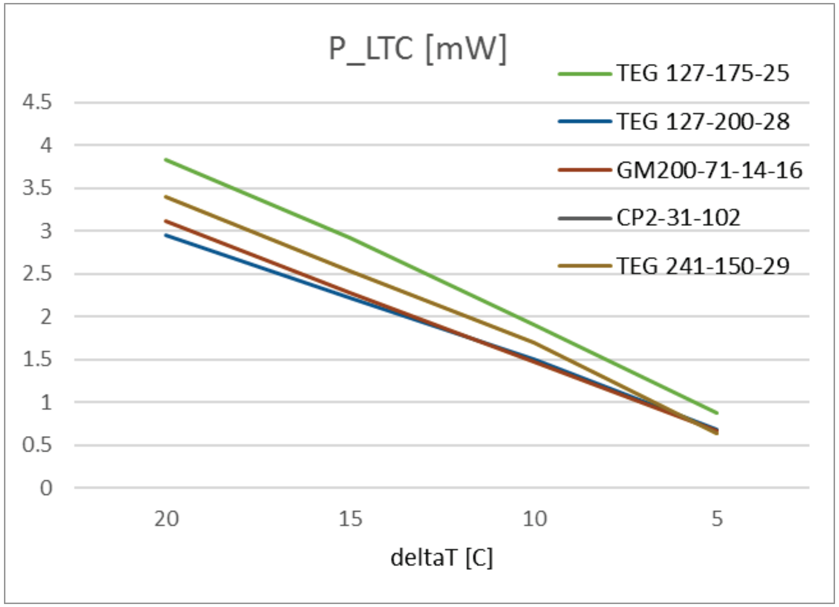




Auxiliary Slides: BQ25570 vs LTC3109

- BQ25570
  - MPPT
  - Buck converter
- LTC3109
  - fixed input impedance
  - low-dropout regulator

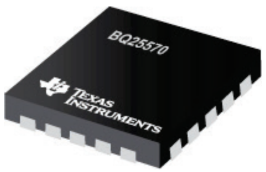




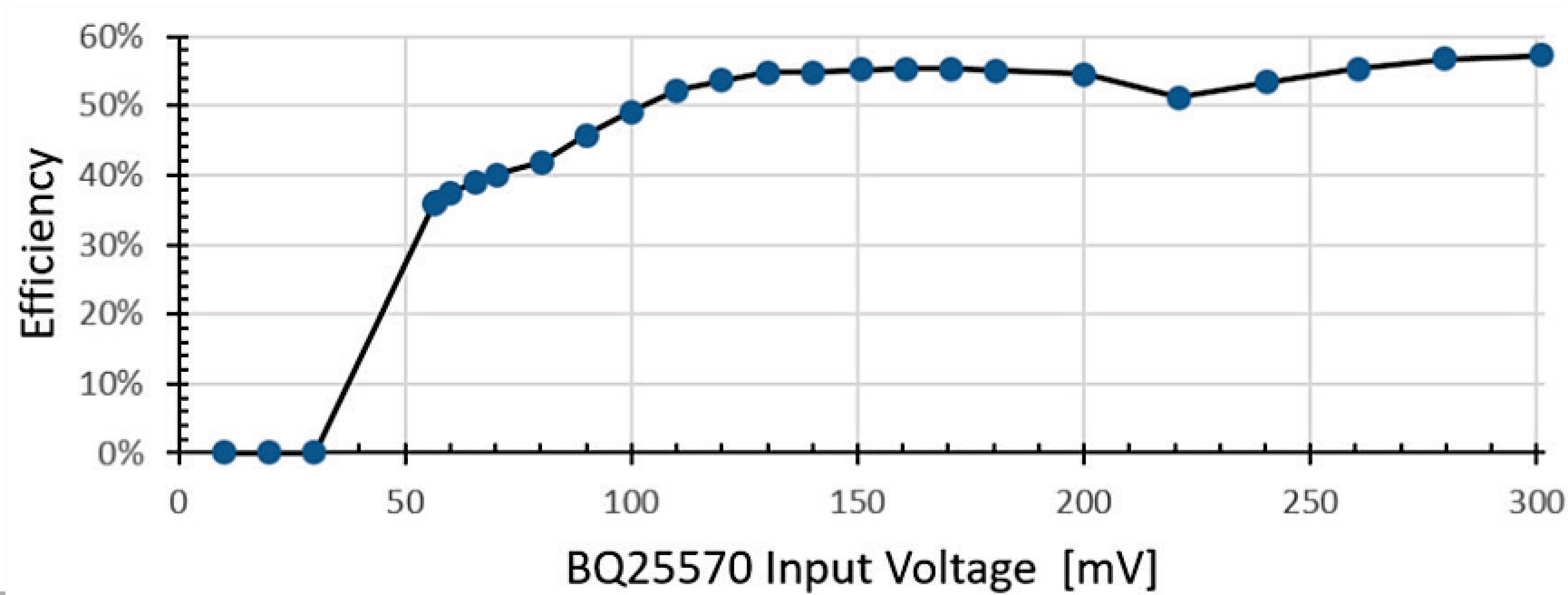
ETH zürich

Boosting Milivolts to Volts

- TEG: -300 - 300mV
- Storage: 3.6 - 4.2V
- Boost converter: BQ25570 + rectifier
  - Maximum Power Point Tracking (MPPT)



Measurement

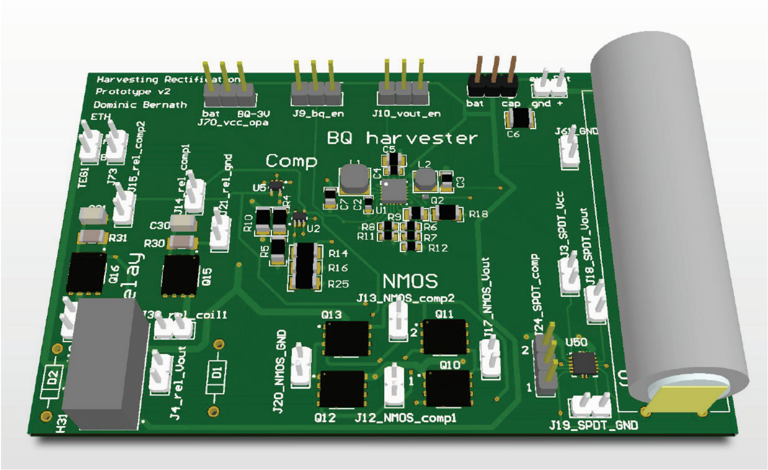


Rectification of TEG Input

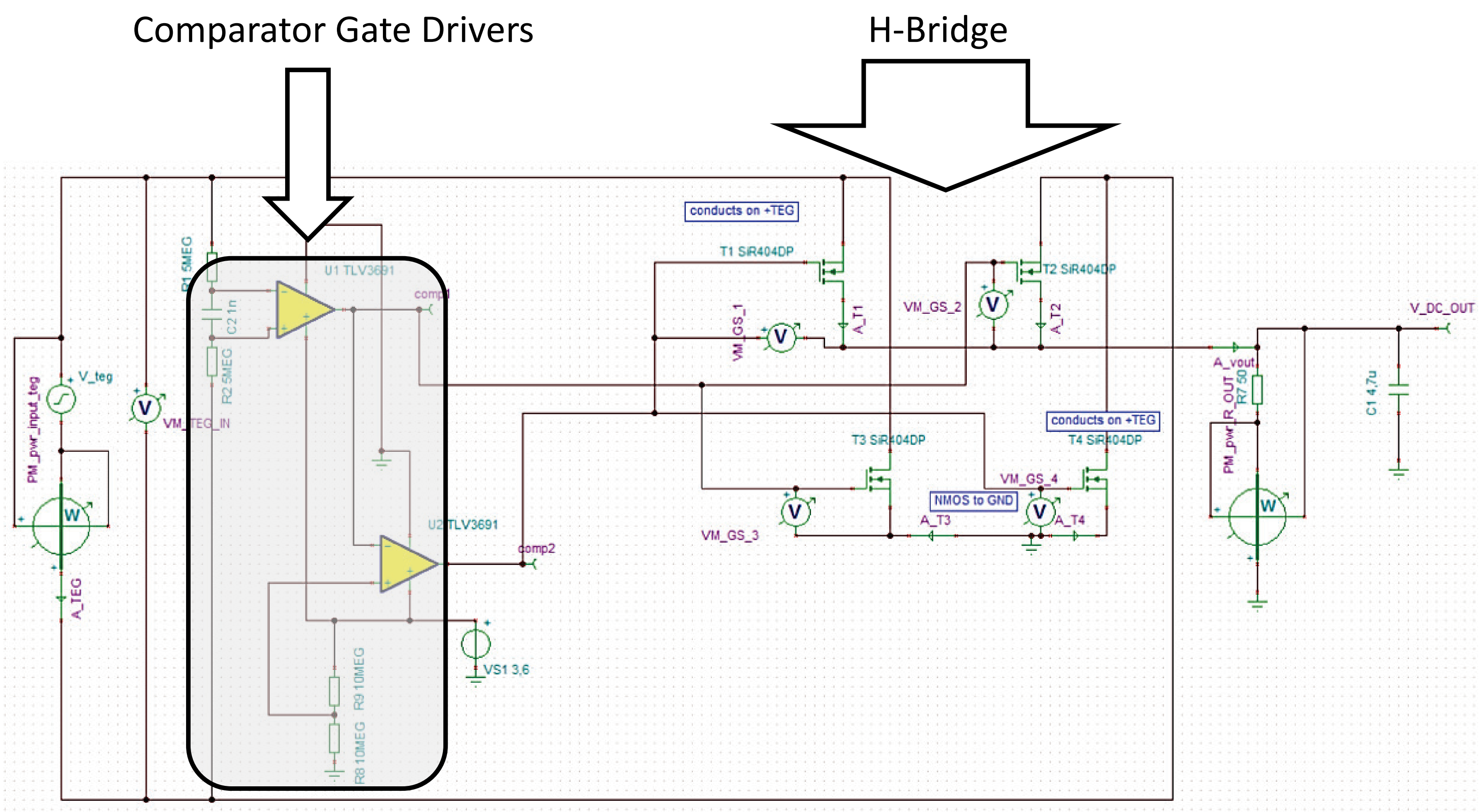
Type	Resistance	Quiescent power	Disadvantage
Passive			
Schottky diode		-	> 70mV forward voltage
Active			
Latching relay	0.2 Ω	23 nW	mechanical sensitivity
SPDT	0.7 Ω	10 nW	high resistance
Mosfet	0.2 Ω	-	not break before make

Gate driver

- Two comparators
- 0.5 µW quiescent power

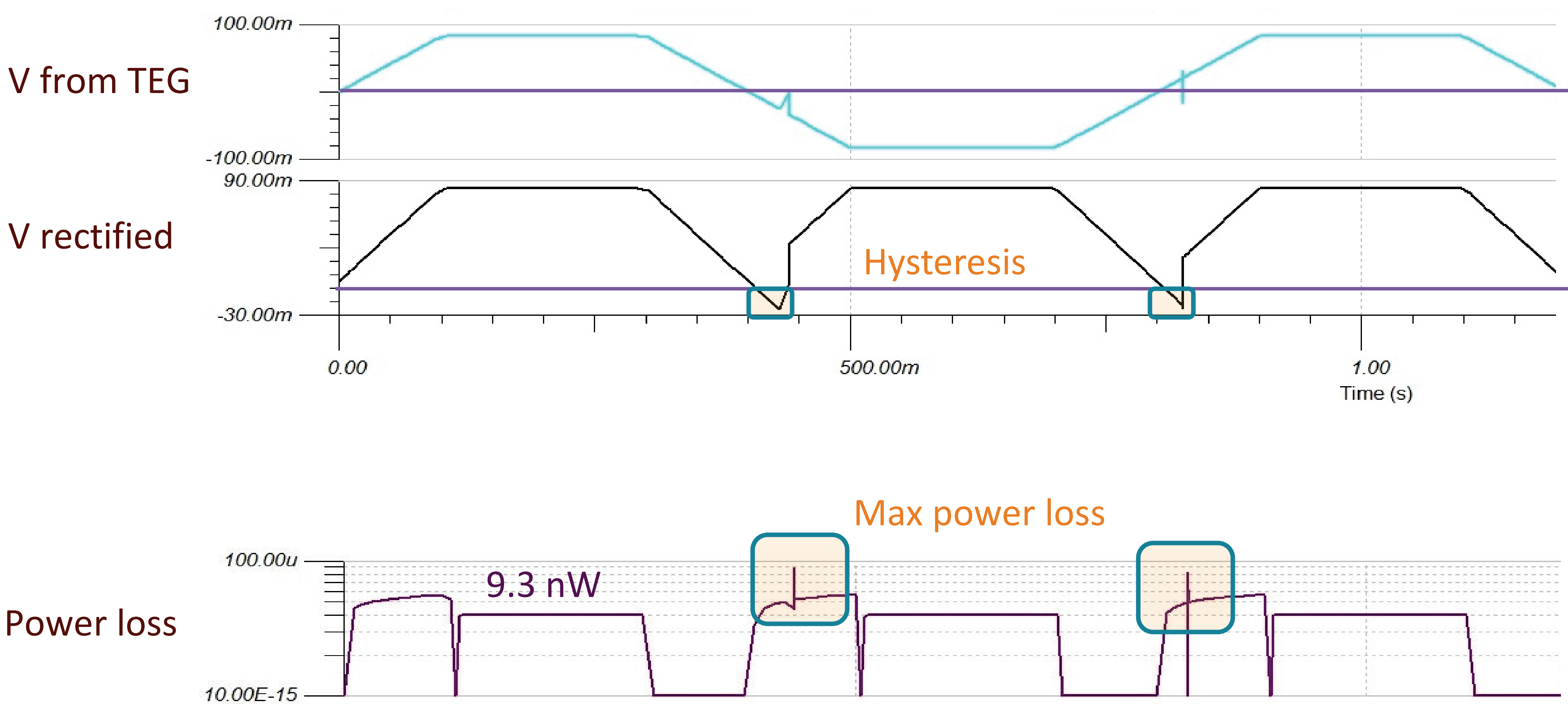


SPICE Simulation of NMOS H-Bridge Rectifier

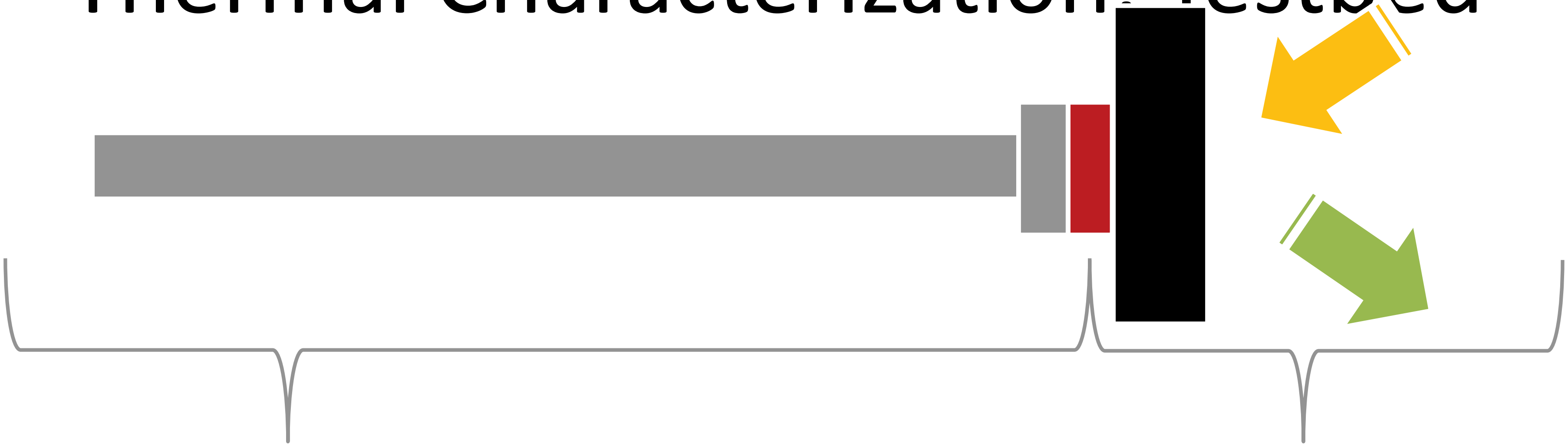


SPICE Simulation of NMOS H-Bridge Rectifier

Break before make not guaranteed



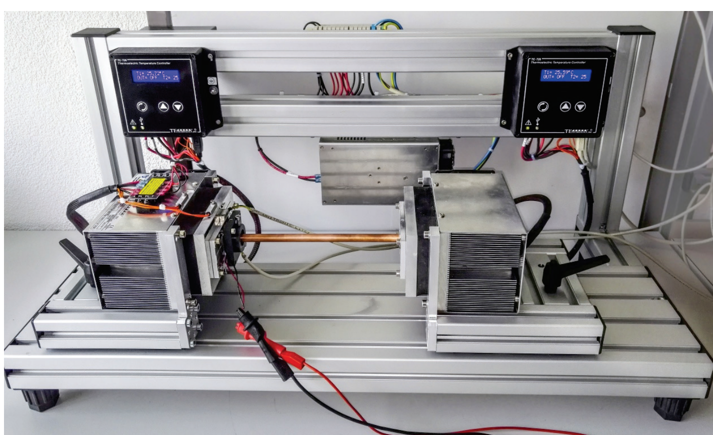
Thermal Characterization: Testbed

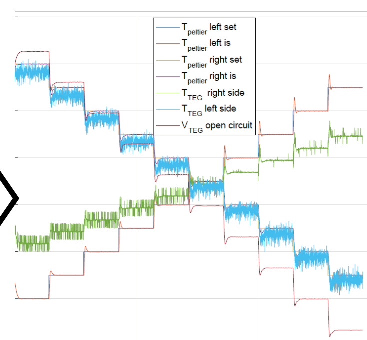


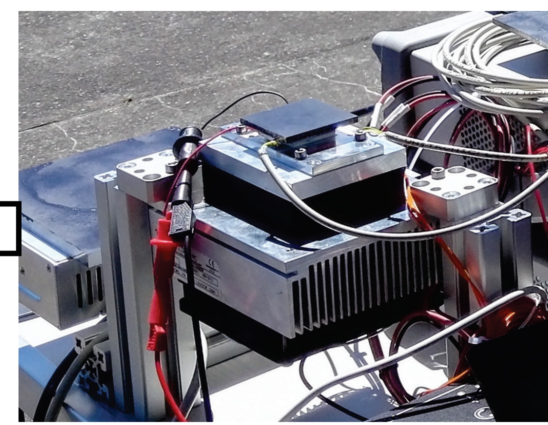
Two sided temperature control

- Temperature characteristics
- System response

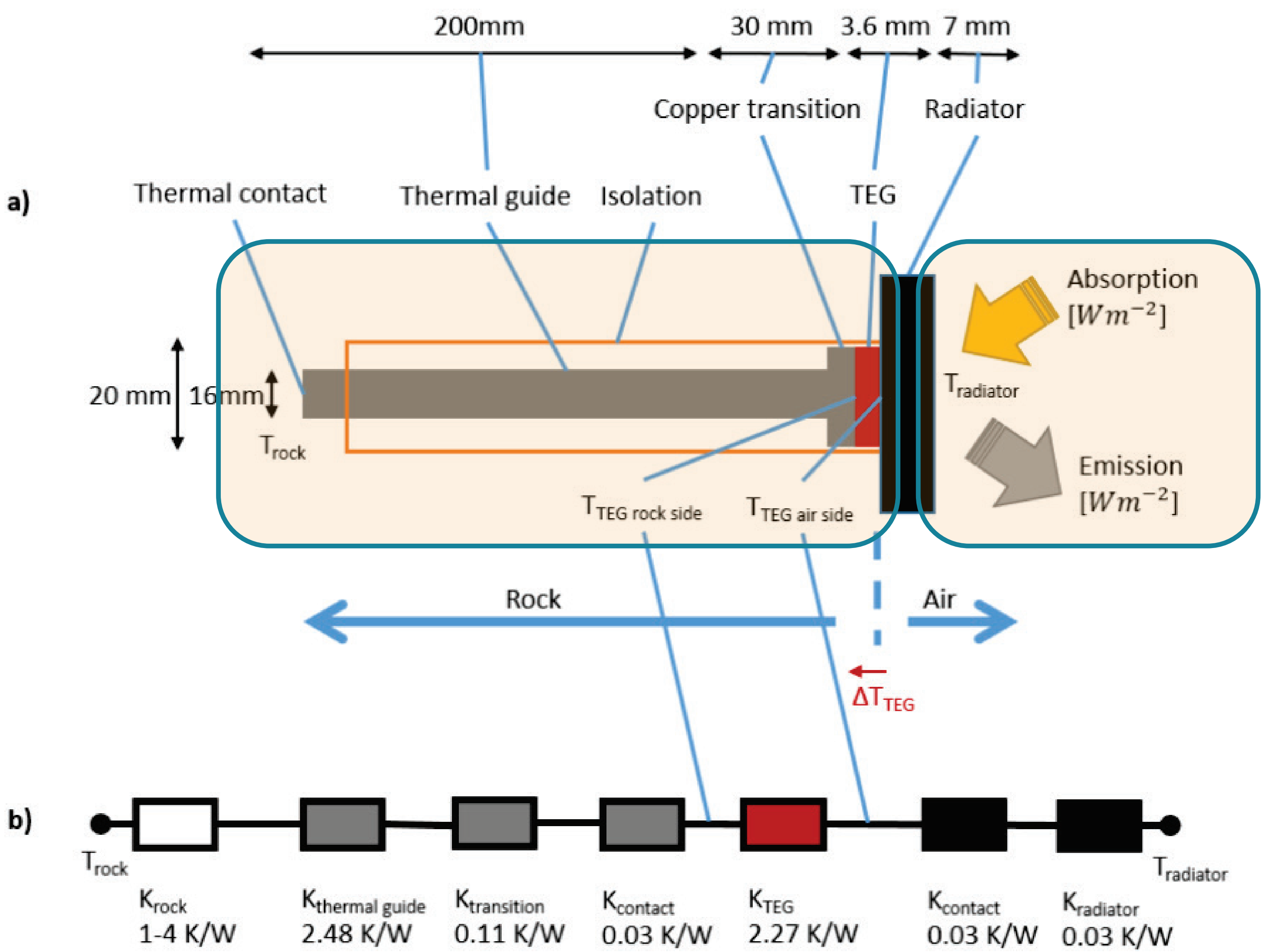
Temperture vs radiation







Thermal Modelling



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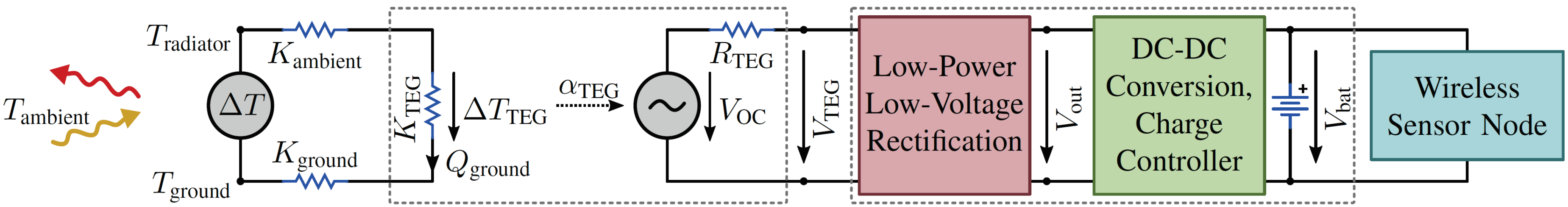
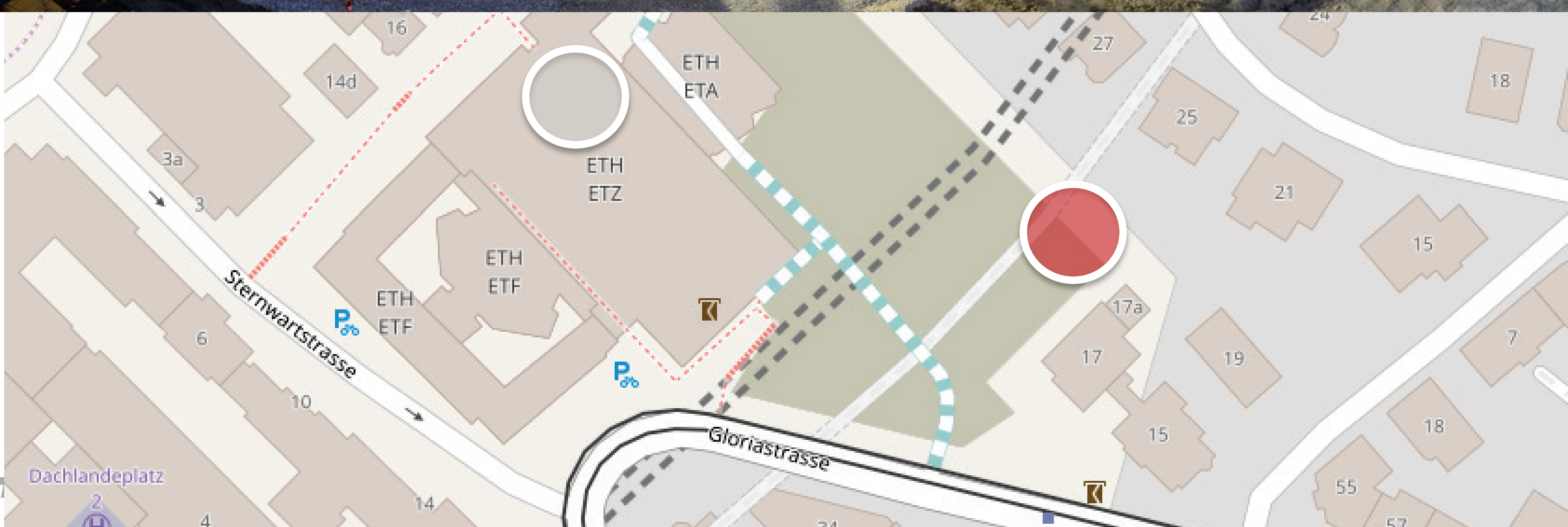
System Design



Field Test Site



Field Test – Different Thermal Guides

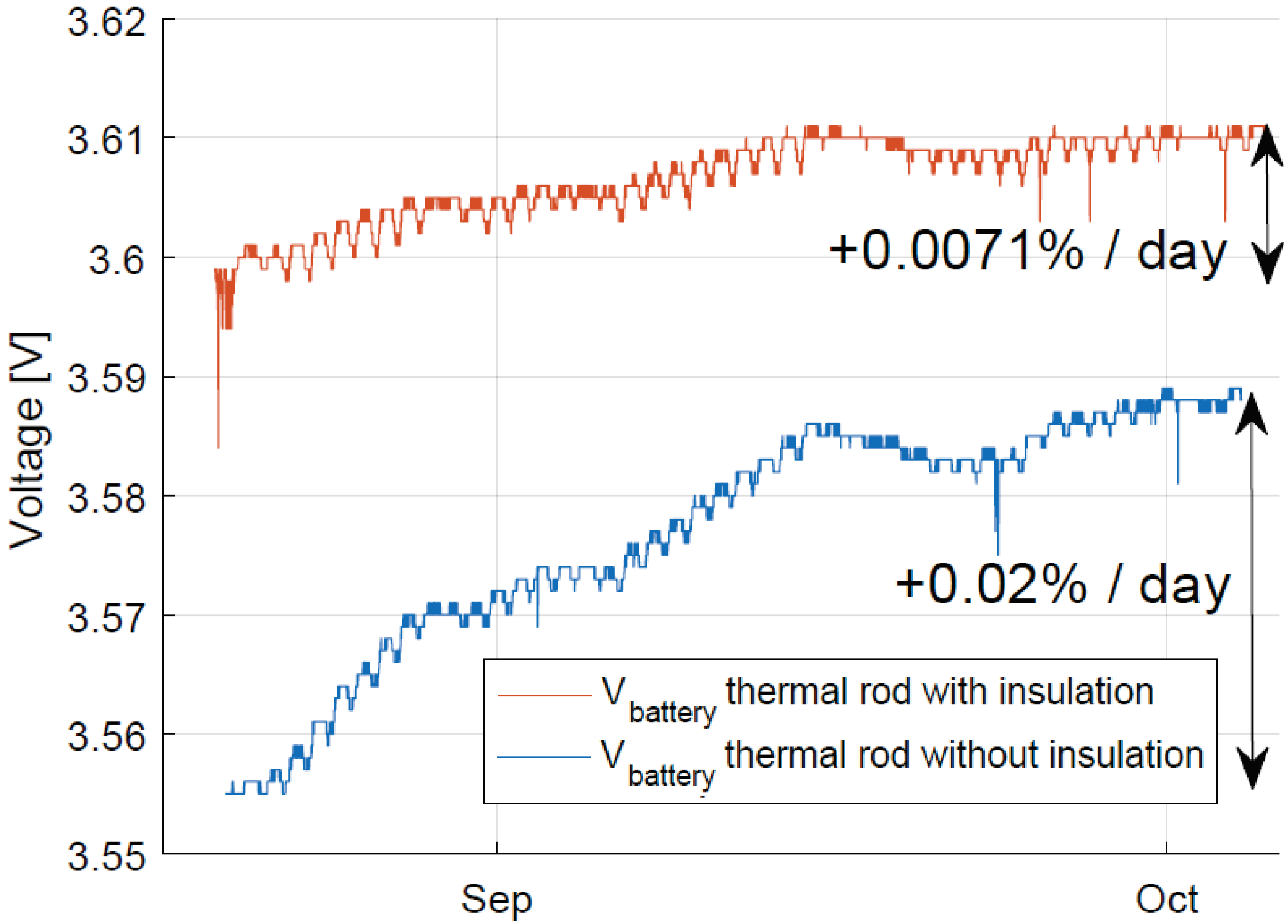
YES it works!

0.8mW average

power margin: 61%

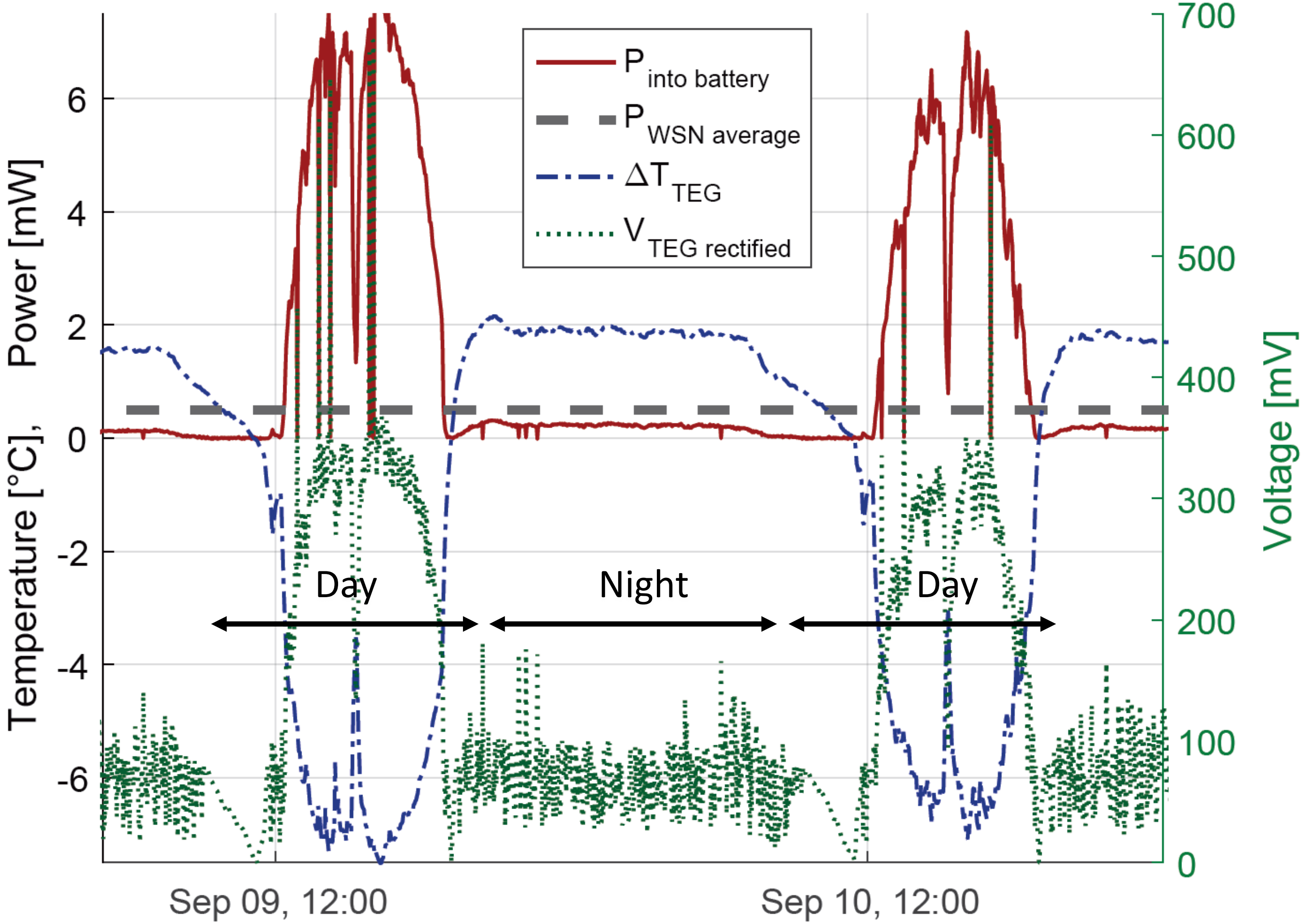
43 days of testing

Long Term Energy Budget



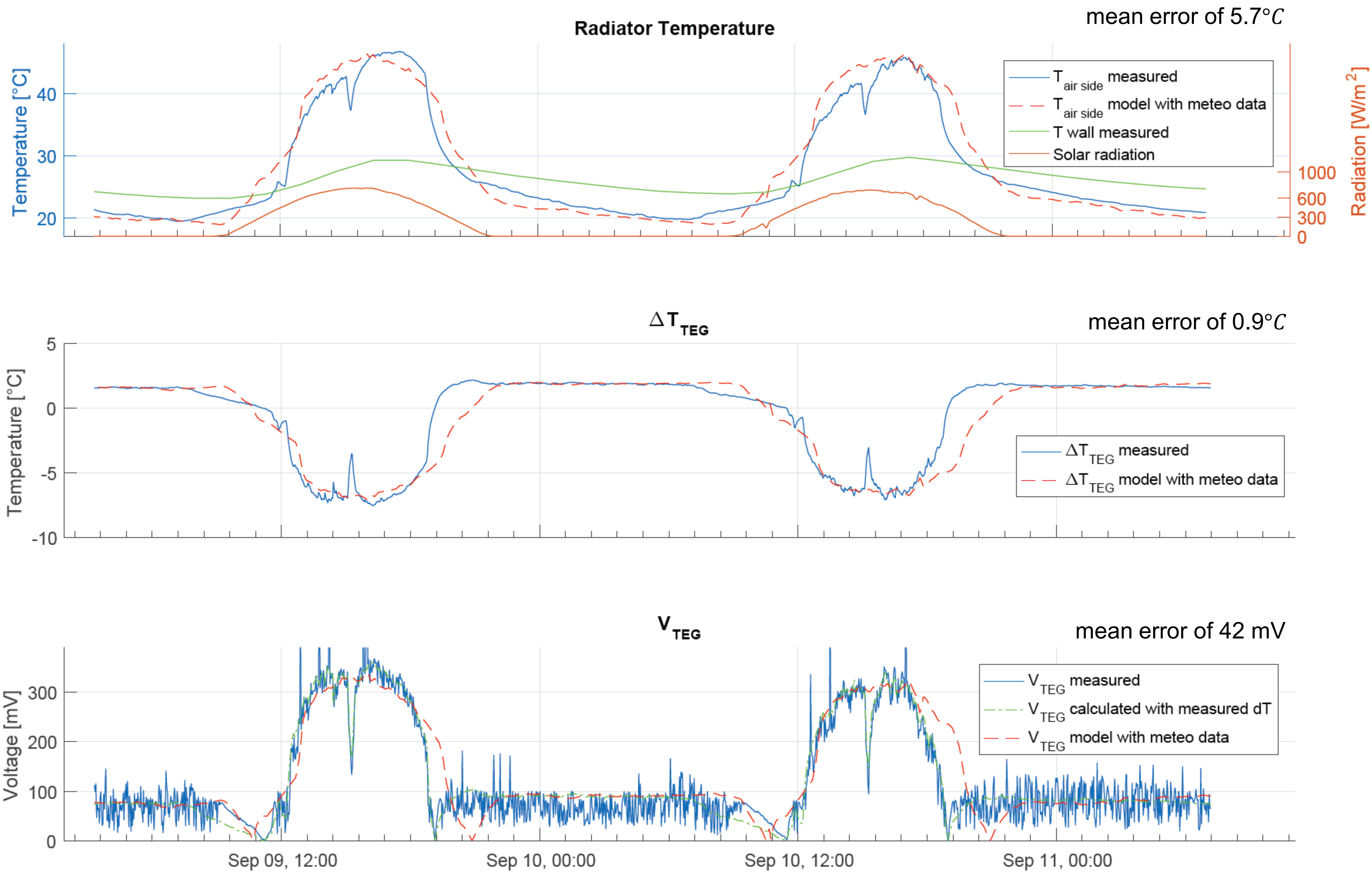
2.8 times more surplus energy without insulation

Diurnal Power Generation

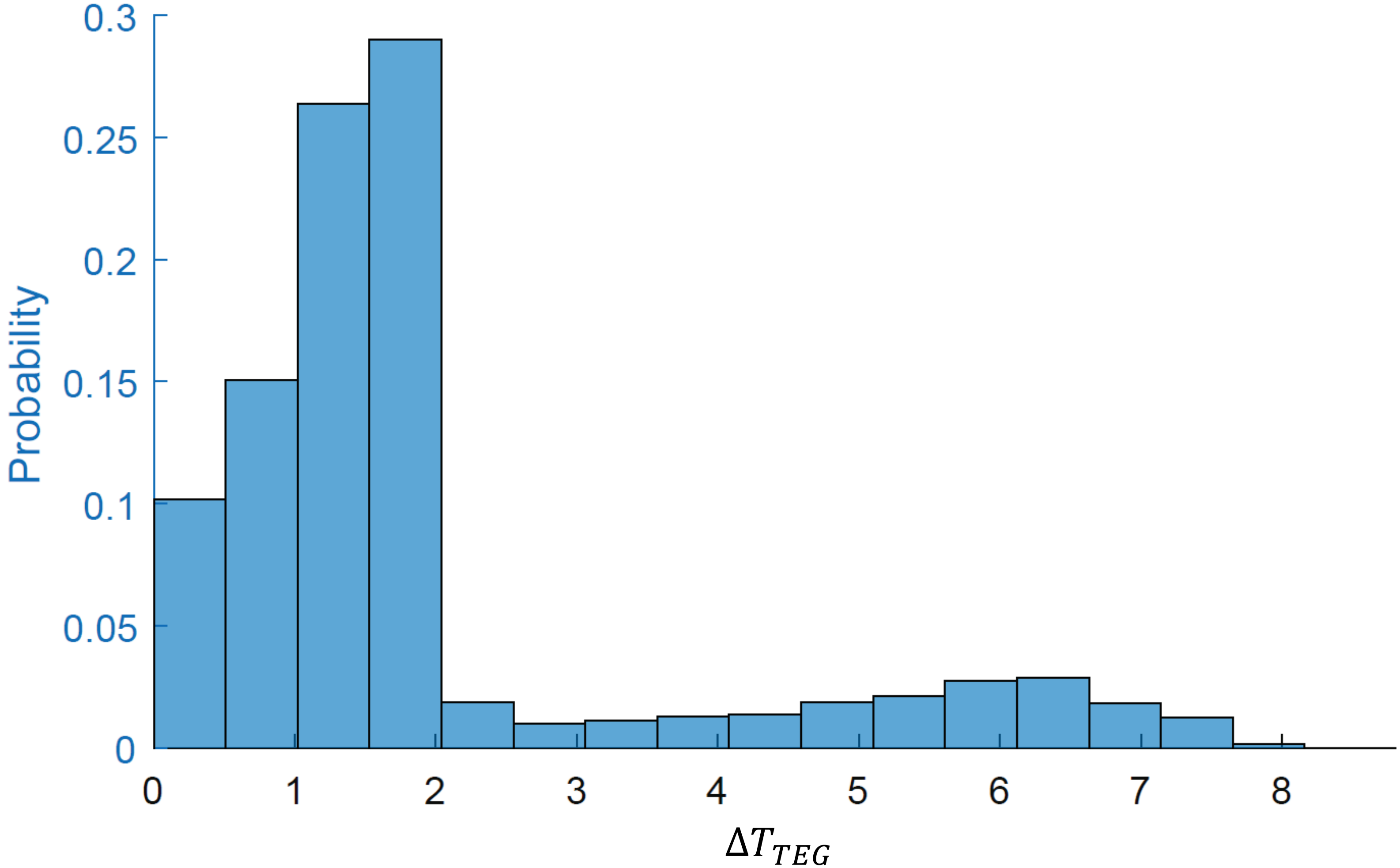


0.8mW mean power

Model Validation

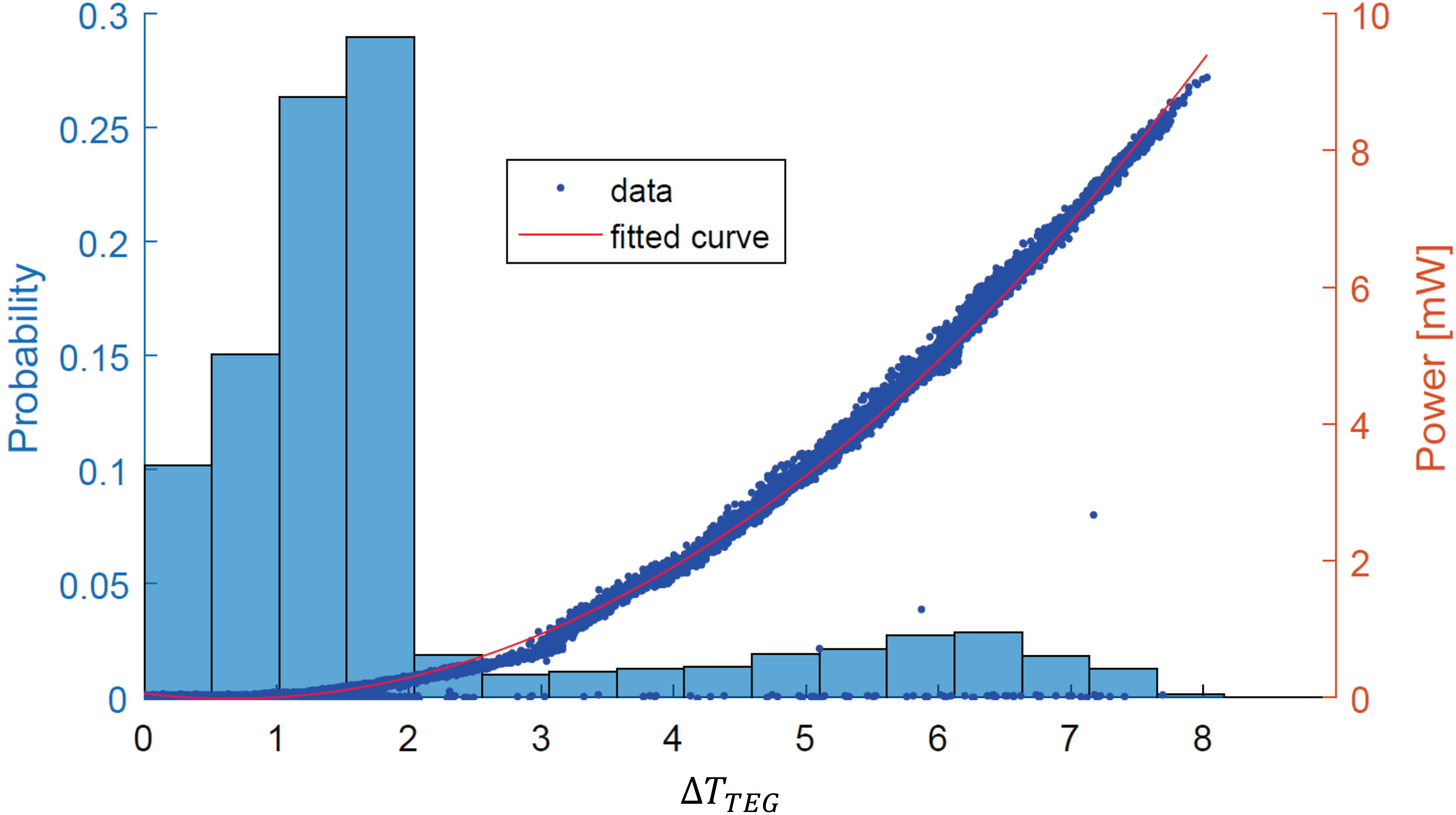


Energy Yield Distribution



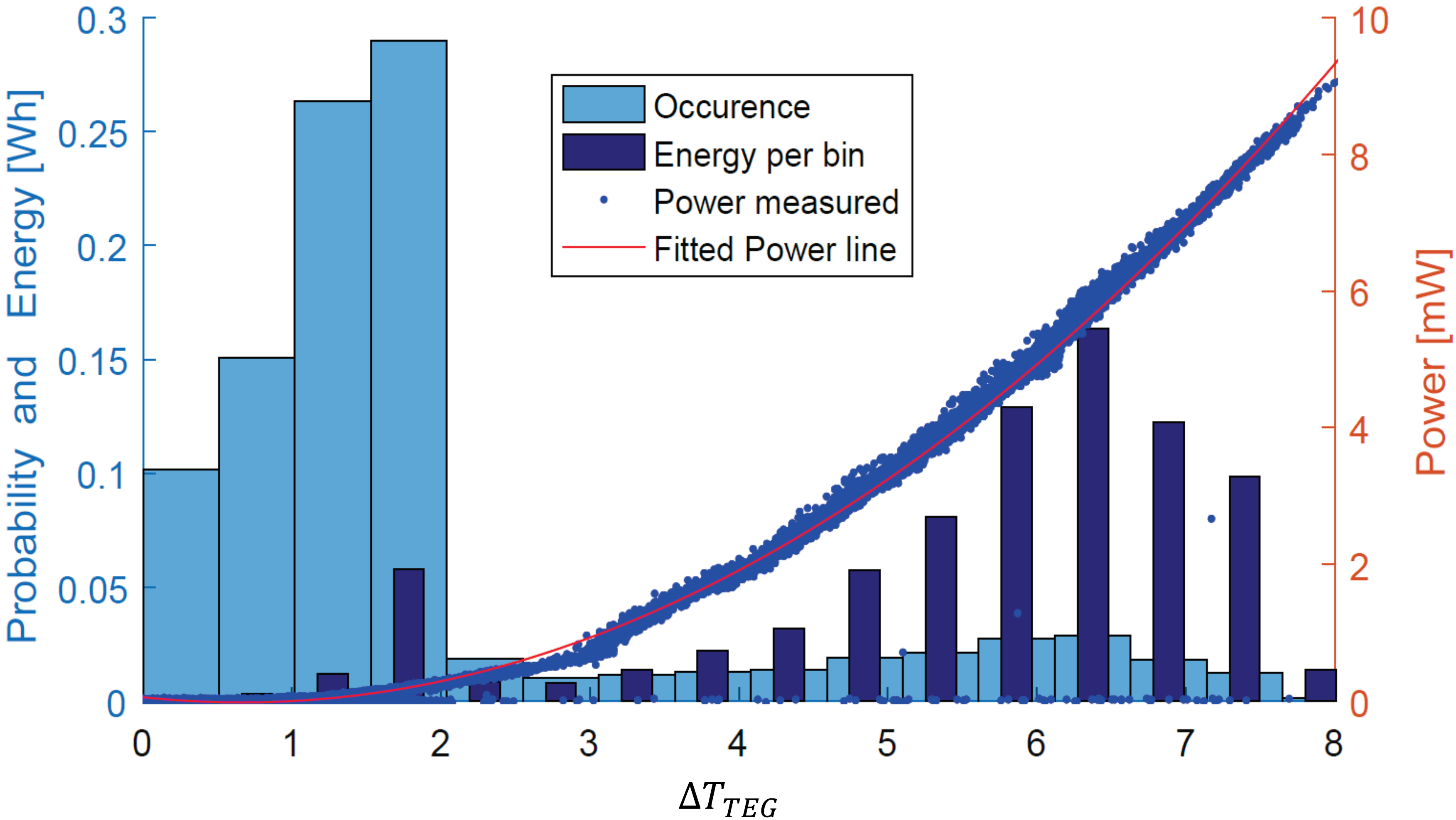
Maximum energy is generated around 6.5°C.

Energy Yield Distribution



Maximum energy is generated around 6.5°C.

Energy Yield Distribution



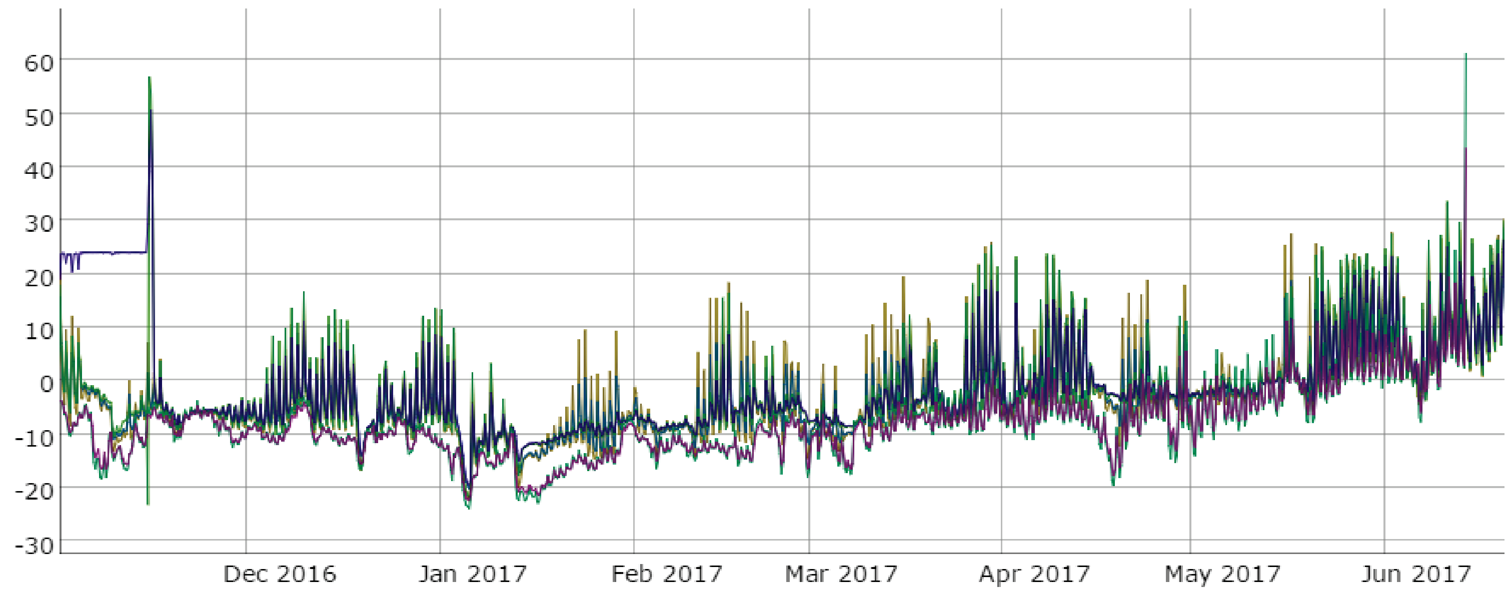
Maximum energy is generated around 6.5°C.

Jungfraujoch Field Test – South

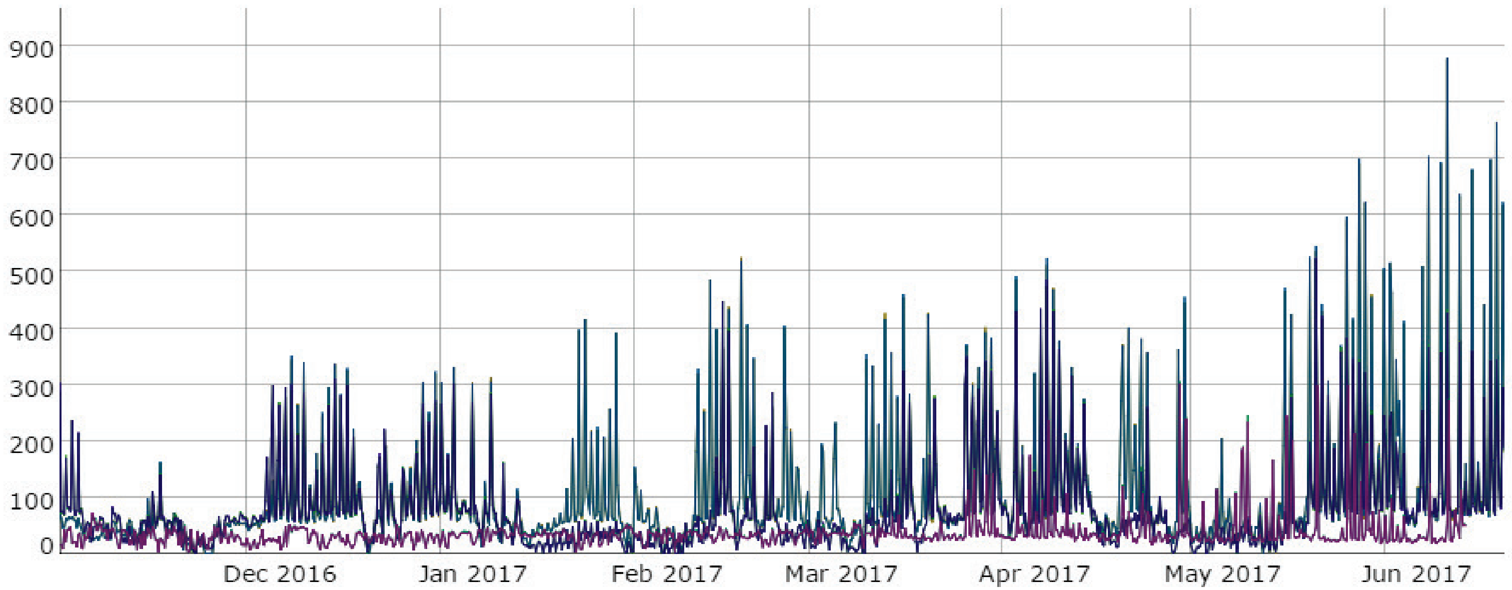
Jungfraujoch Field Test – North

Jungfraujoch Field Test – Partial Snow Cover

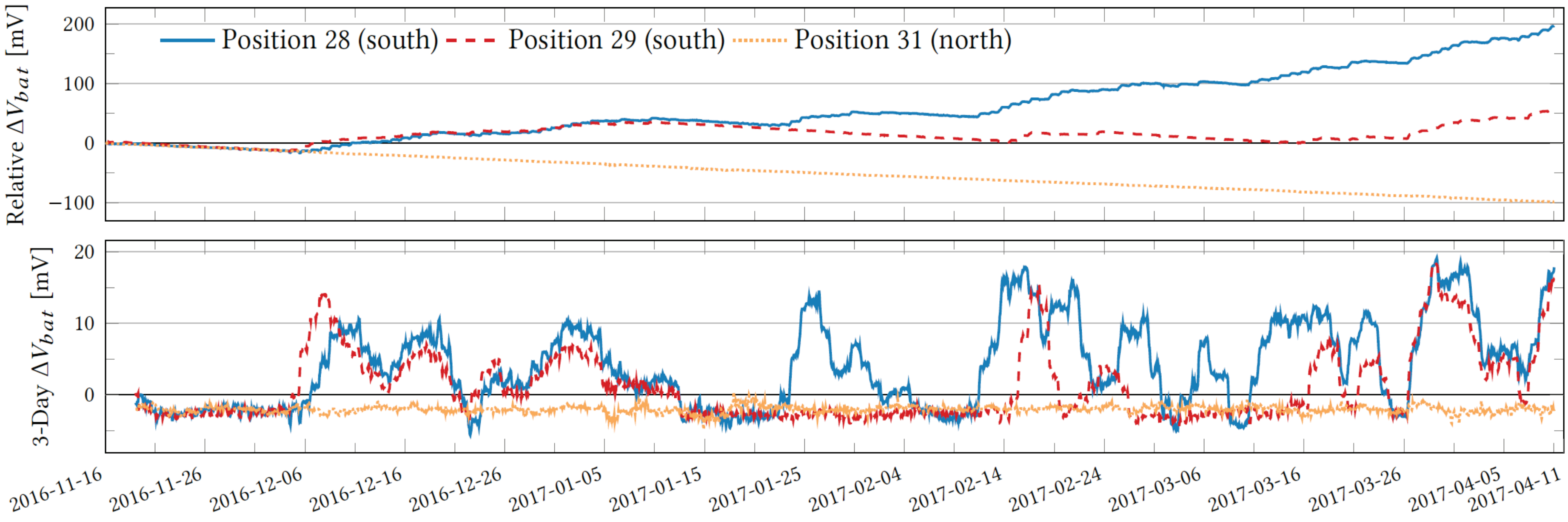
TEG Temperatures



TEG Rectified Voltage



Long-term Evolution: Steady Charging



Performance on Jungfraujoch

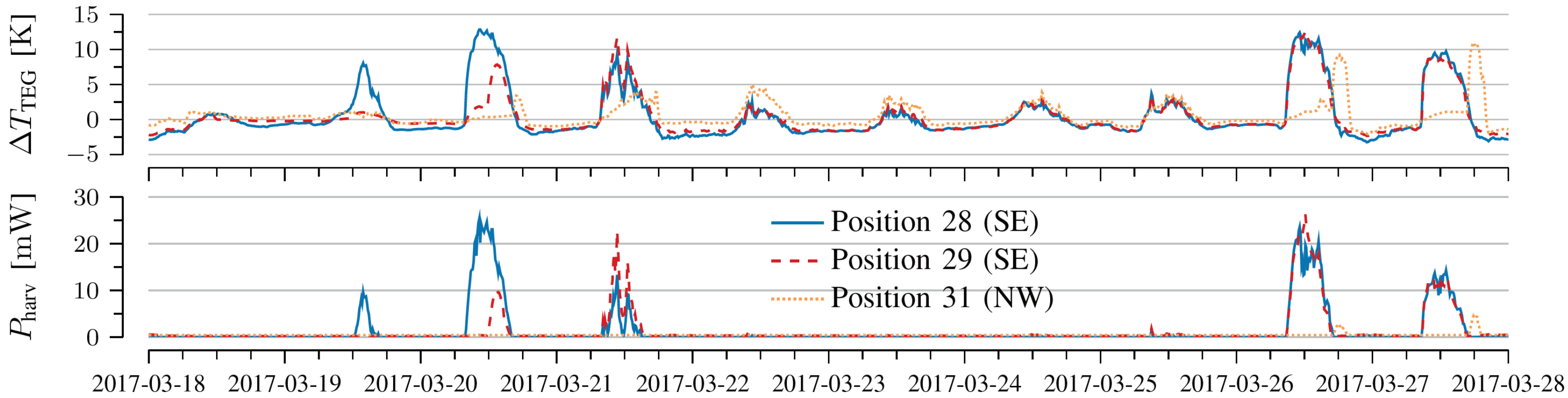


Figure 10. Ten days of temperature difference and resulting harvested power showing the influence of weather and location.

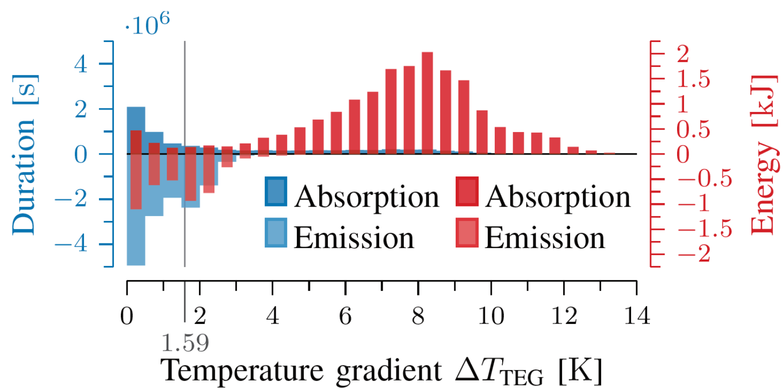


Figure 11. Histogram of temperature gradients and generated energy during 237 days, SE facing sensor node deployment.

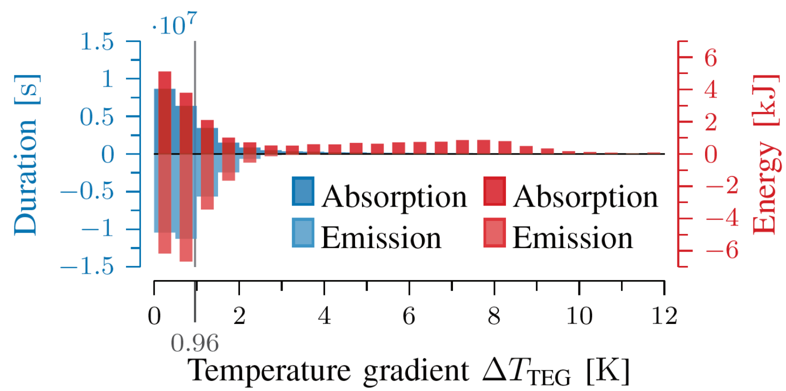
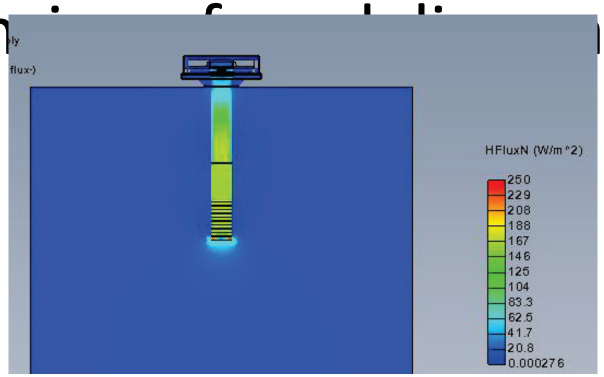


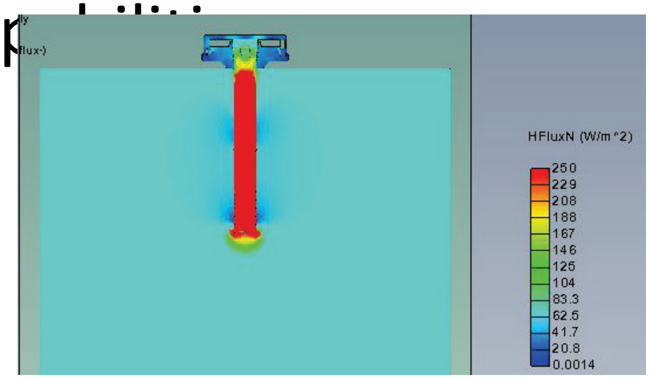
Figure 12. Histogram of temperature gradients and generated energy during 625 days, NW facing sensor node deployment.

ETH zürich

Challenges Ahead

- Advantage/disadvantage TEG vs. photovoltaic cannot yet be answered quantitatively
  - Head to head comparison?
- ~50% of parameters are base on educated guesses; scaling/transfer is difficult
  - Exten





Recap of Today

- All energy storage technologies have severe limitations
- Battery technology is slow in improvement vs. Moores Law

- Energy scavenging methods are widely researched
  - No real breakthrough yet
  - Most promising is solar and mechanical, TEGs play a side role
  - Increased complexity through control

- LP architectures are increasingly designed with power subsystem in mind

Today's Hot Researcher & Paper

- Shad Roundy
  - Faculty Mechanical Engineering
    University of Utah
    (Integrated Self-Powered Sensing Lab)
  - PhD University of California, Berkeley

- Very early work on energy harvesting systems
  - Focus on vibration energy sources

- Roundy, S., Wright PK, Rabaey JM 2003. *Energy Scavenging for Wireless Sensor Networks*, Kluwer Academic Publishers, Boston MA.
- Briand, D., Yeatman, E., Roundy, S., (Eds.). (2015). *Micro Energy Harvesting (Advanced Micro and Nanosystems)* . John Wiley & Sons.