Low-Power System Design

227-0781-00L

Fall Semester 2019

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Plan for Today

- Renewable Energy Sources – Harvesting Systems

- Energy Harvesting Systems Integration
  - Maximum Power Point Tracking

- System Design
  - TEG- based Energy Scavenging

- Modeling
  - Harvesting Control
  - Battery State-of-Charge Approximation
  - Long-term Energy Neutral Operation

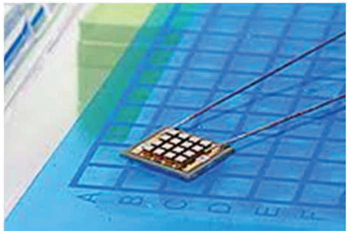
- Slides contain material from J. Rabaey, D. Brunelli, D. Bernath, C. Moser and B. Buchli

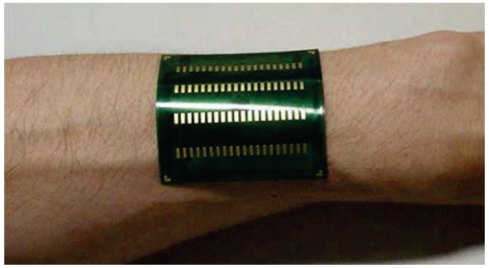
Low-Power System Design

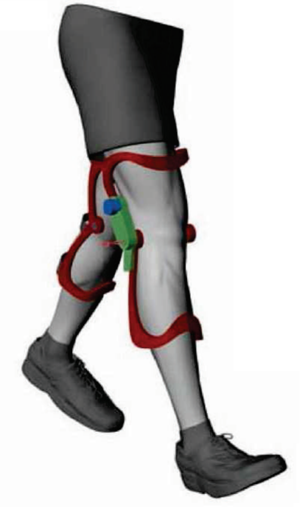
RENEWABLE ENERGY SOURCES – HARVESTING SYSTEMS

Energy Harvesting Basics

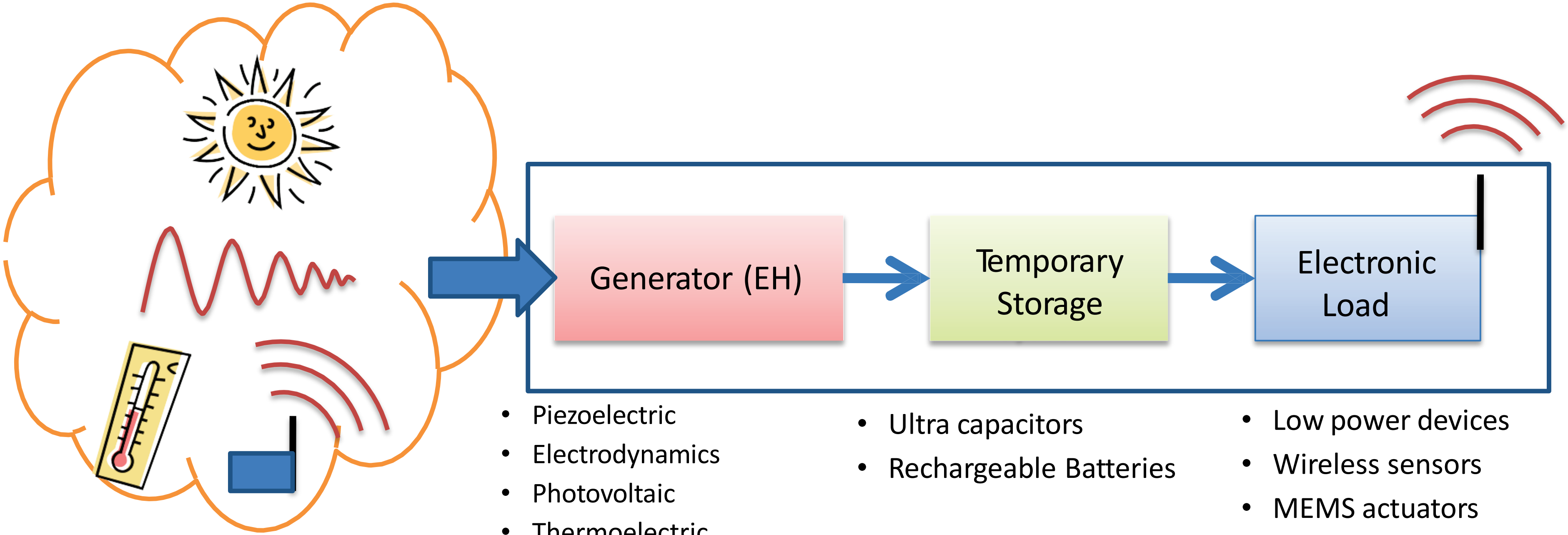
- **Energy harvesting** is the process by which energy is **captured** and **stored**
- This term often refers to small, autonomous devices: **micro energy harvesting**
  - Energy harvesting shrinks or replaces batteries or extends recharge periods
  - Power output of energy harvesting transducers is 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



Generator (EH)

Temporary Storage

Electronic Load

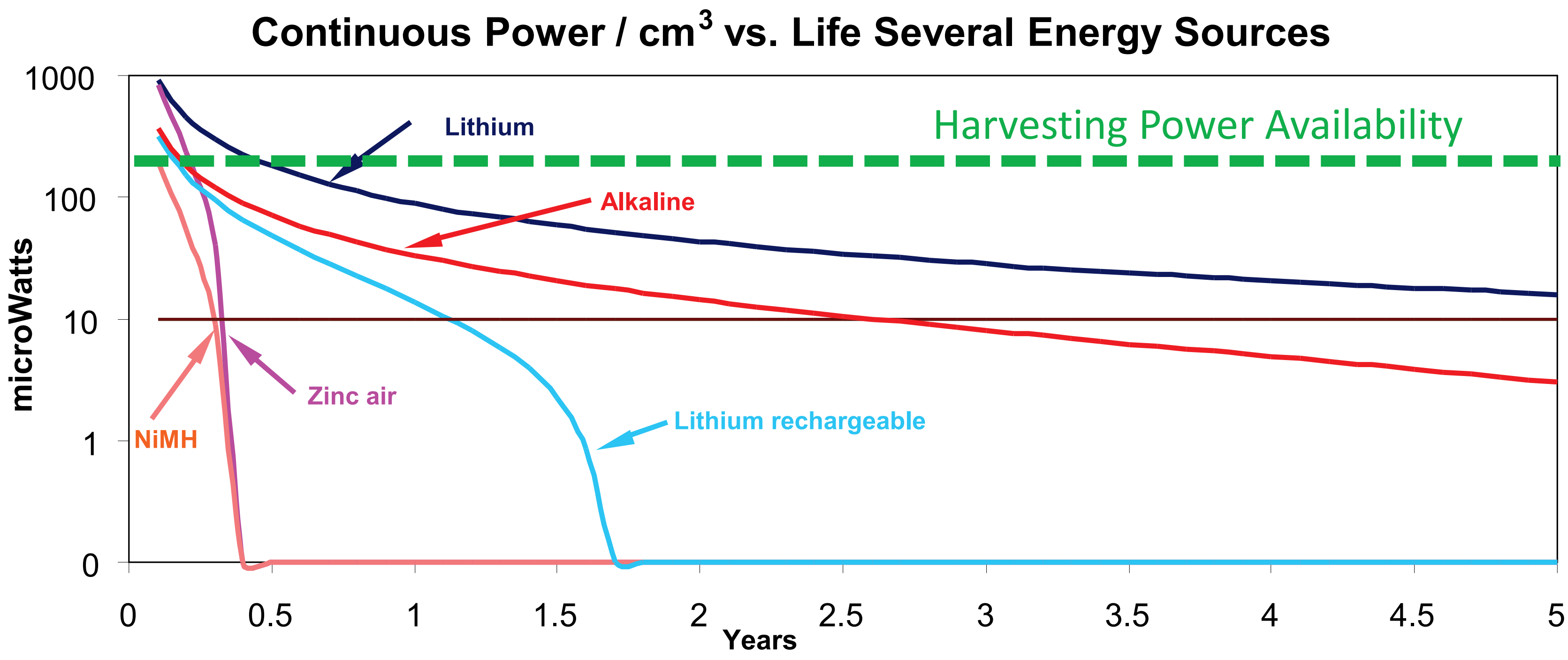
- Piezoelectric
- Electrodynamics
- Photovoltaic
- Thermoelectric

- Ultra capacitors
- Rechargeable Batteries

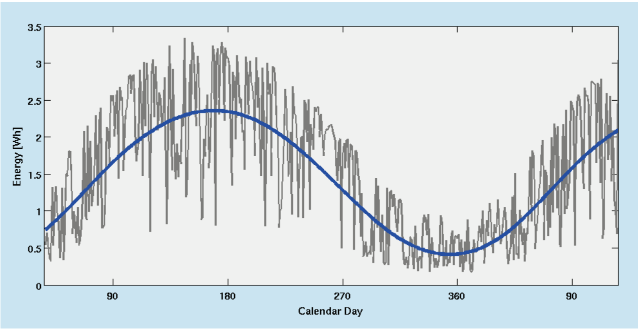
- Low power devices
- Wireless sensors
- MEMS actuators
- Consumer electronics

- 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



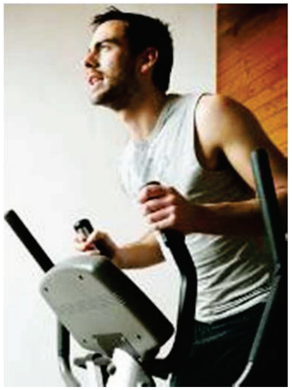
Available Energy is All Around

Light

EM waves

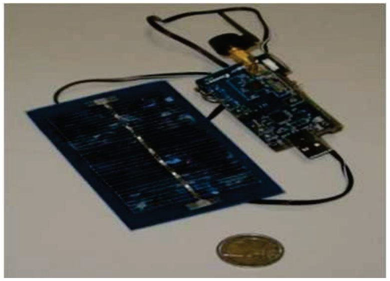
Motion and vibration

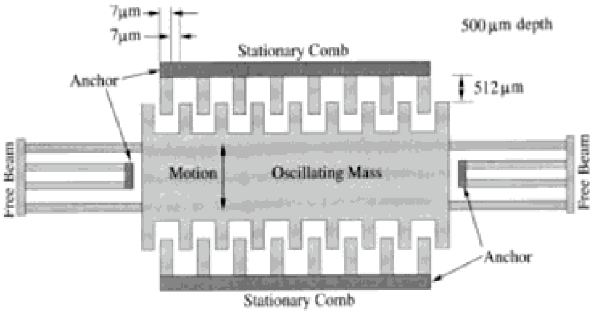
Heat

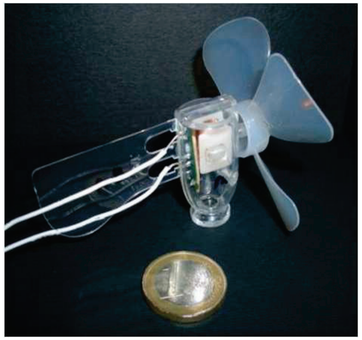


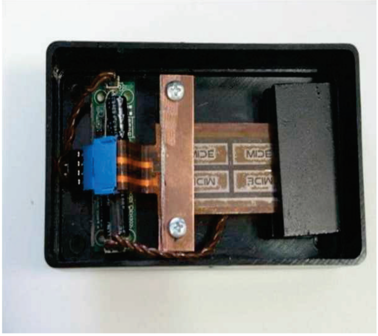
Ambient Energy Sources

- 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







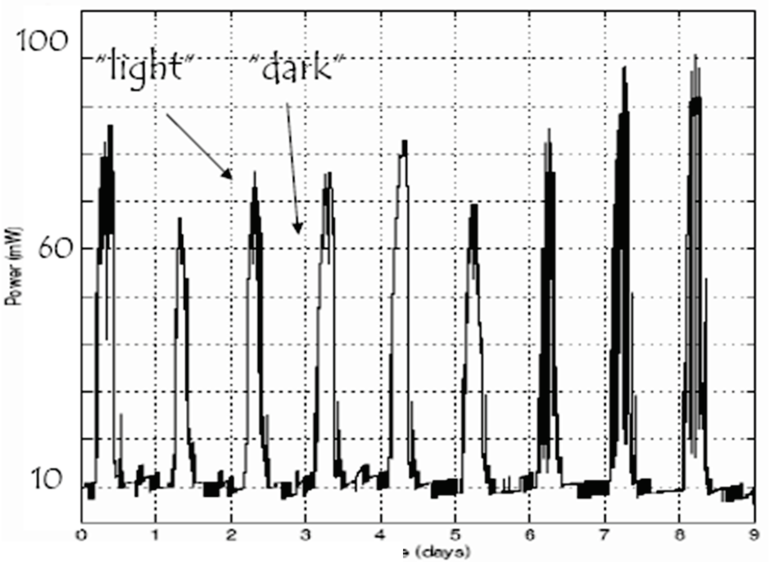


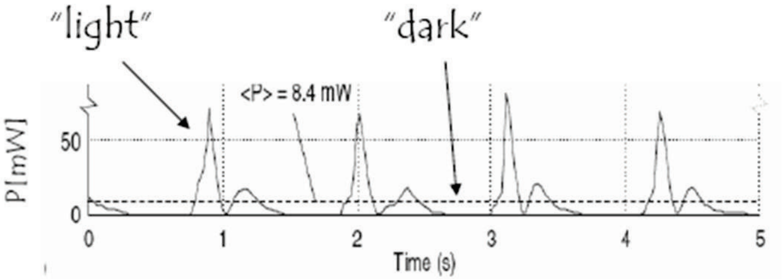
Energy Harvesting Sources

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)





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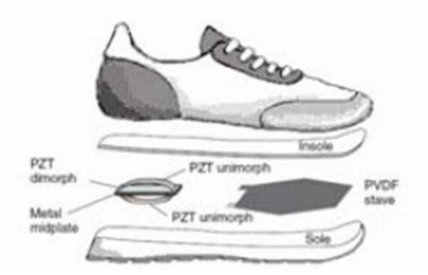
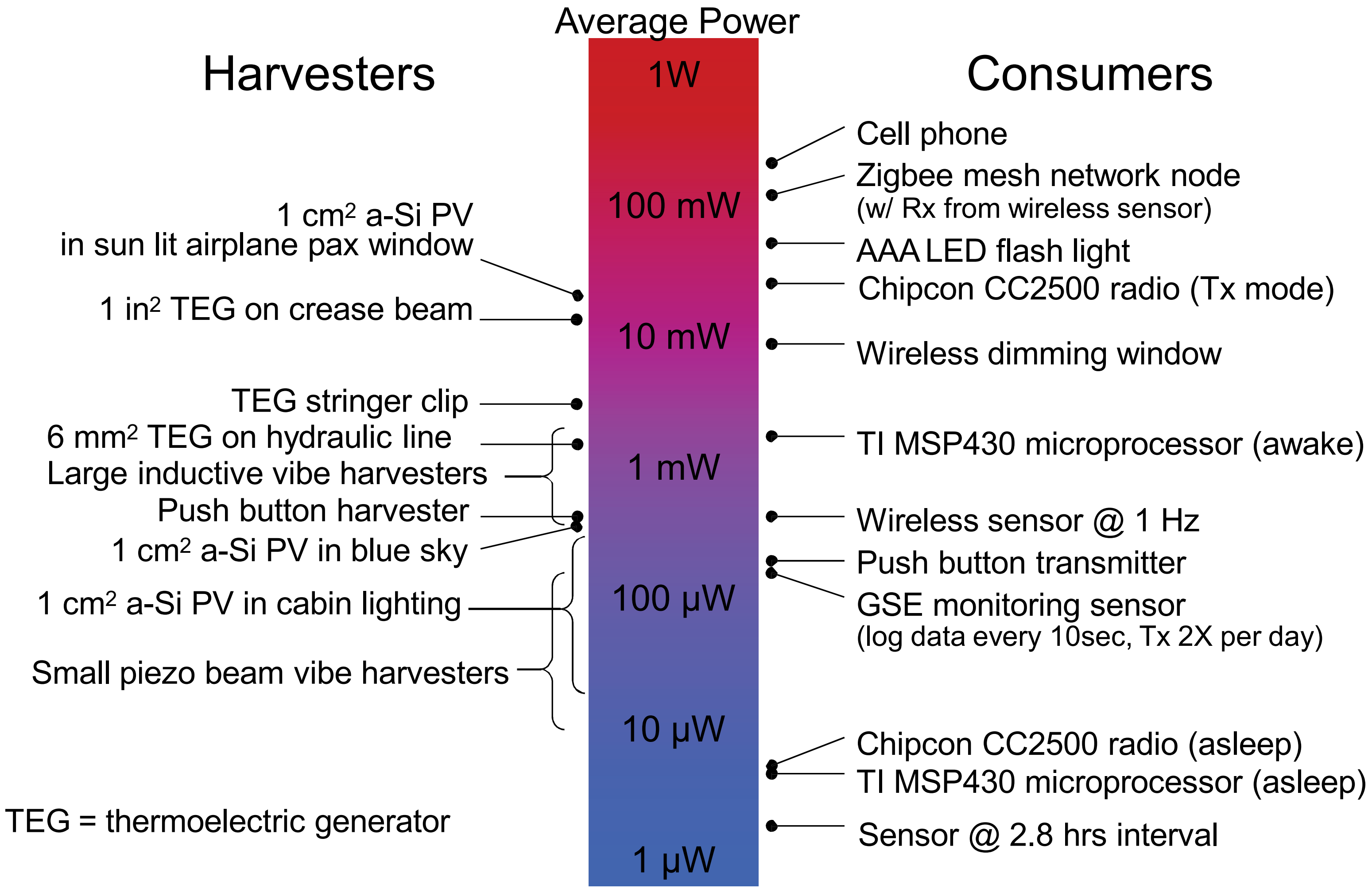


Power Generation & Utilization



Average Power

Harvesters

1 cm^2 a-Si PV
in sun lit airplane pax window

1 in^2 TEG on crease beam

TEG stringer clip

6 mm^2 TEG on hydraulic line

Large inductive vibe harvesters

Push button harvester

1 cm^2 a-Si PV in blue sky

1 cm^2 a-Si PV in cabin lighting

Small piezo beam vibe harvesters

TEG = thermoelectric generator

Consumers

Cell phone

Zigbee mesh network node
(w/ Rx from wireless sensor)

AAA LED flash light

Chipcon CC2500 radio (Tx mode)

Wireless dimming window

TI MSP430 microprocessor (awake)

Wireless sensor @ 1 Hz

Push button transmitter

GSE monitoring sensor
(log data every 10sec, Tx 2X per day)

Chipcon CC2500 radio (asleep)

TI MSP430 microprocessor (asleep)

Sensor @ 2.8 hrs interval

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 1/10th 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

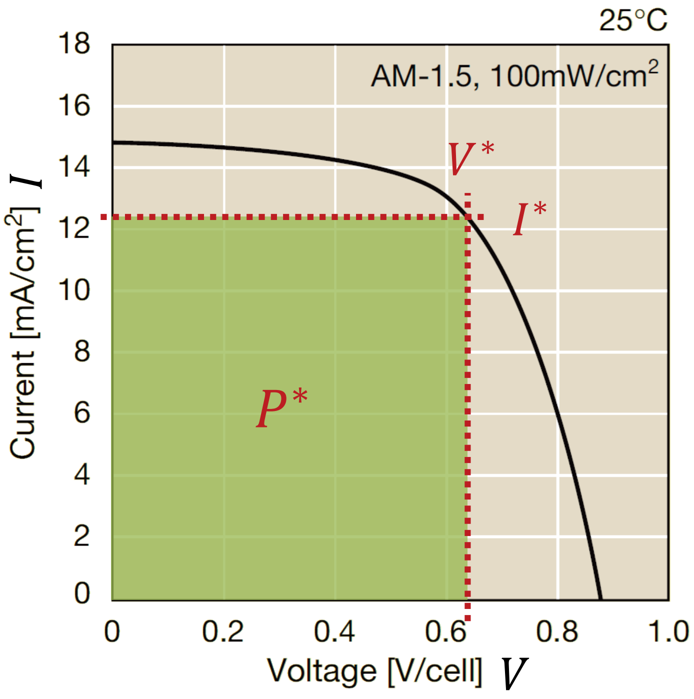
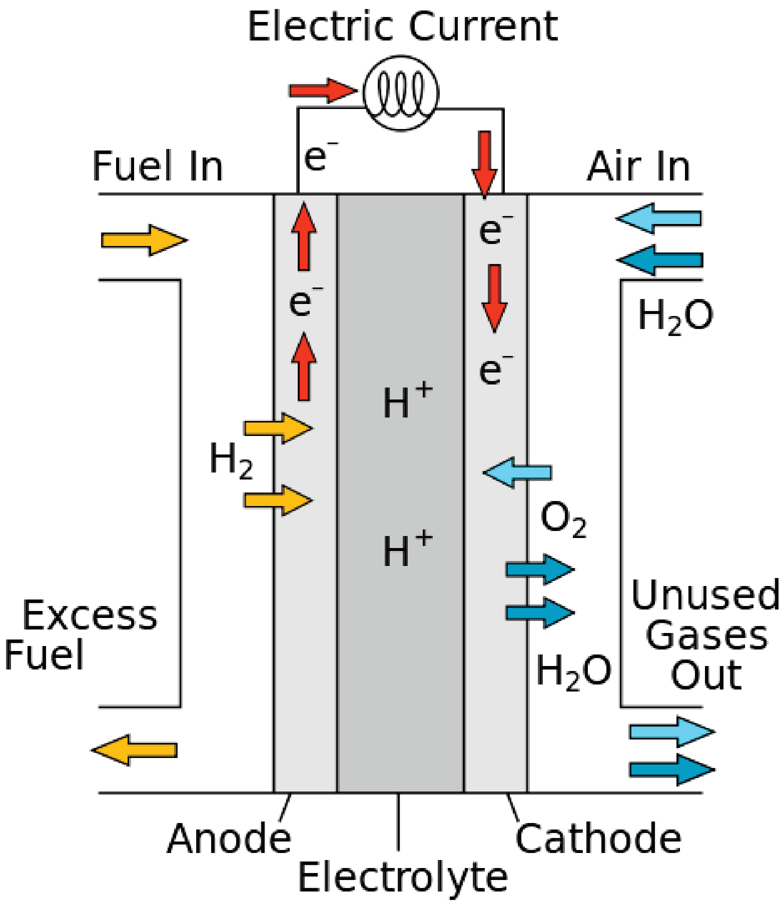


Diagram: *Amorton Amorphous Silicon Solar Cells Datasheet,* © Panasonic

- Variable output power
  - Illuminance level
  - Electrical operation point
  - (Temperature, age, …)
- I-V-Characteristics
  - Non-linear
- Efficient Use
  - Dynamic algorithms to find P^*

Technology: Micro-Fuel Cells

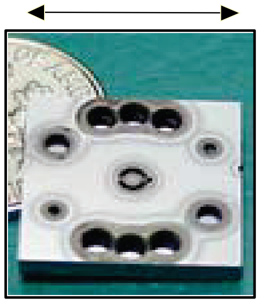


- Max current is a limiting factor due to surface area constraints (as with micro-batteries).
- Methanol energy density is 17.6 kJ/cm3. (6 X lithium and 15 X rechargeable lithium).
- Efficiencies of large fuel cells is about 45% (up to almost 90% if cogeneration is employed.)
- Efficiencies of demonstrated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

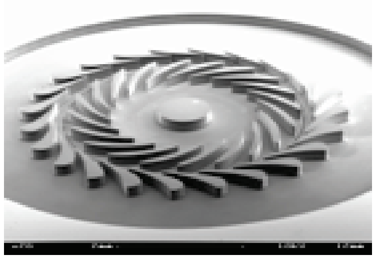
Technology: Micro-Heat Engines

4 mm Turbine – top view

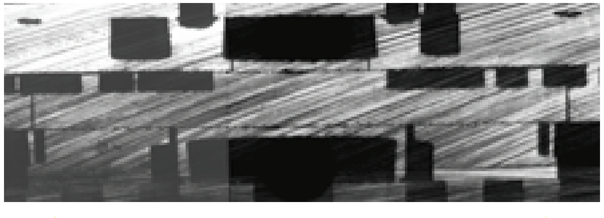
15 mm



ROTOR



Microturbine bearing rig



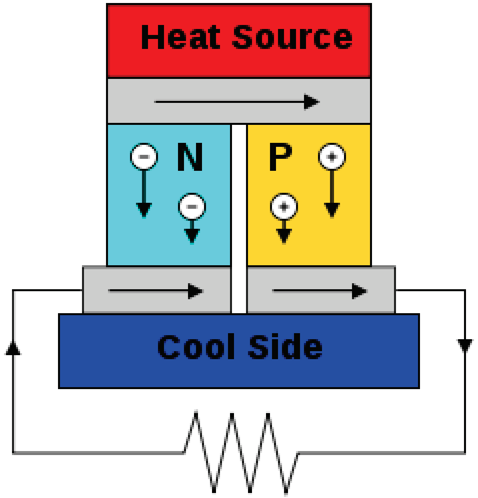
4 mm dia

- 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:

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

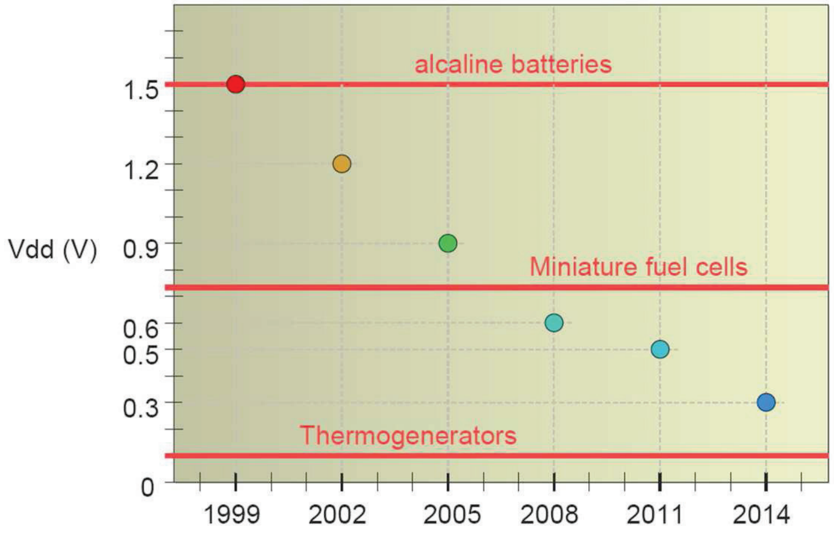
  - At T = 20°C and ΔT = 5°C, η = 1.6%
  - However, demonstrated efficiencies are far lower.

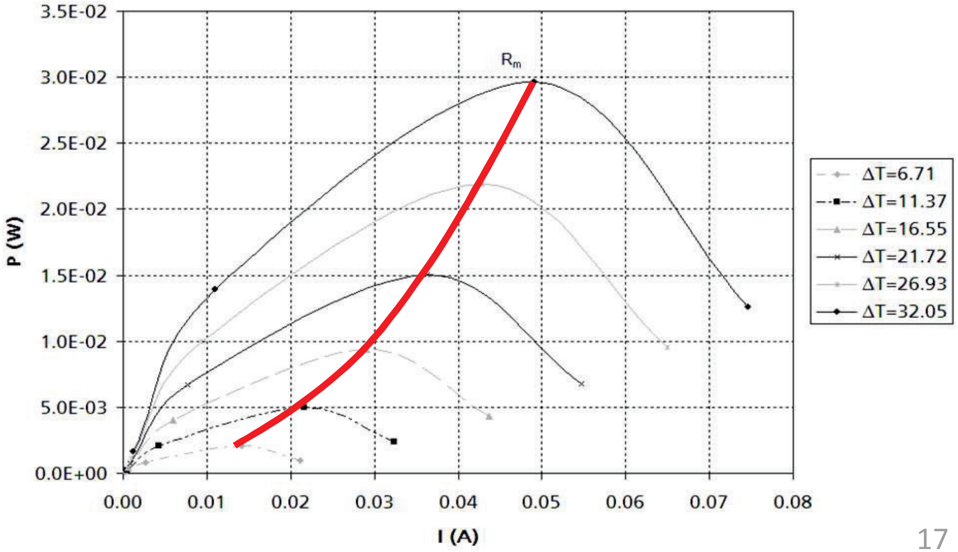
- Power is proportional to ΔT^2

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

TEG Characteristics

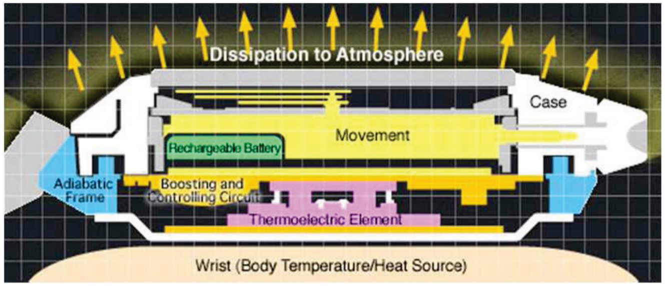
- TEGs output voltage is very low
- TEGs have a maximum power point (MPP) which changes with ΔT
- MPP is usually the half of the open circuit voltage (V_{teg} - V_{oc})
- Problem
  - Internal resistance of TEG depends on temperature and aging

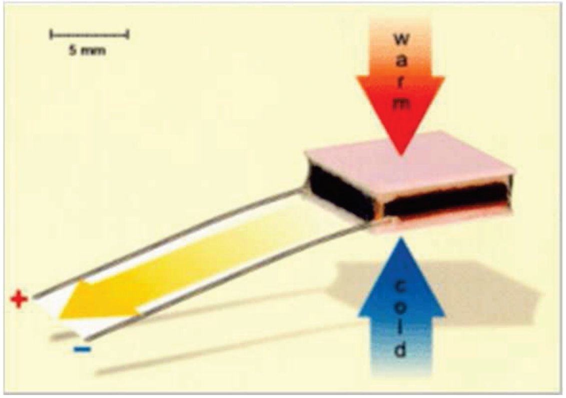


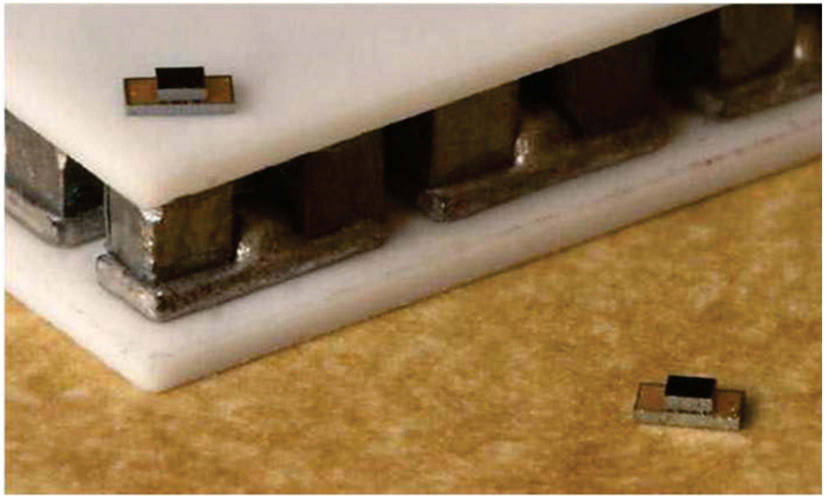


Example: Thermo Electric Generator

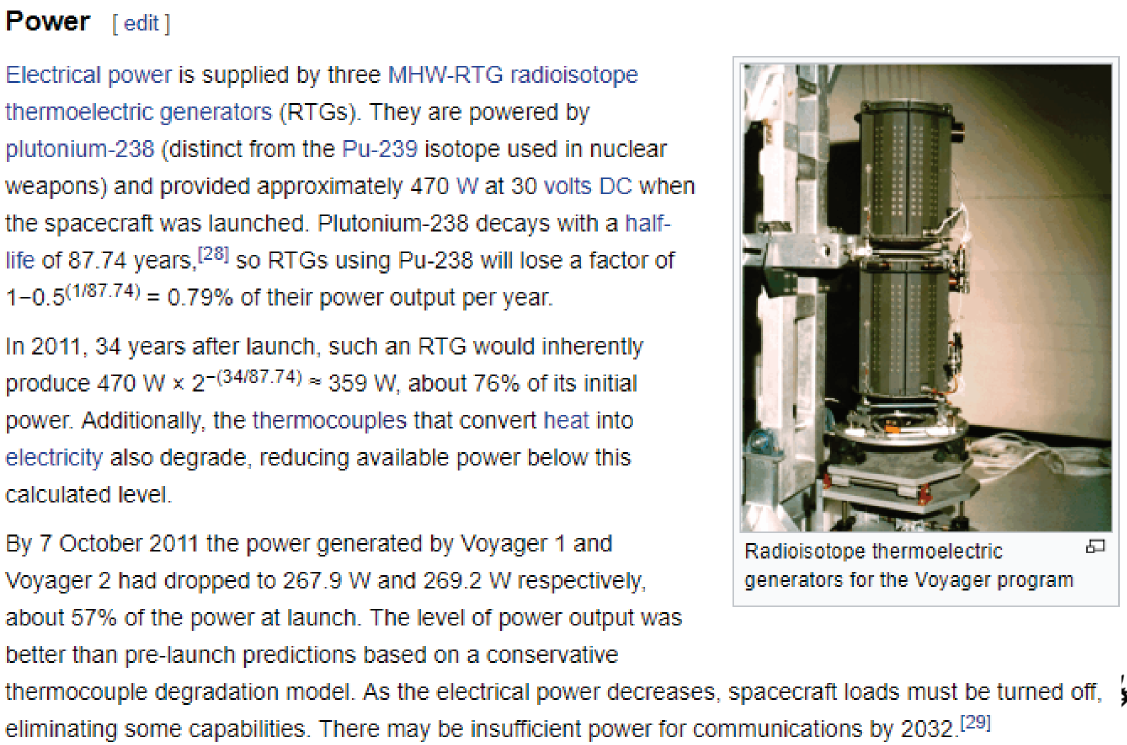
Seiko Thermic wristwatch, convert heat from the wrist (body heat) into electricity.







Powering the Voyager Spacecraft



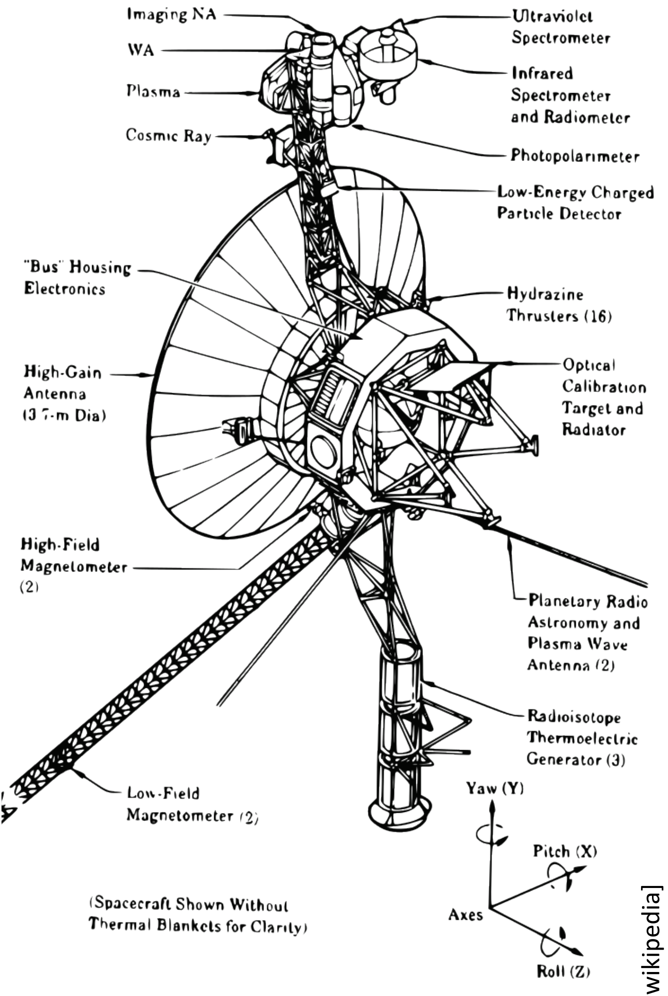
Power [edit]

Electrical power is supplied by three MHW-RTG radioisotope thermoelectric generators (RTGs). They are powered by plutonium-238 (distinct from the Pu-239 isotope used in nuclear weapons) and provided approximately 470 W at 30 volts DC when the spacecraft was launched. Plutonium-238 decays with a half-life of 87.74 years,[28] so RTGs using Pu-238 will lose a factor of $1-0.5^{(1/87.74)}$ = 0.79% of their power output per year.

In 2011, 34 years after launch, such an RTG would inherently produce 470 W × $2^{-(34/87.74)}$ ≈ 359 W, about 76% of its initial power. Additionally, the thermocouples that convert heat into electricity also degrade, reducing available power below this calculated level.

By 7 October 2011 the power generated by Voyager 1 and Voyager 2 had dropped to 267.9 W and 269.2 W respectively, about 57% of the power at launch. The level of power output was better than pre-launch predictions based on a conservative thermocouple degradation model. As the electrical power decreases, spacecraft loads must be turned off, eliminating some capabilities. There may be insufficient power for communications by 2032.[29]

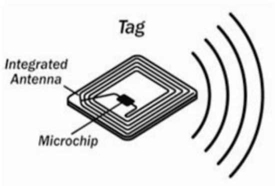
Radioisotope thermoelectric generators for the Voyager program

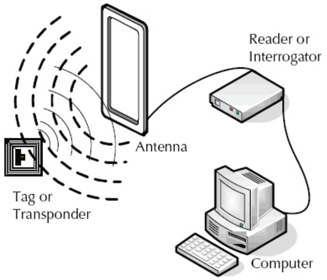


[wikipedia]

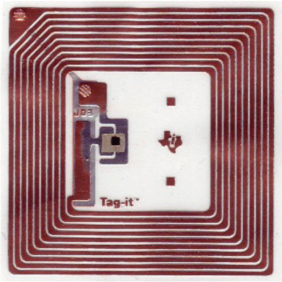
Technology: RF Radiation Sources

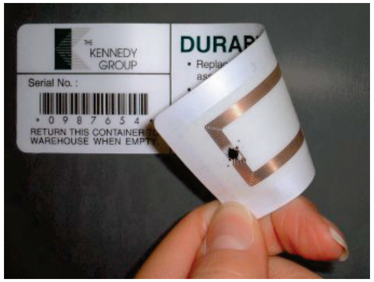
- Remote powering of systems from RF sources

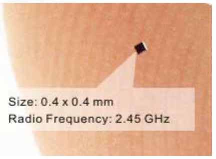




- Inductive coupling using a large excitation coil and a small pickup coil
  - Medical Implants
  - RFID Tags
  - Smart Cards
  - Wristwatches
  - Badges
- Experimental systems with higher power capabilities are explored







- Issue: Attenuation

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

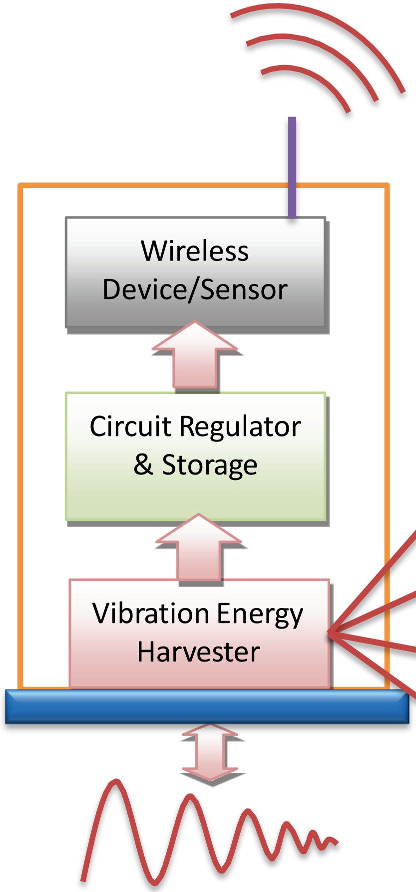
P_0 = transmit power
P_r = power received
λ = wavelength
R = transmit distance

- 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

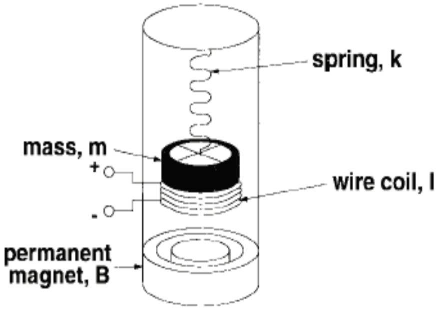


Wireless Device/Sensor

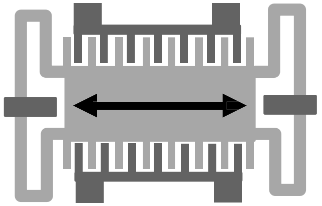
Circuit Regulator & Storage

Vibration Energy Harvester

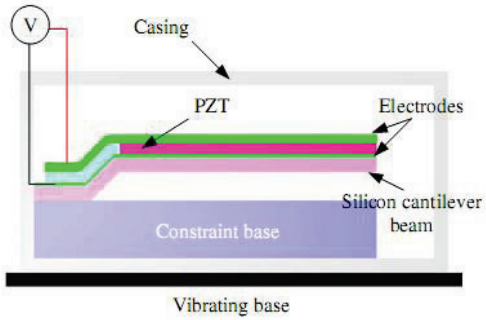
- Ambient vibrations
- Human motion
- Wind, Hydro



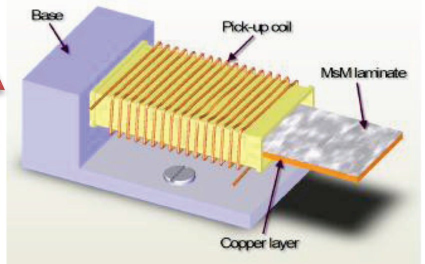
Electromagnetic



Electrostatic/Capacitive



Piezoelectric



Magnetostrictive

Vibrations – Electrostatic Conversion

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

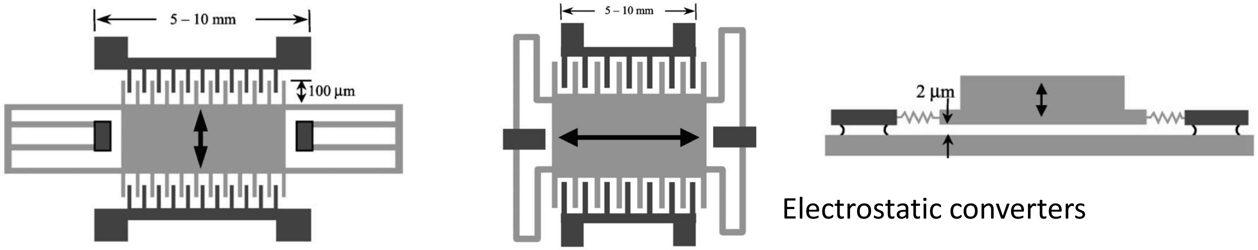
$$P = \frac{m\zeta_e^2 A^2}{4\omega(\zeta_e+\zeta_m)^2}$$

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	2.25	121
HVAC 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

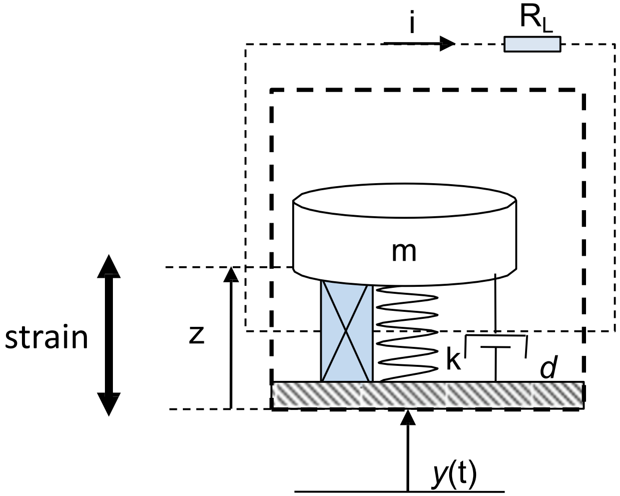


Electrostatic converters

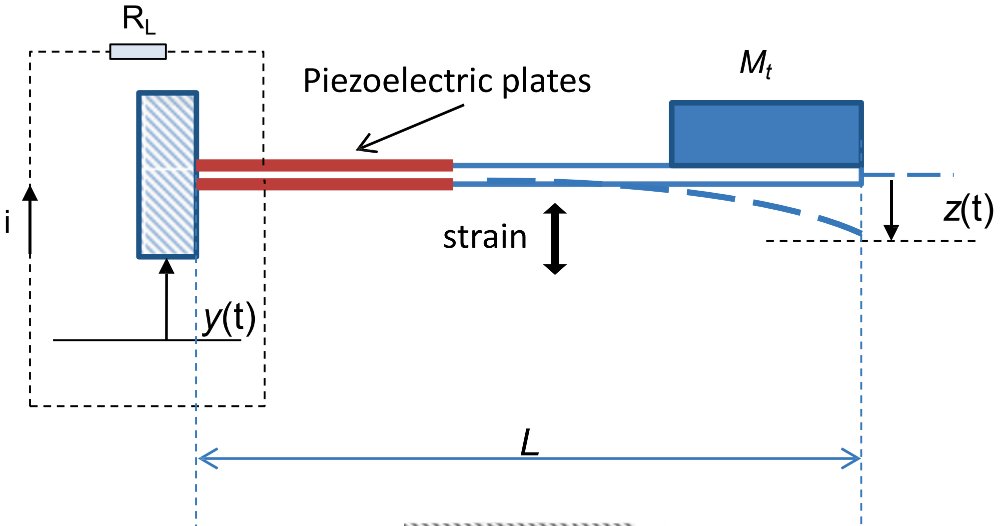
[S. Roundy, UC Berkeley]

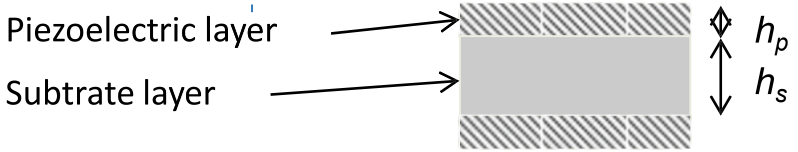
Vibrations – Piezoelectric Conversion

Piezoelctric bulk (33 mode)

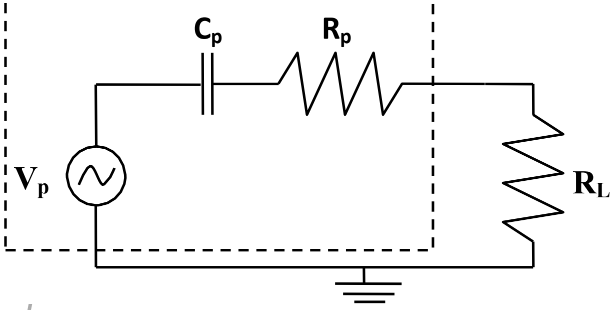


Cantilever beam (31 mode)





Piezoelectric generator



At open circuit

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

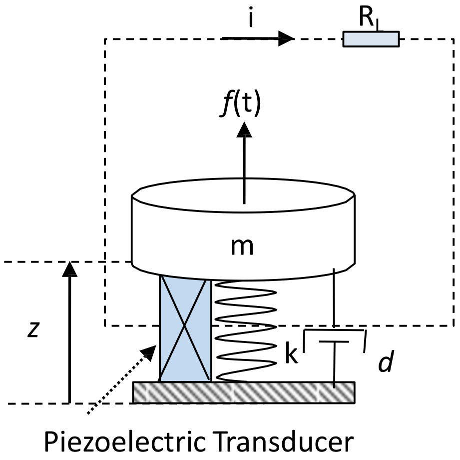
The power delivered to the load is simply

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

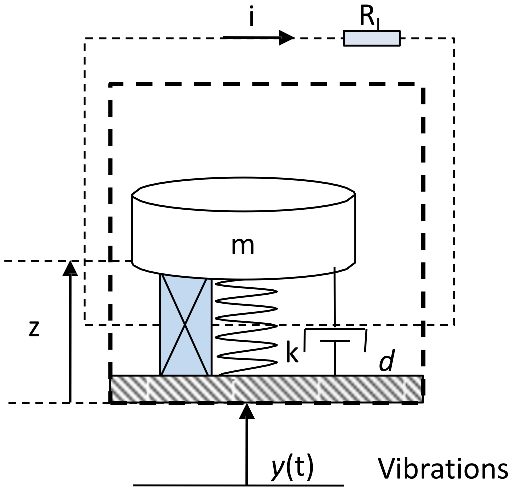
[S. Roundy, Energy scavenging for wireless sensor networks, Kluwer]

Vibration – Basic Operating Principles

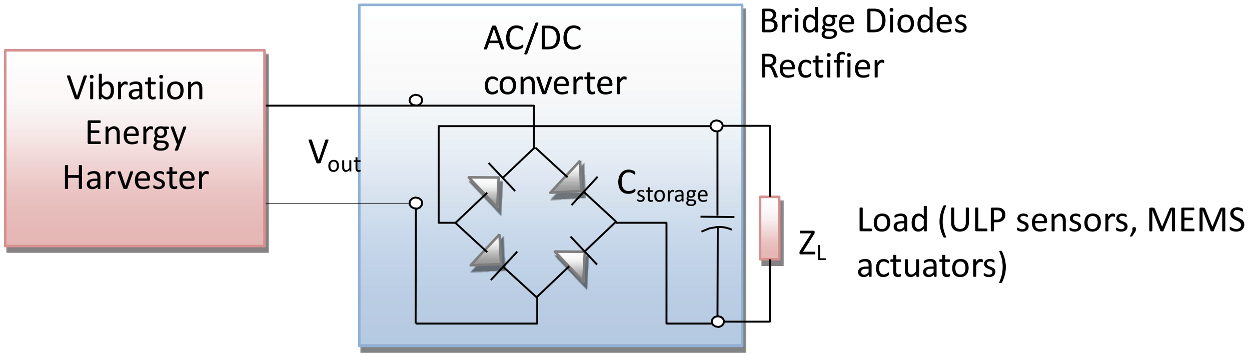
Direct force



Inertial force



- 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.



[S. Roundy, UC Berkeley]

Energy Harvesting Methods - Overview

Power Source	P/cm³ (uW/cm³)	E/cm³ (J/cm³)	P/cm³/a (uW/cm³/a)	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

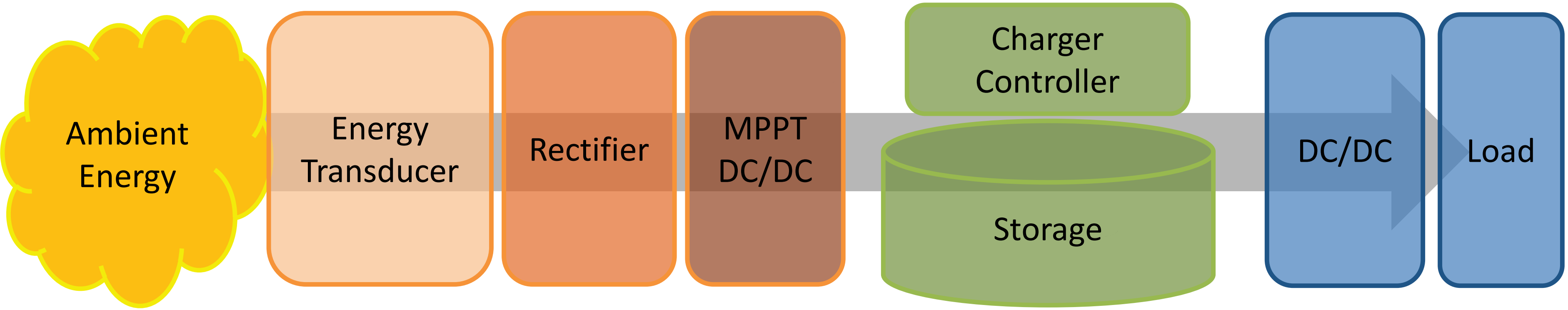
[S. Roundy, UC Berkeley]

Low-Power System Design

ENERGY HARVESTING – SYSTEMS INTEGRATION

Generic Energy Harvesting Design

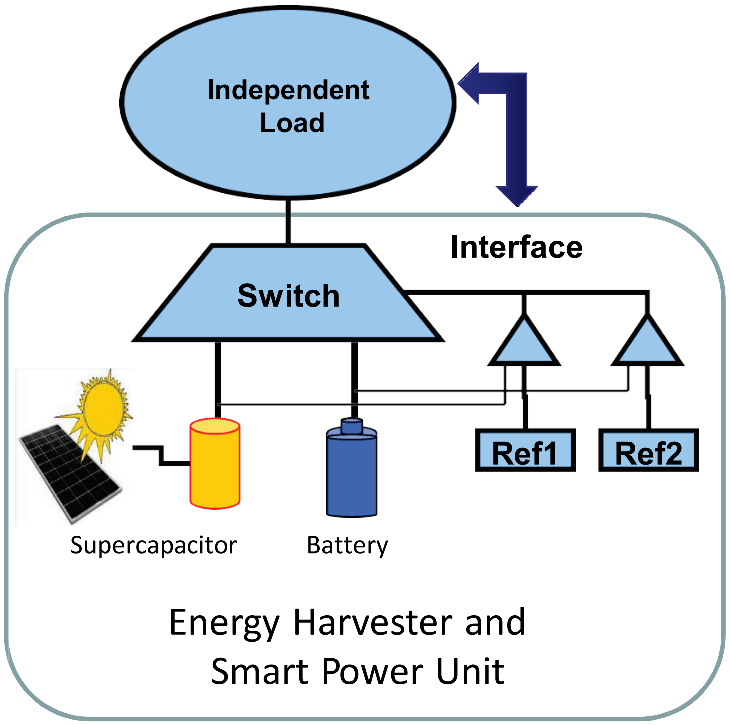
- **Dedicated blocks**, depending on energy source, ambient conditions and application
- **Not always all are required** in a given application/source
- Design process of rectifier, DC-DC converter and MPPT is **challenging**
- Charger/limiter/protection consumes additional power and are often to some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



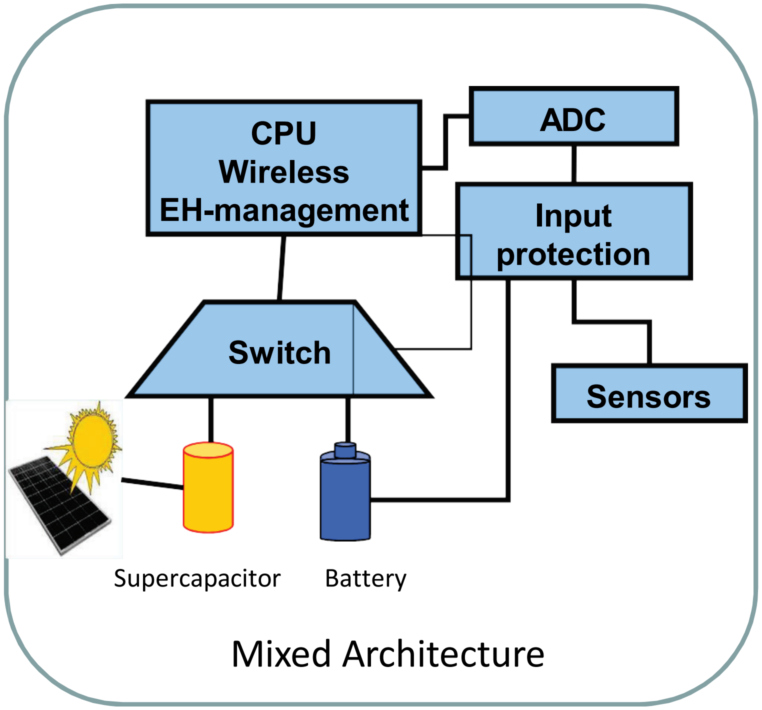
Opens up significant control-space issues w.r.t. energy usage

This needs algorithmic/software support!

Integration Into Mixed Architectures



Energy Harvester and Smart Power Unit



Mixed Architecture

- 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:

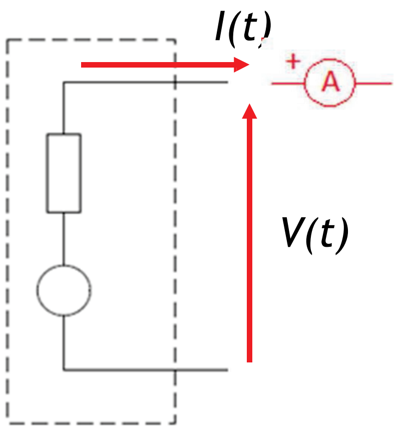
$$P(t) = I(t)\,V(t)$$

- In case of resistive loads, then

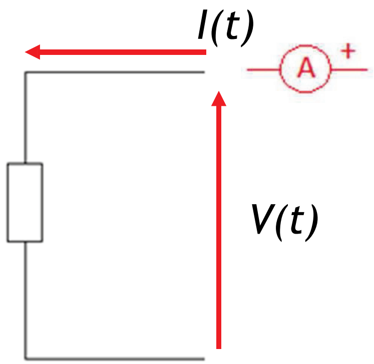
$$P(t) = R\,I(t)^2 = \frac{V(t)^2}{R}$$

- 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]

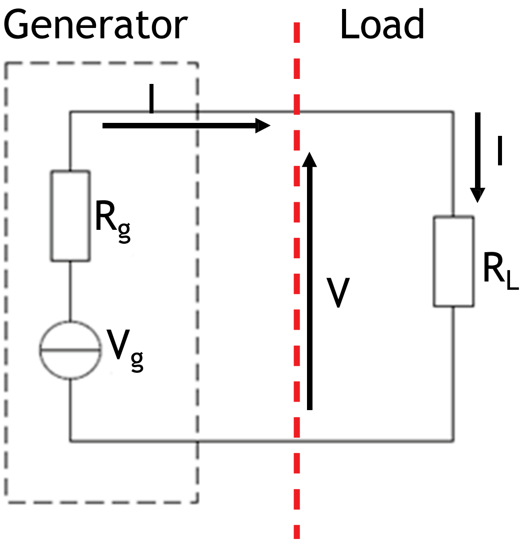
GENERATOR (delivered power >0)



USER (incoming power >0)



Maximum Power Transfer



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

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

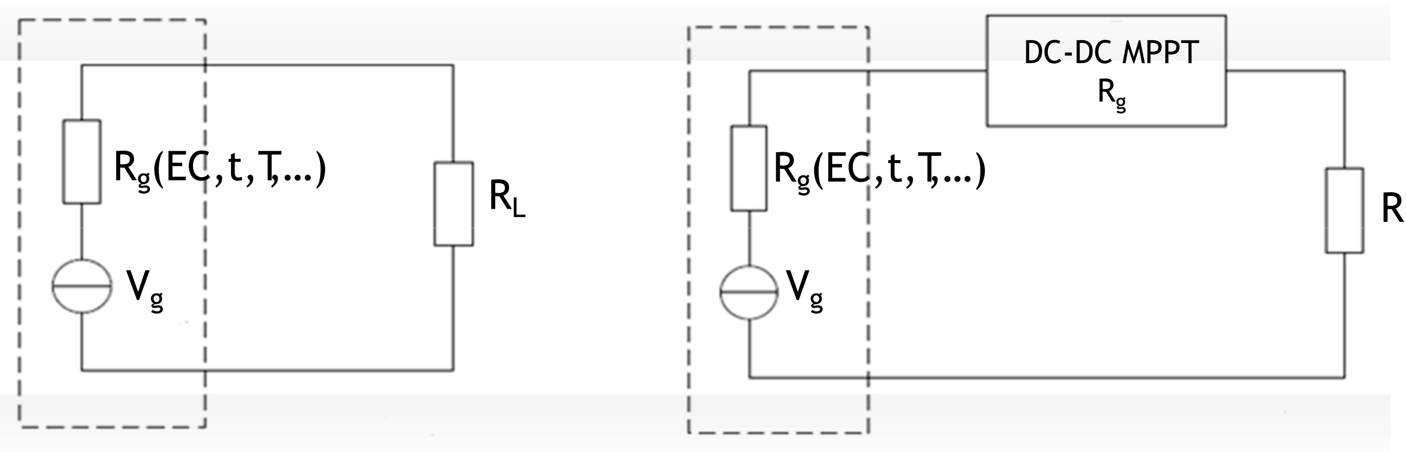
$$P = R_L\, I^2 = V_g{}^2 \frac{R_L}{(R_g + R_L)^2}$$

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

$R_L = R_g$ 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, …)



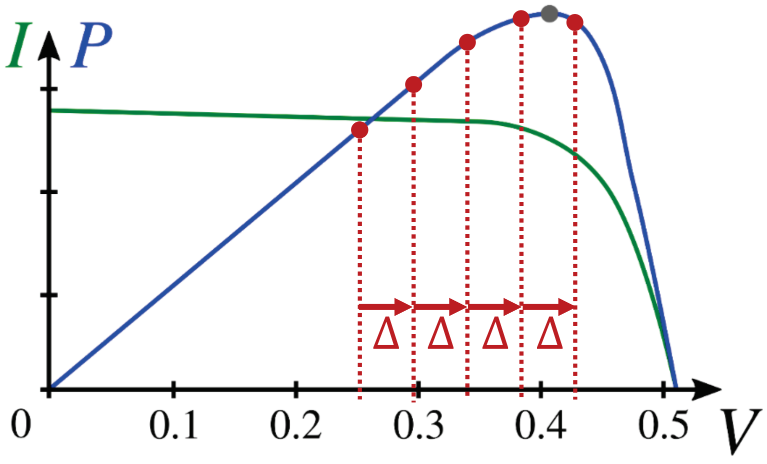
Ideal situation:

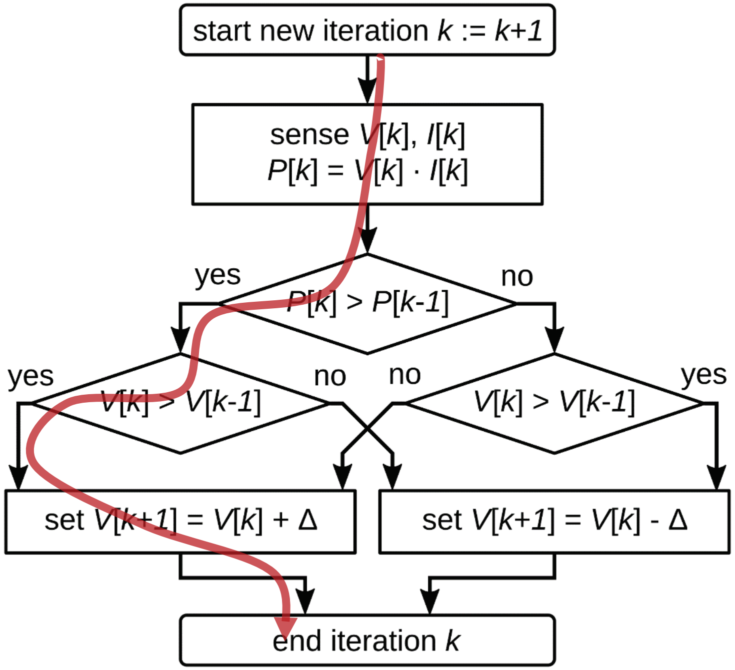
- *Load R_L and internal resistance R_g are naturally matched*
- *V_g in the correct range*

Typical situation:

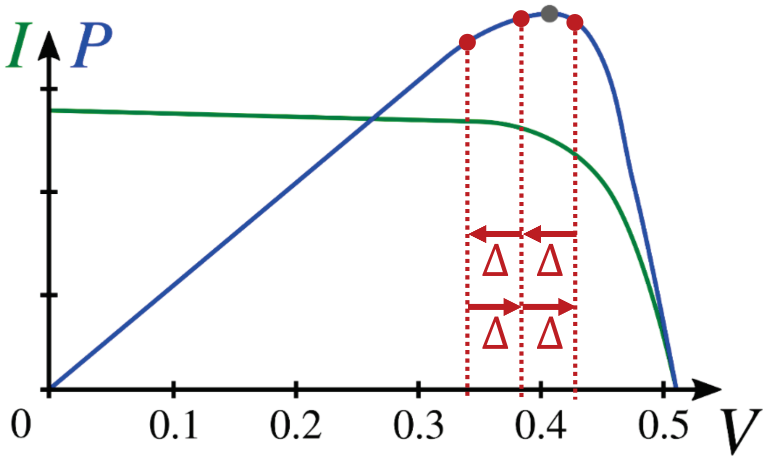
- *DC/DC with MPPT to match R_L and R_g and /or to adjust V_g*
- ***MPPT adjusts resistance matching over time***

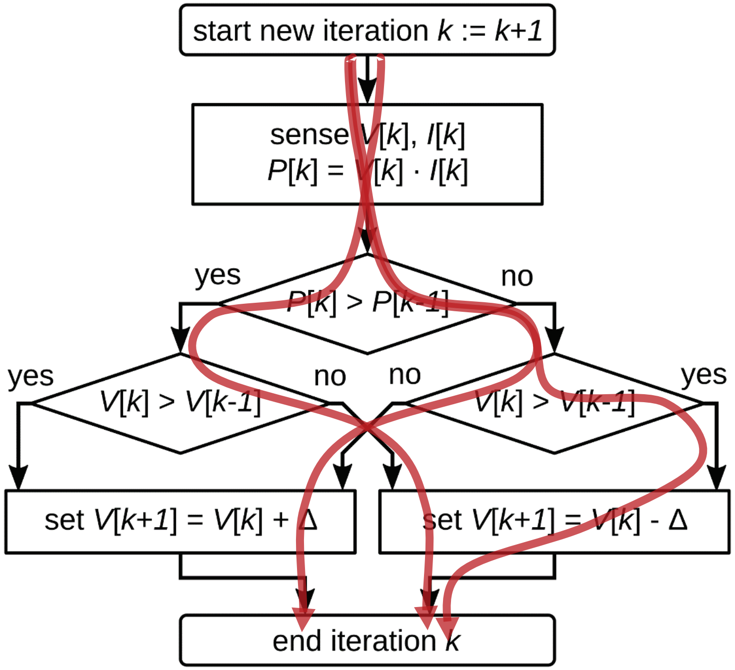
Maximum Power Point Tracking





Maximum Power Point Tracking





start new iteration *k* := *k+1*

sense *V*[*k*], *I*[*k*]
P[*k*] = *V*[*k*] · *I*[*k*]

P[*k*] > *P*[*k-1*]

yes / no

V[*k*] > *V*[*k-1*]

yes / no

V[*k*] > *V*[*k-1*]

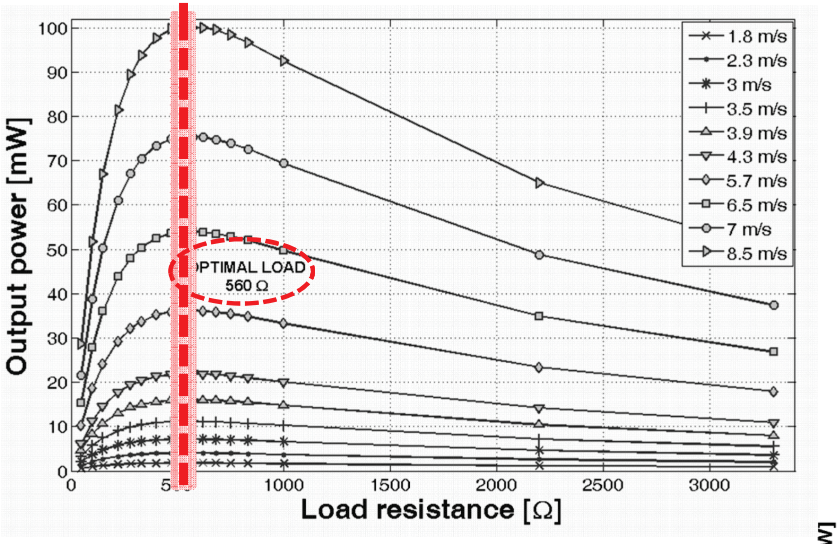
no / yes

set *V*[*k+1*] = *V*[*k*] + Δ

set *V*[*k+1*] = *V*[*k*] - Δ

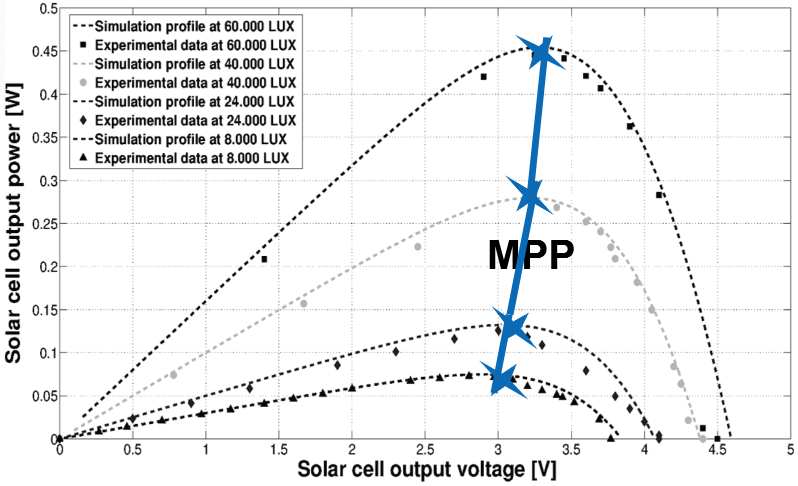
end iteration *k*

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)

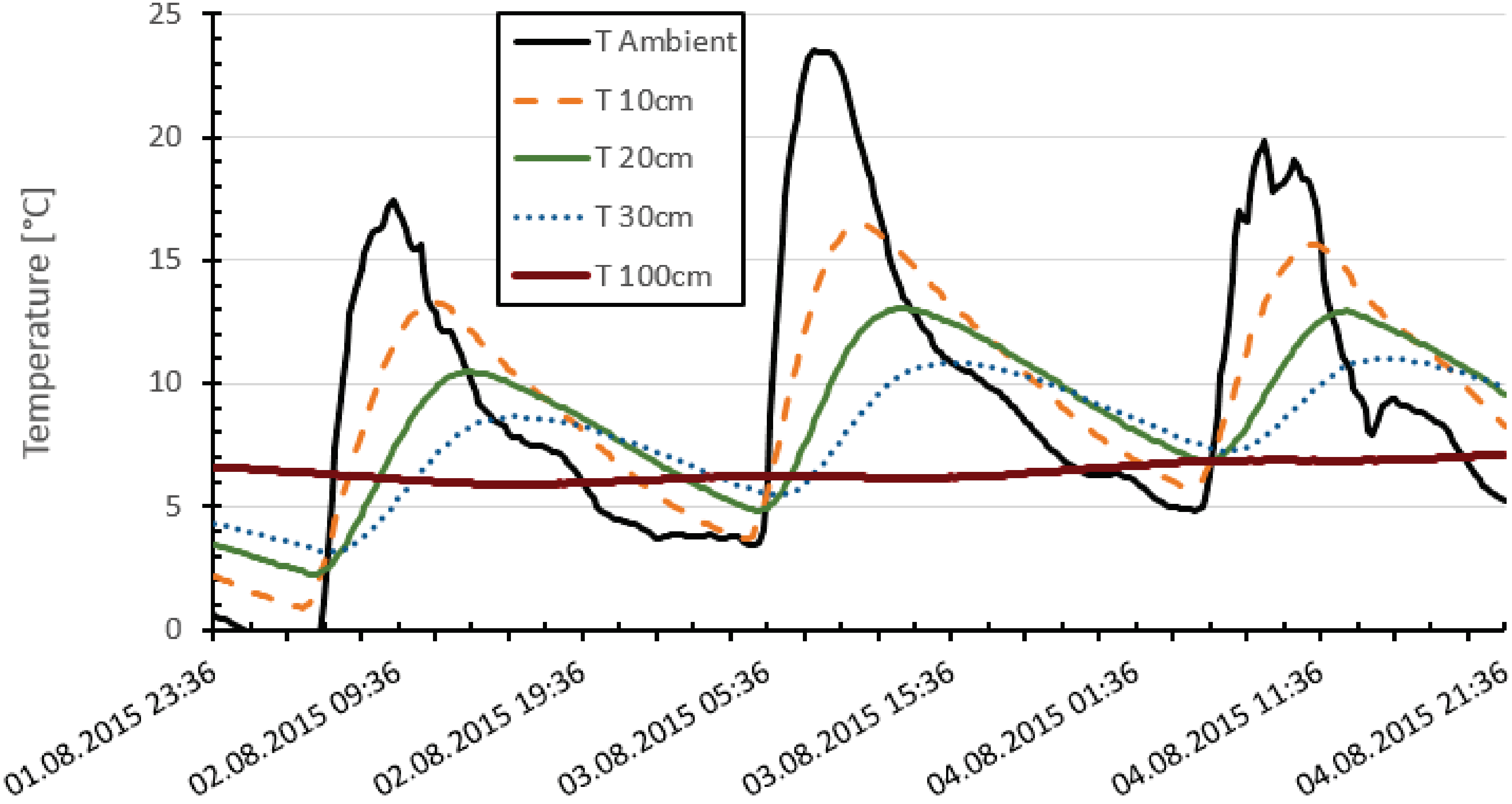


Low-Power System Design

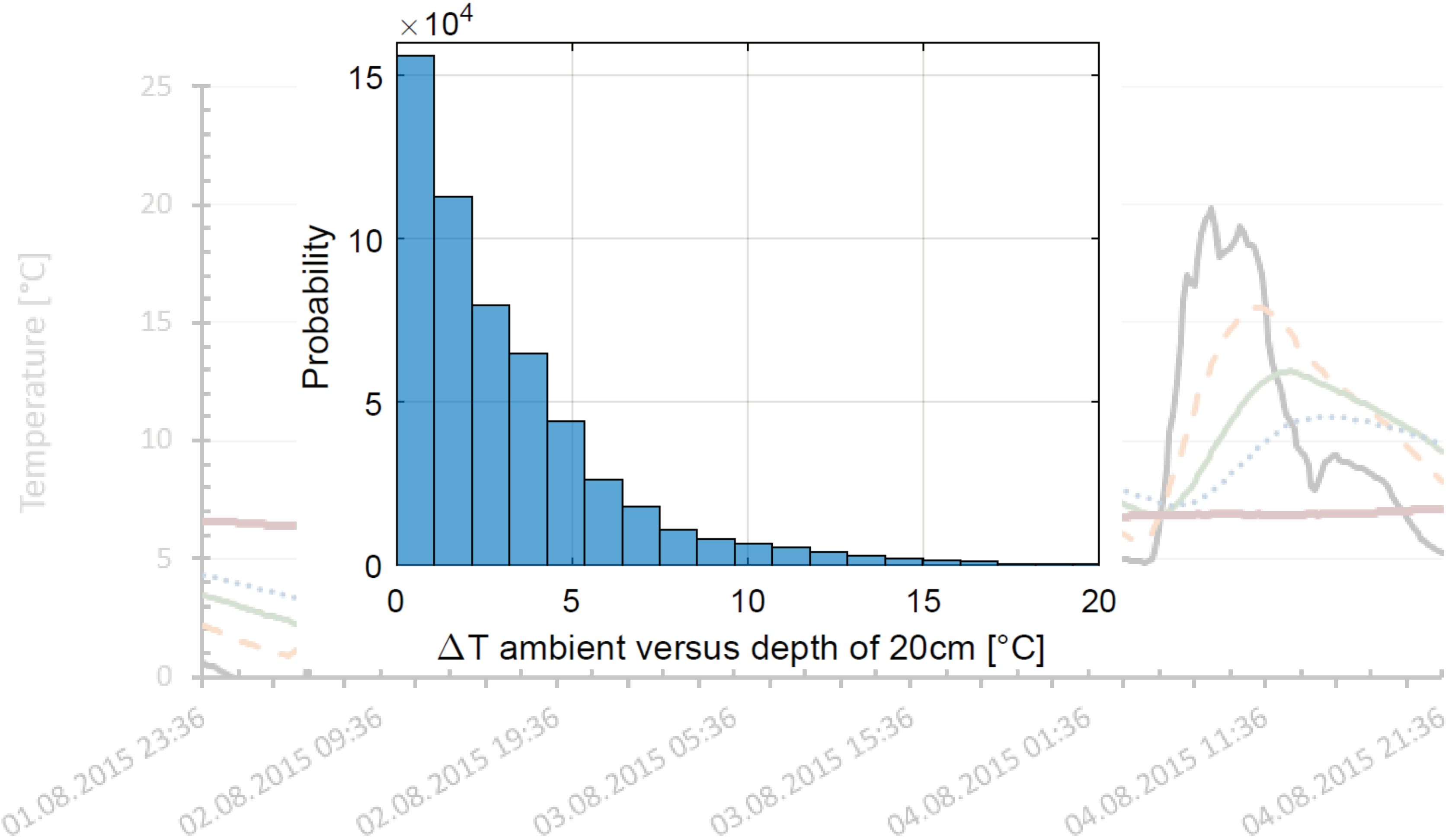
TEG-BASED ENERGY HARVESTING (FOR PERMASENSE SENSOR NODES)

[Master Thesis by D. Bernath, 2016]

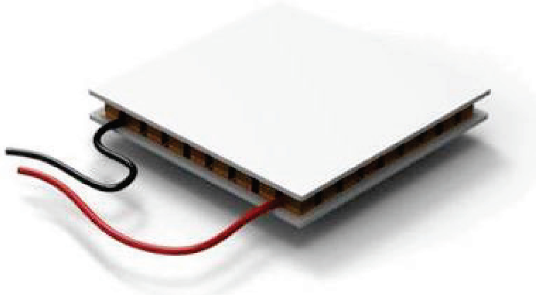
Motivation – Diurnal Temperature Differences in Rock Walls



Motivation – Diurnal Temperature Differences in Rock Walls



Thermoelectric Generator (TEG)



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

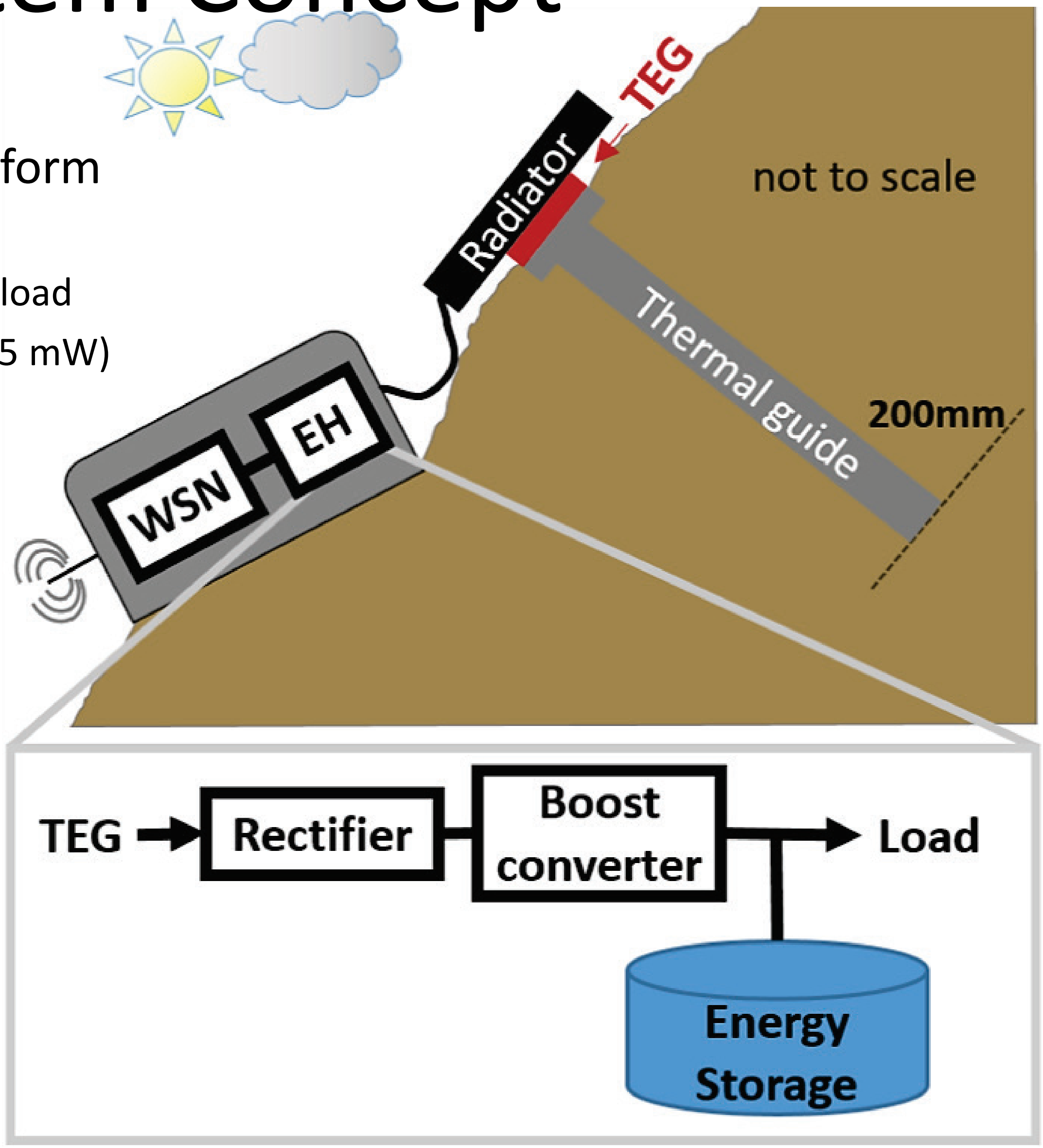
0-300 mV

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

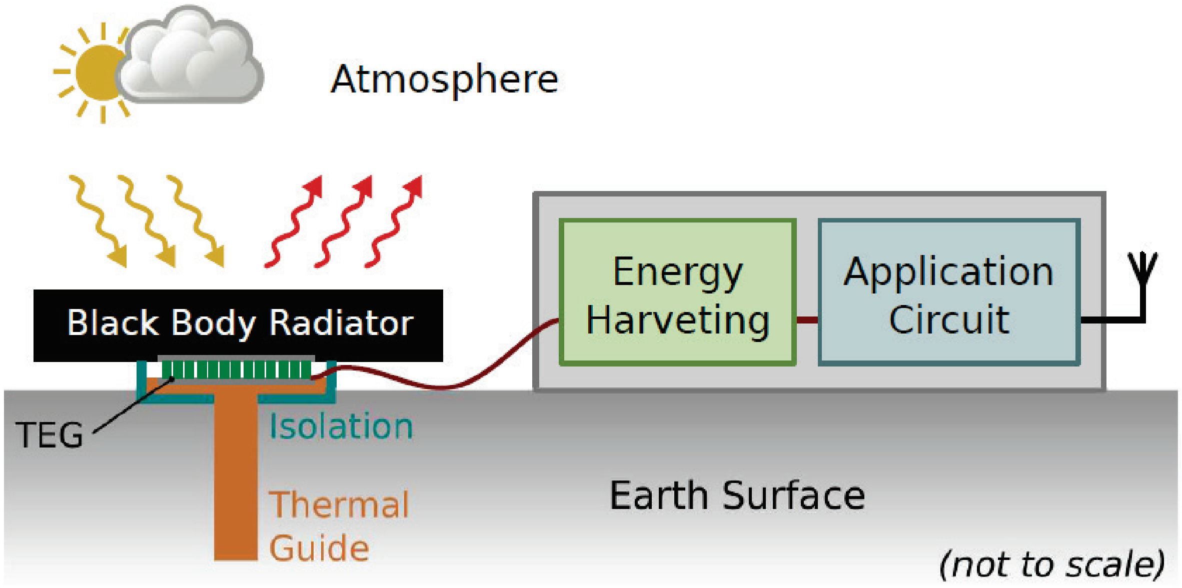
System Concept

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

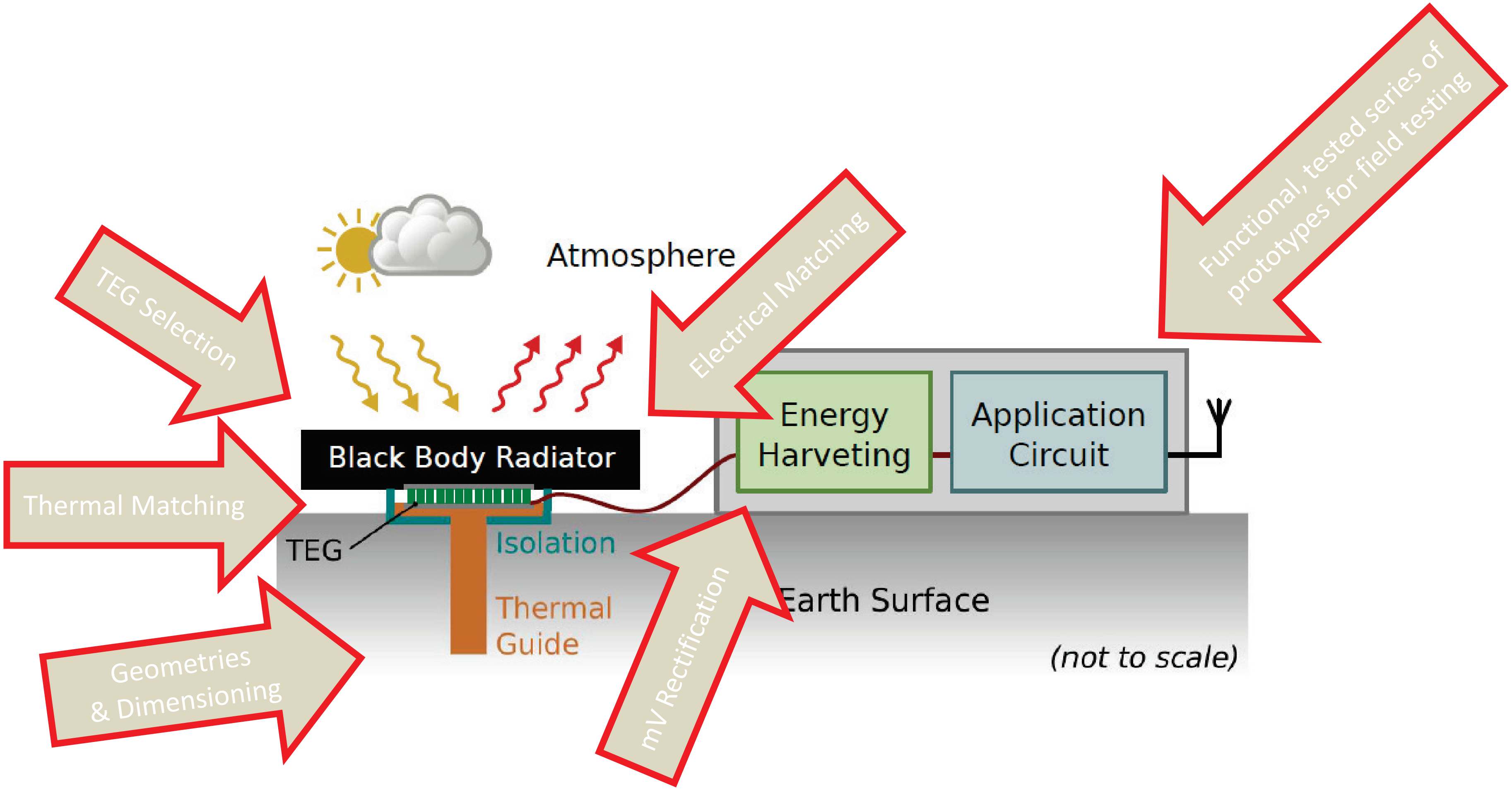
- Optimization areas
  - Thermal guide
  - Radiator
  - TEG
  - Rectifier
  - Boost converter



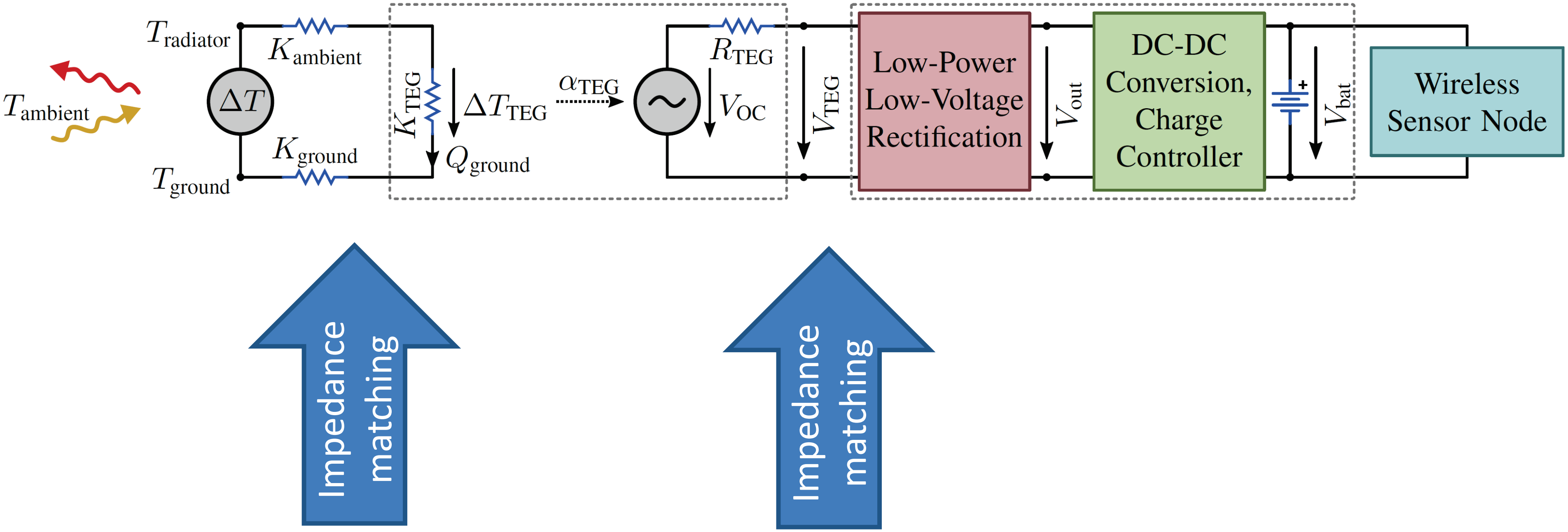
System Design



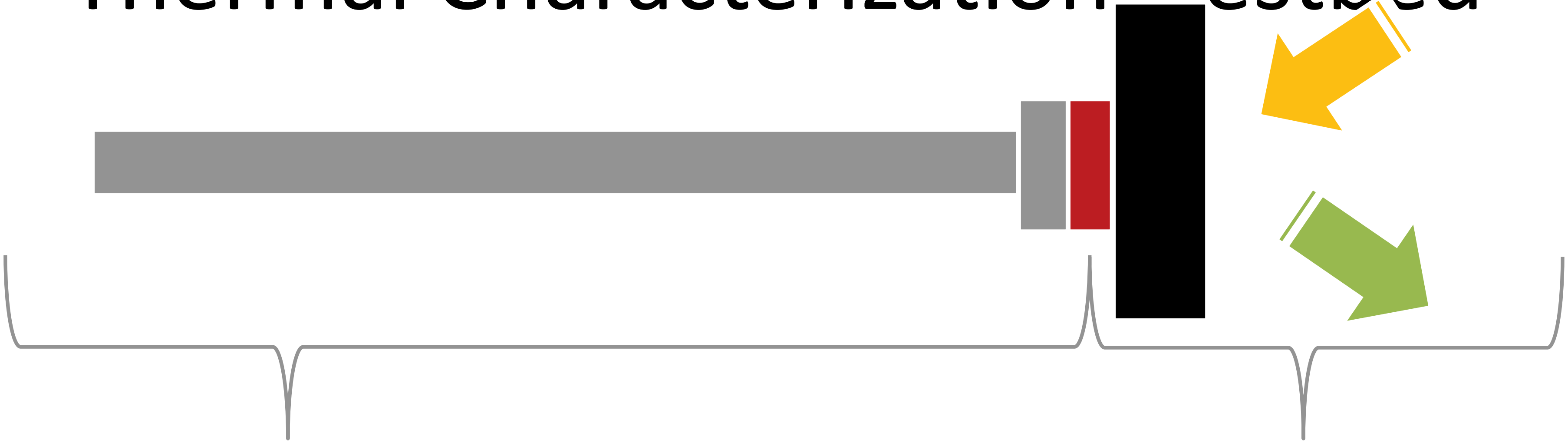
System Design Challenges



System Overview



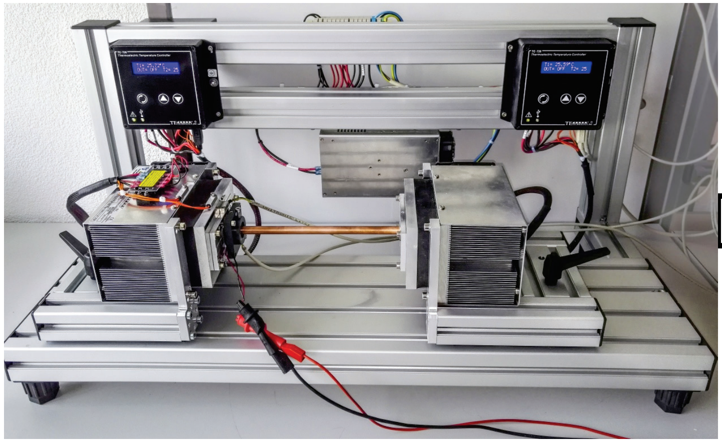
Thermal Characterization: Testbed

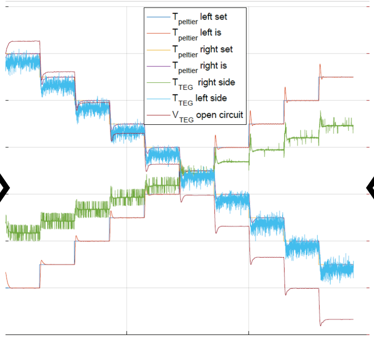


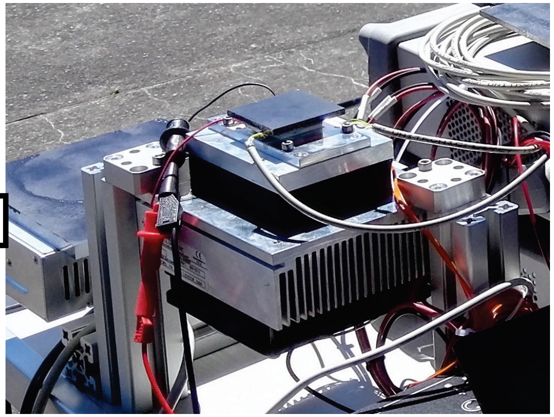
Two sided temperature control

- Temperature characteristics
- System response

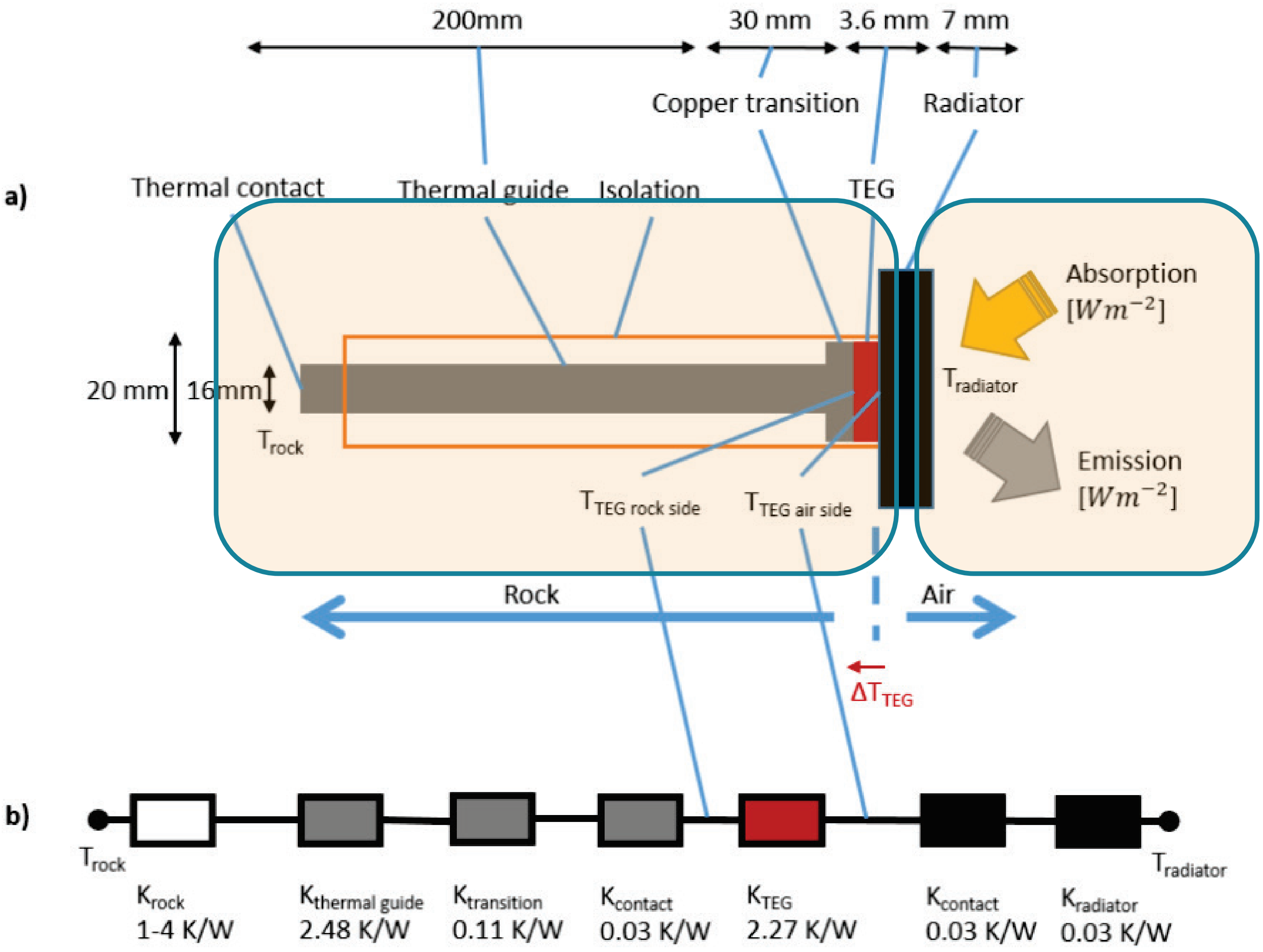
Temperture vs radiation





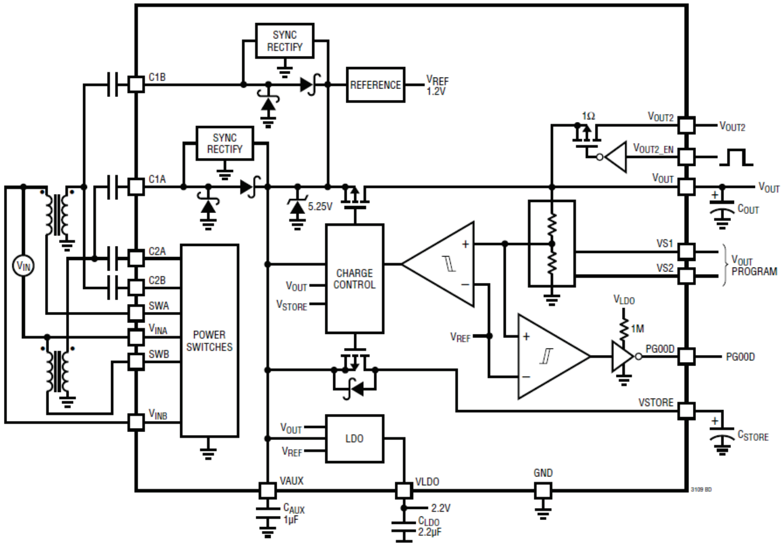


Thermal Modelling



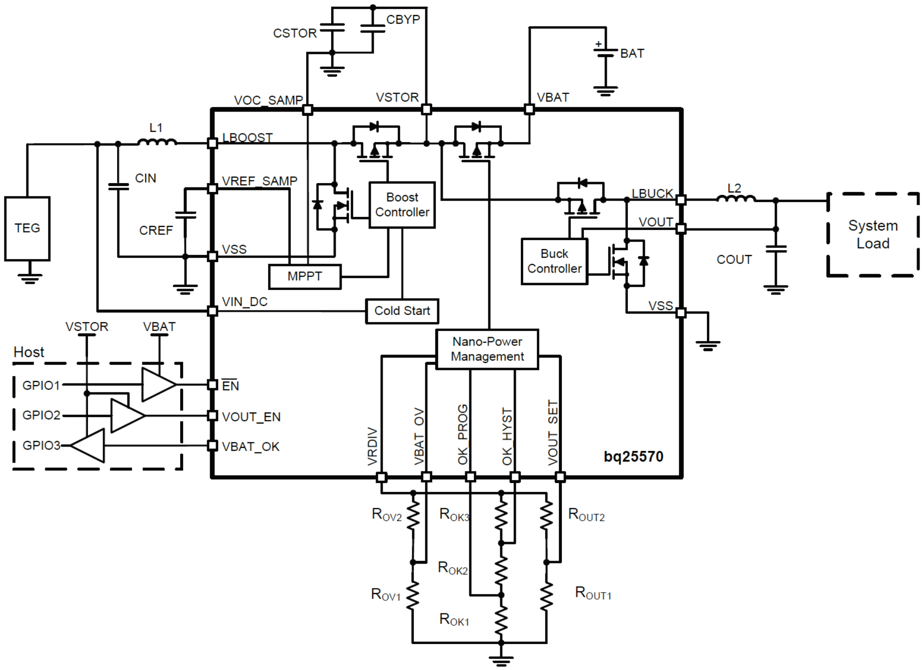
Harvesting Charge Controller Options

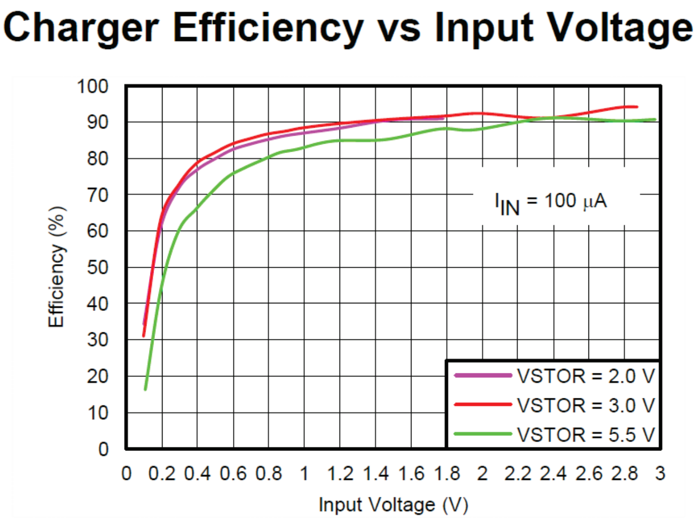
	TI BQM255xx	Analog LTC3109
Regulator design	MPPT	Sync. Regulator
Input polarity	Unipolar	Bipolar
Min. harvesting voltage	100 mV	30 mV
Efficiency	0.6	0.3
Output	Unregulated	Regulated
Storage management	Yes	Partly
Power good output	Yes	Yes



LTC 3109 Block Diagram

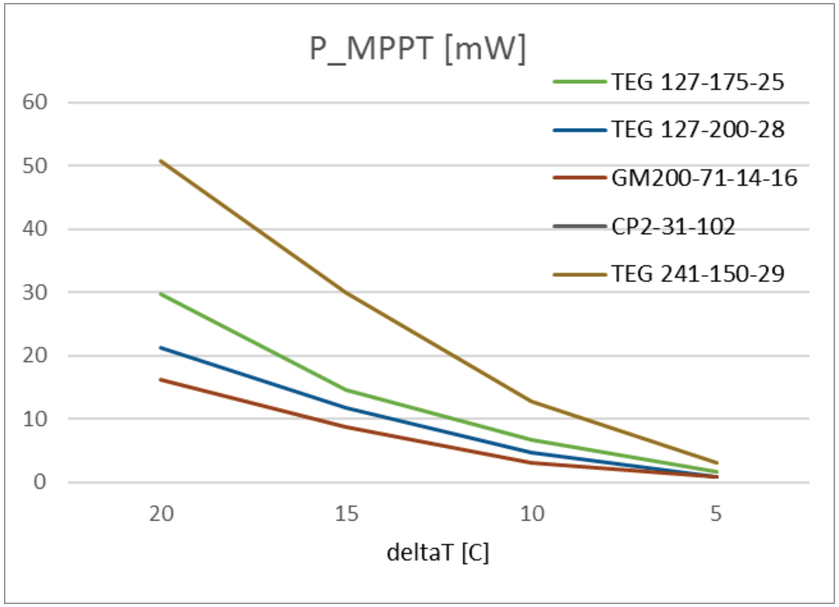
BQ25570 MPPT Charge Controller



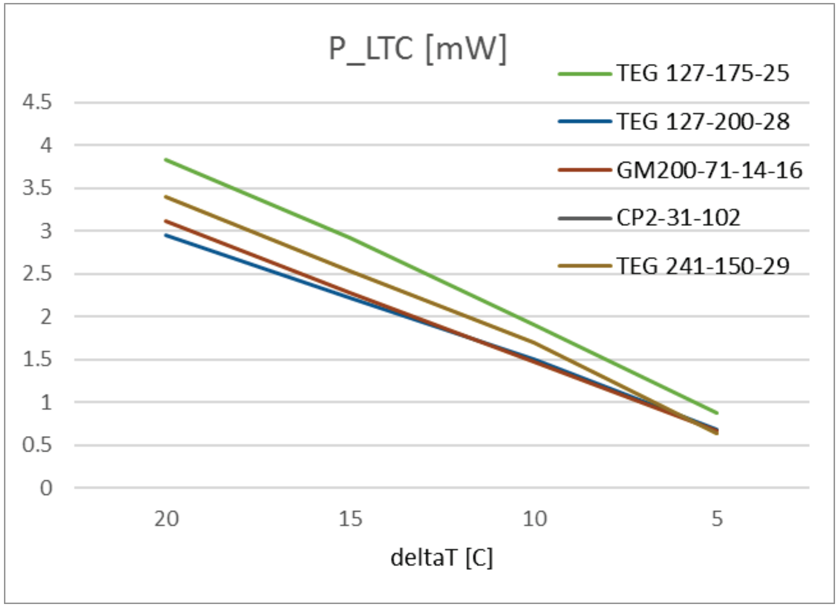

Charger Efficiency vs Input Voltage

Auxiliary Slides: BQ25570 vs LTC3109

- BQ25570
  - MPPT
  - Buck converter



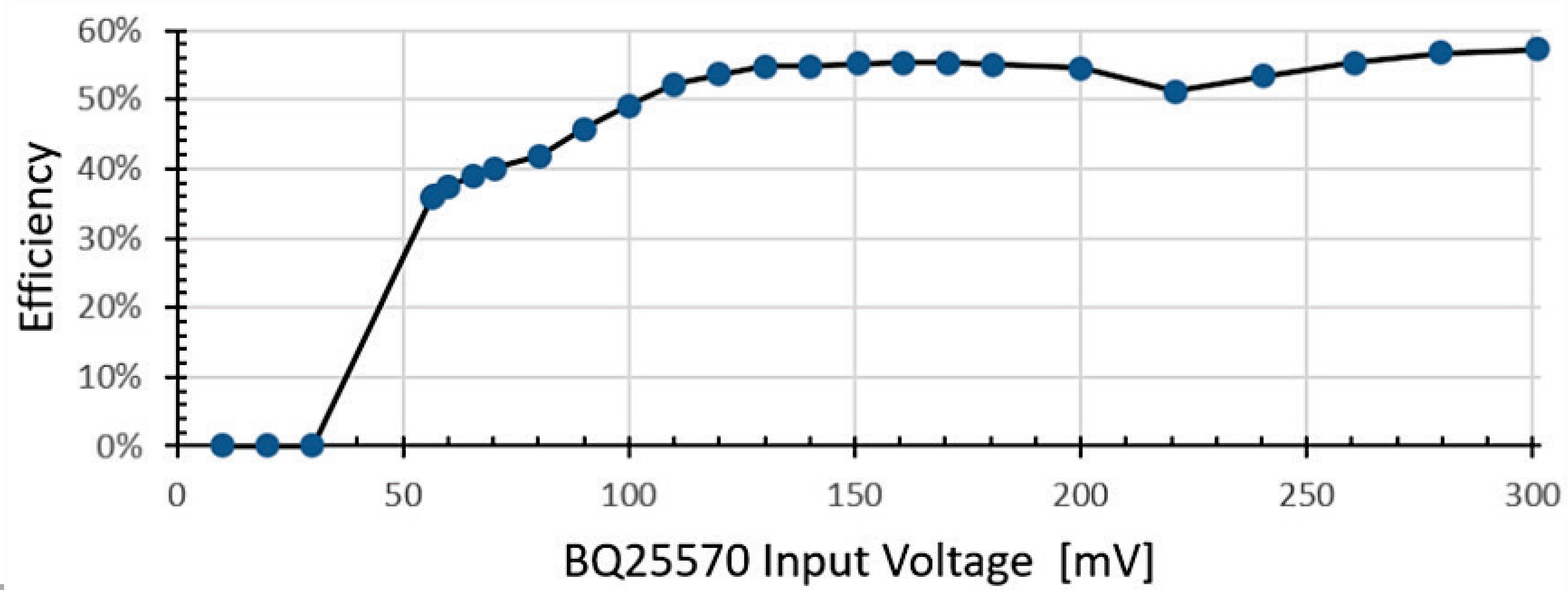
- LTC3109
  - fixed input impedance
  - low-dropout regulator



Boosting Milivolts to Volts

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

Measurement

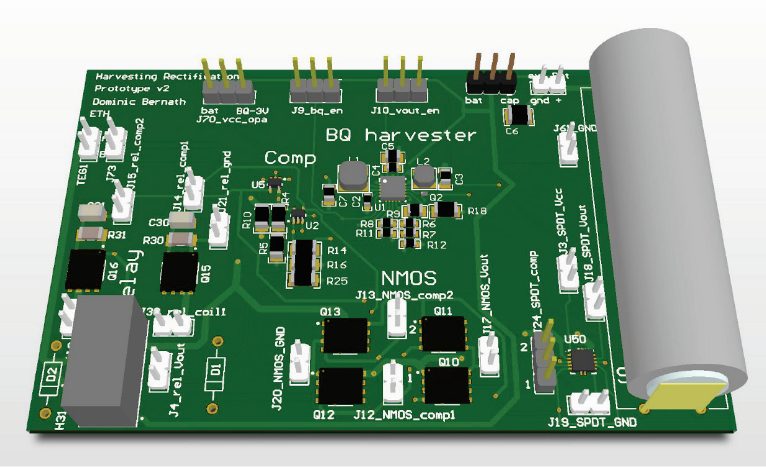


Rectification of TEG Input

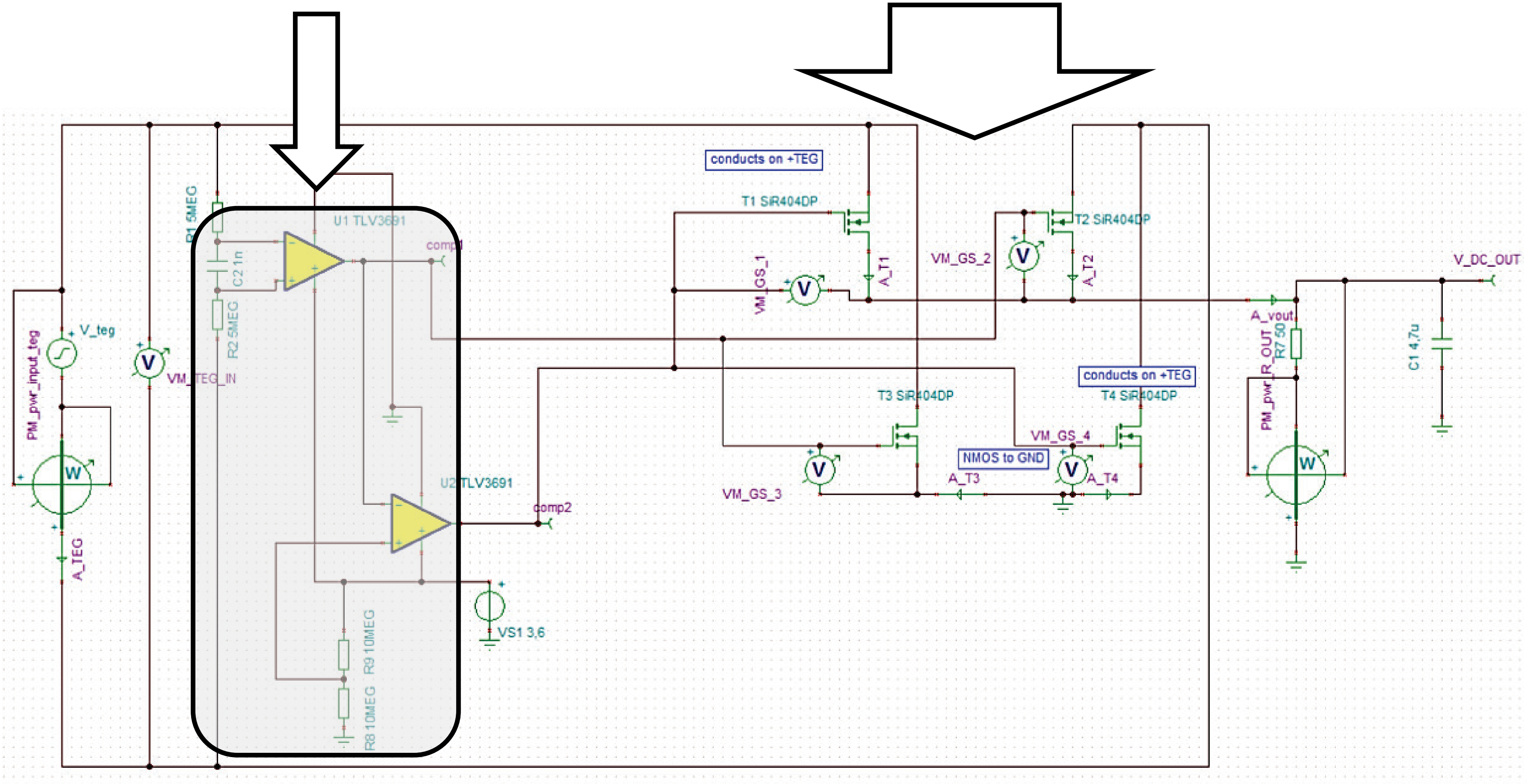
Type	Resistance	Quiescent power	Disadvantage
Passive			
Schottky diode		-	> 70mV forward voltage
Active			
Latching relay	0.2 Ω	23 nW	mechanical sensitivity
SPDT	0.7 Ω	10 nW	high resistance
Mosfet	0.2 Ω	-	not break before make

Gate driver

- Two comparators
- 0.5 µW quiescent power



SPICE Simulation of NMOS H-Bridge Rectifier

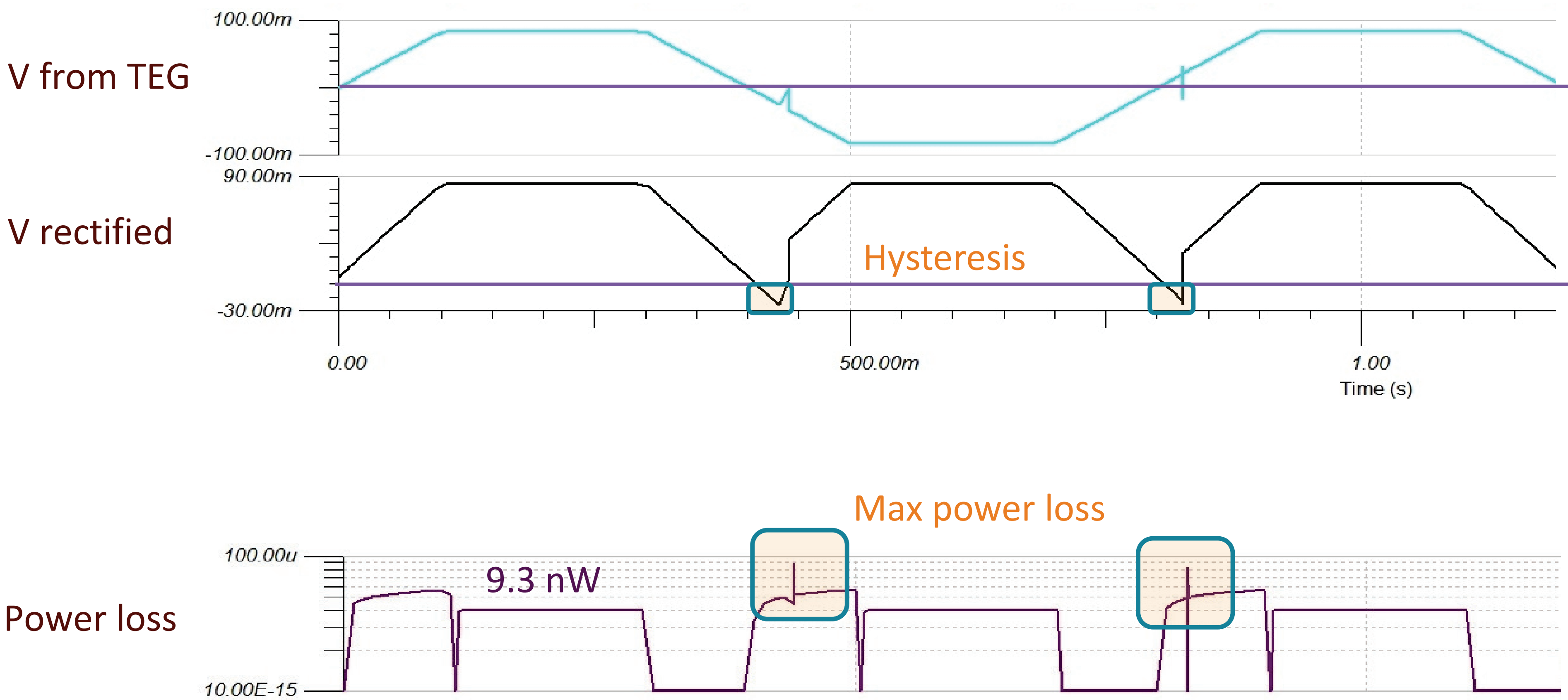


Comparator Gate Drivers

H-Bridge

SPICE Simulation of NMOS H-Bridge Rectifier

Break before make not guaranteed

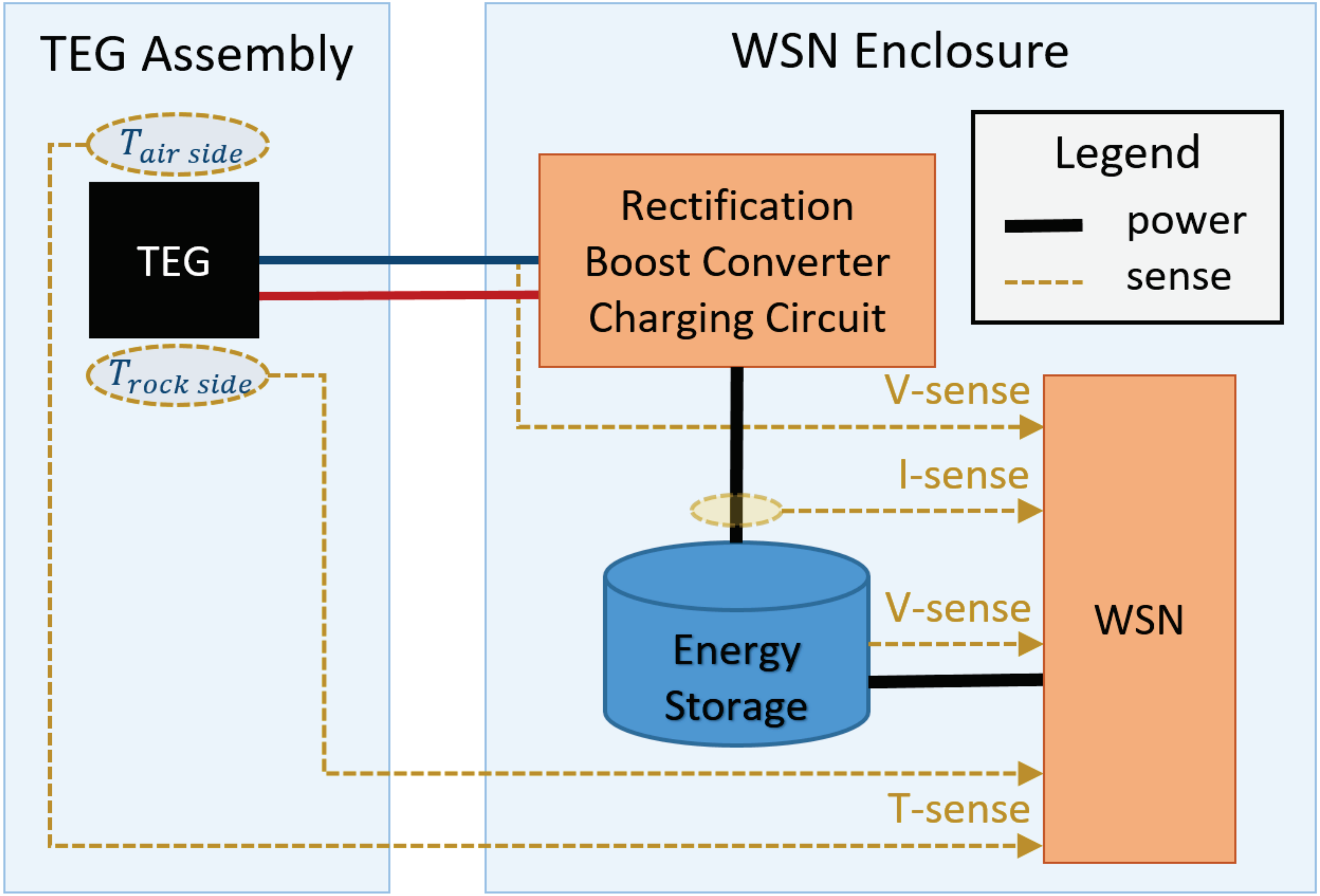


Hysteresis

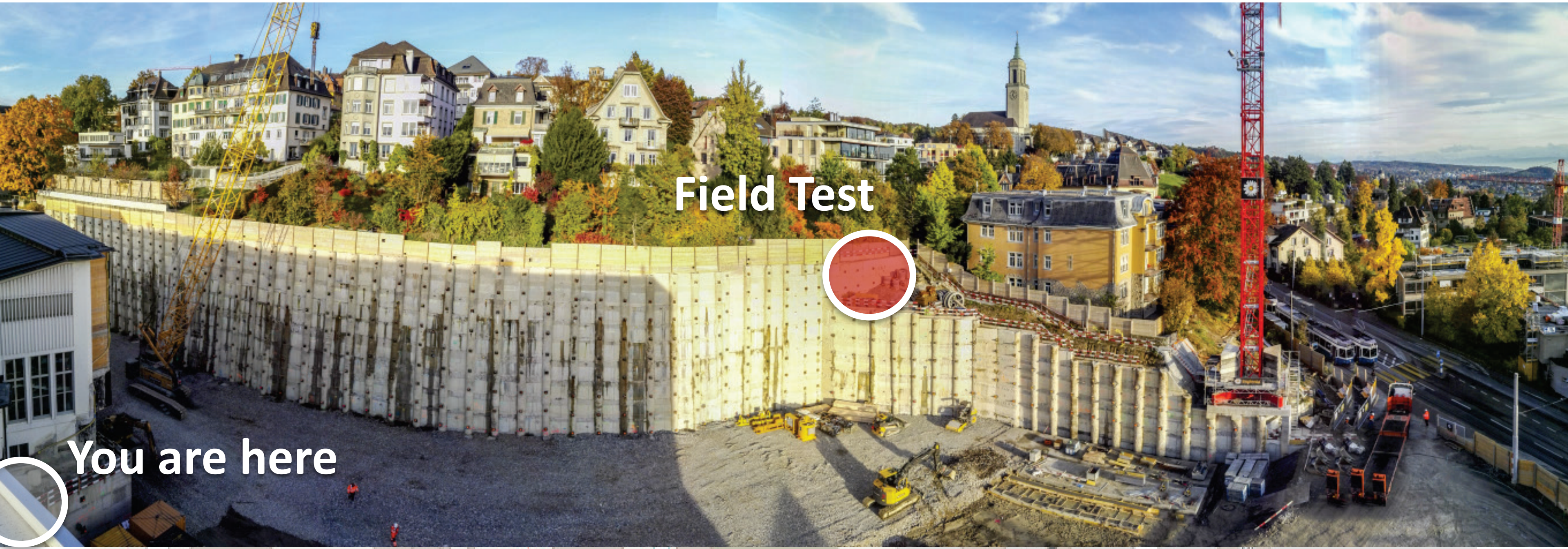
Max power loss

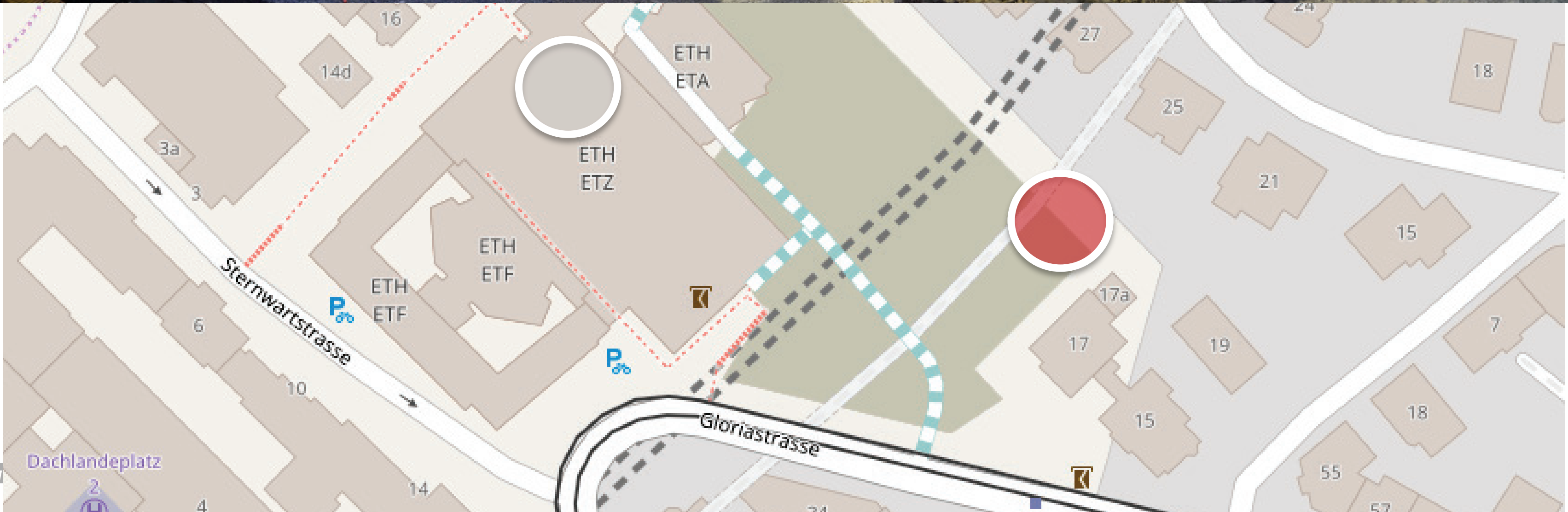
9.3 nW

Electrical Overview



Field Test Site





Field Test – Different Thermal Guides

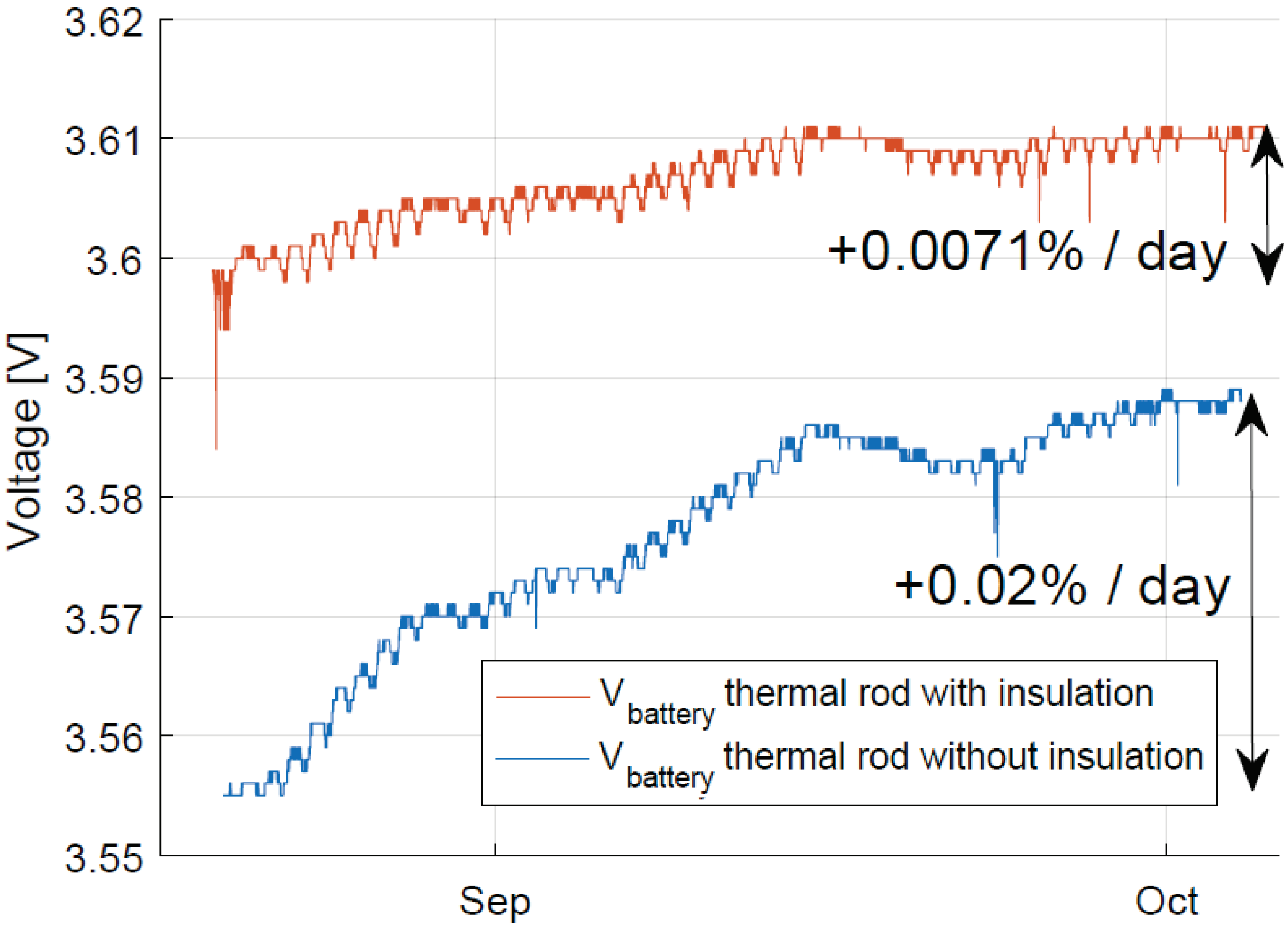
43 days of testing

YES it works!

0.8mW average

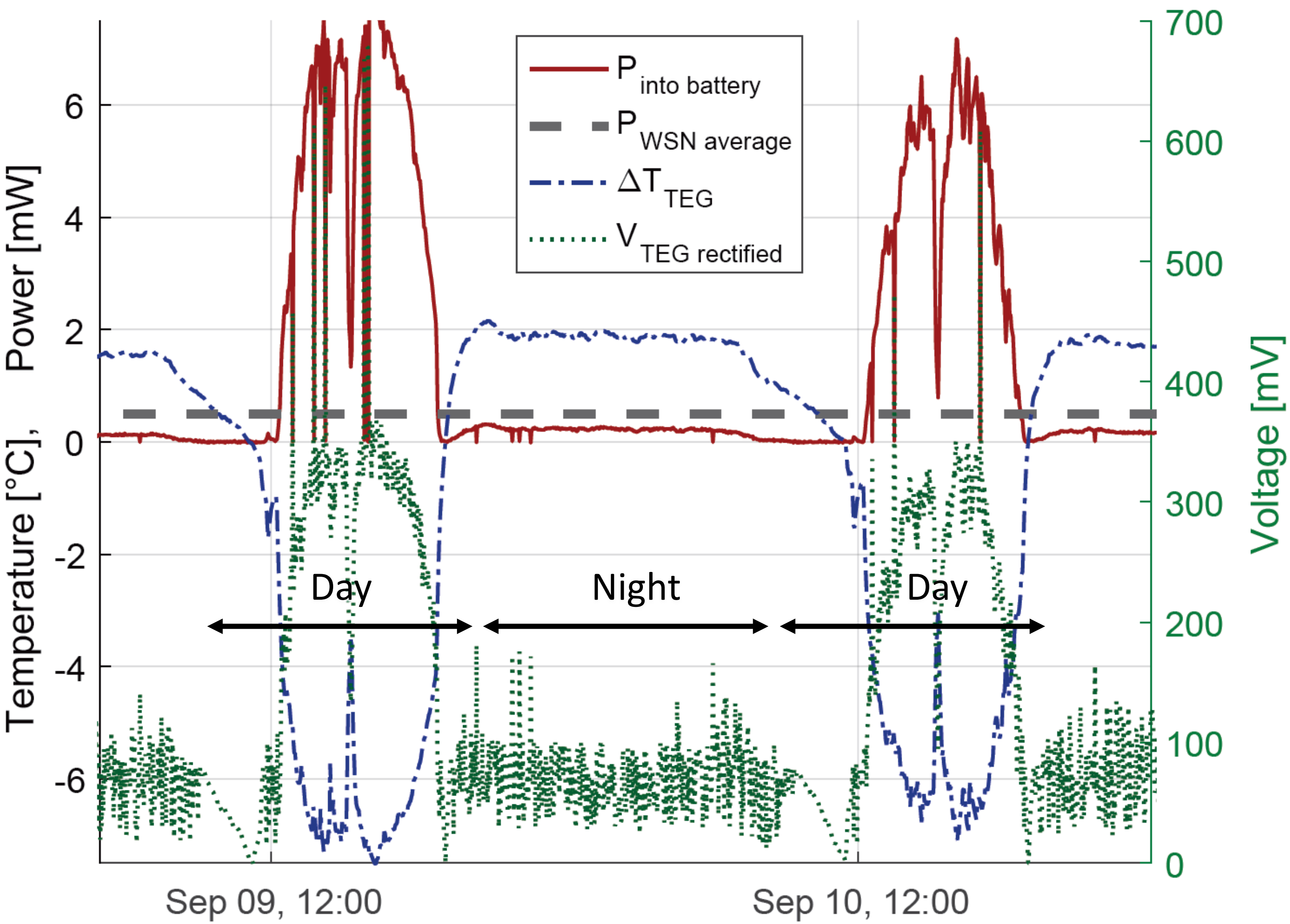
power margin: 61%

Long Term Energy Budget



2.8 times more surplus energy without insulation

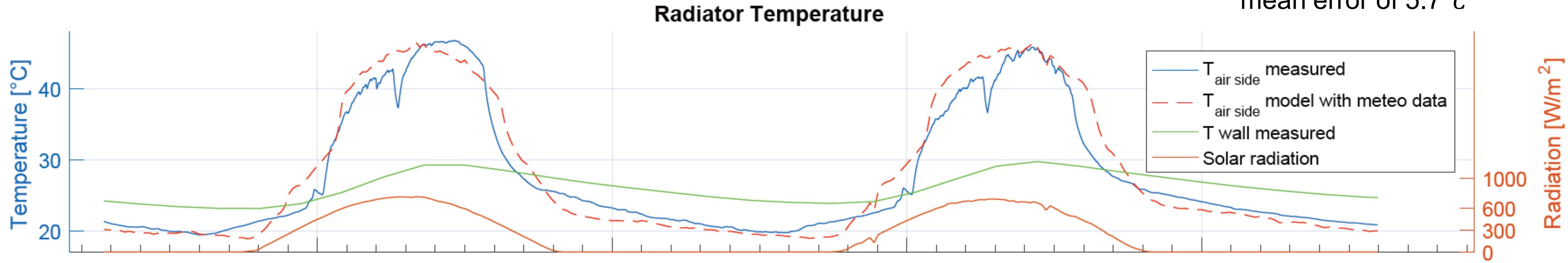
Diurnal Power Generation



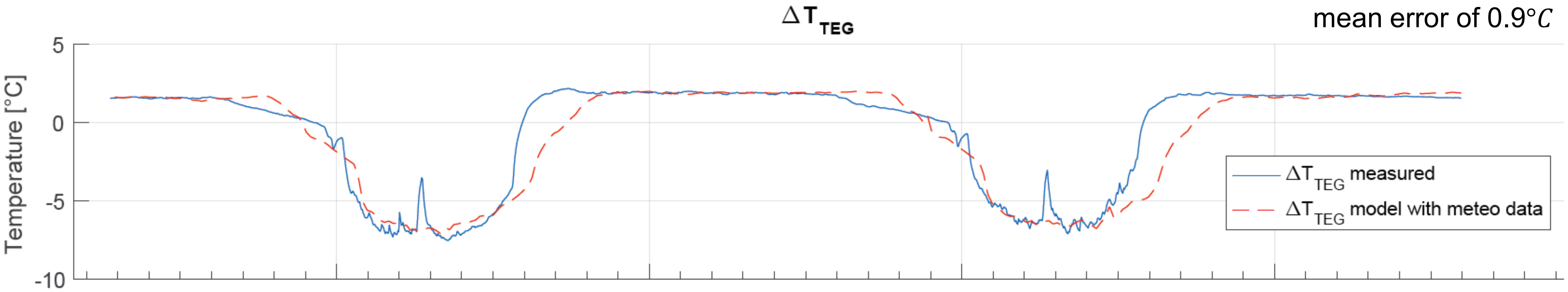
0.8mW mean power

Model Validation

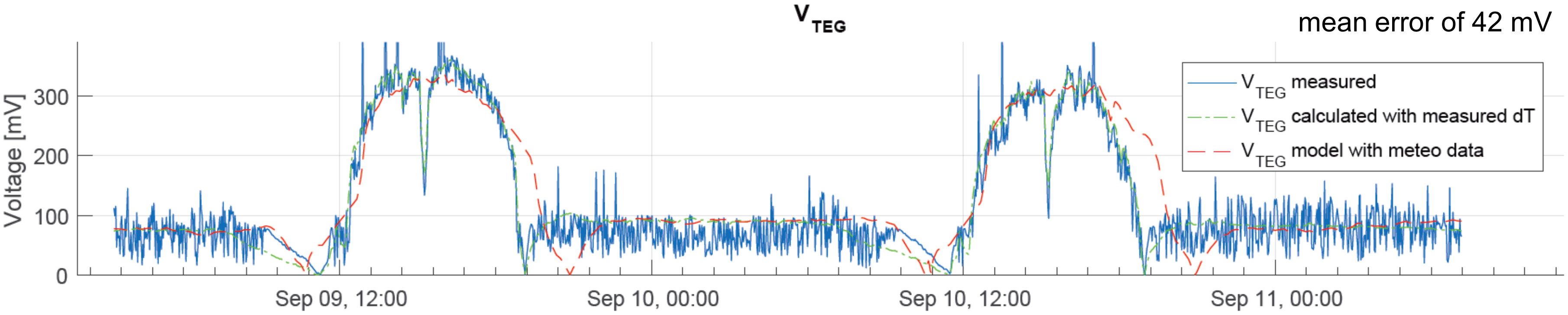
mean error of 5.7°C



mean error of 0.9°C



mean error of 42 mV

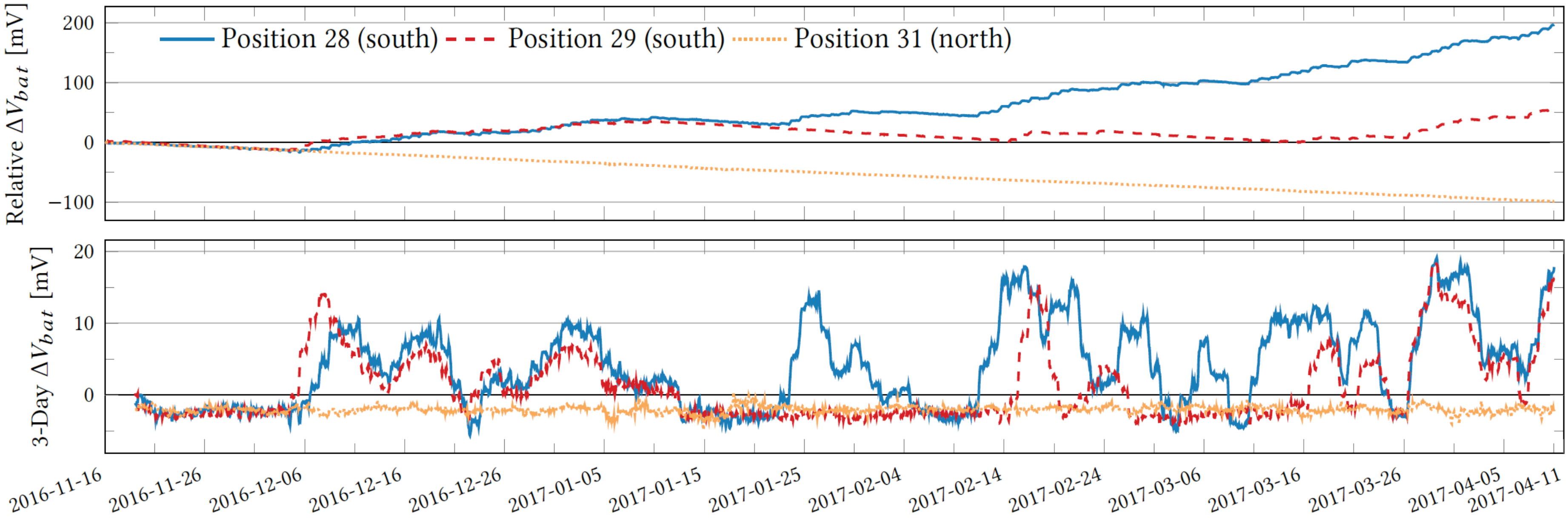


Jungfraujoch Field Test – South

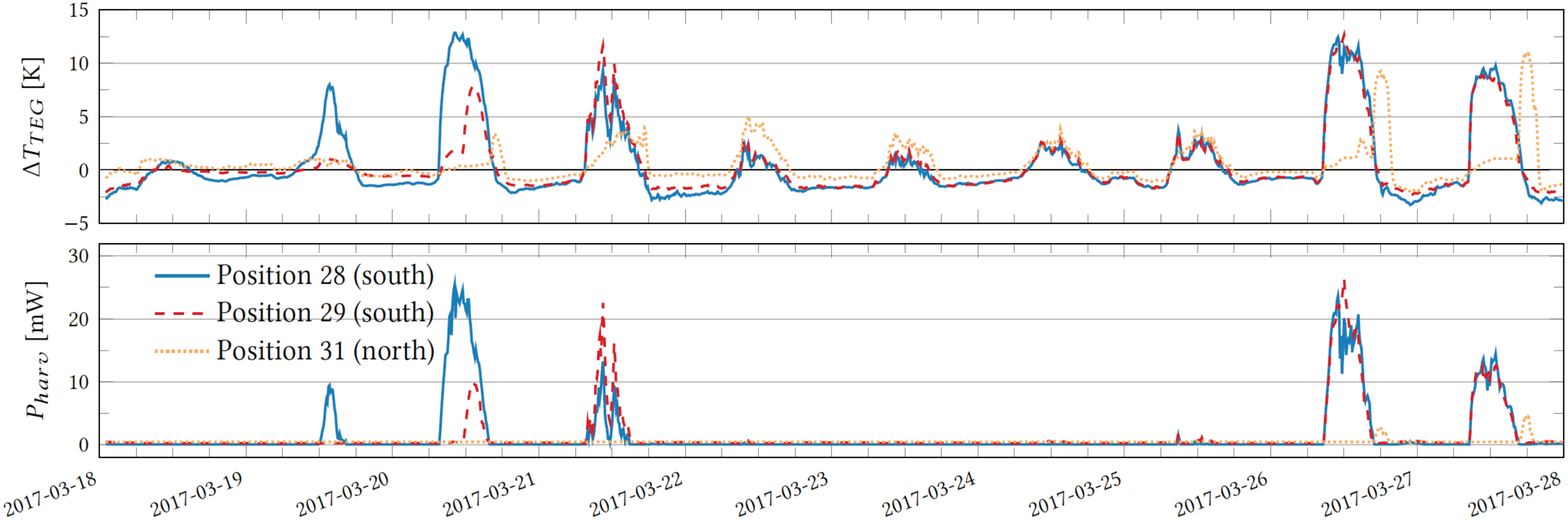
Jungfraujoch Field Test – North

Jungfraujoch Field Test – Partial Snow Cover

Long-term Evolution: Steady Charging



Short-term Differences on Meter-scale



Performance of TEG Generator

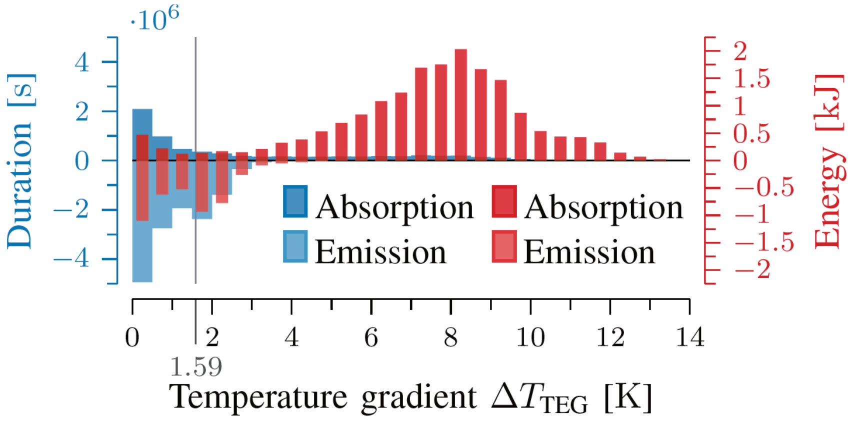


Figure 11. Histogram of temperature gradients and generated energy during 237 days, SE facing sensor node deployment.

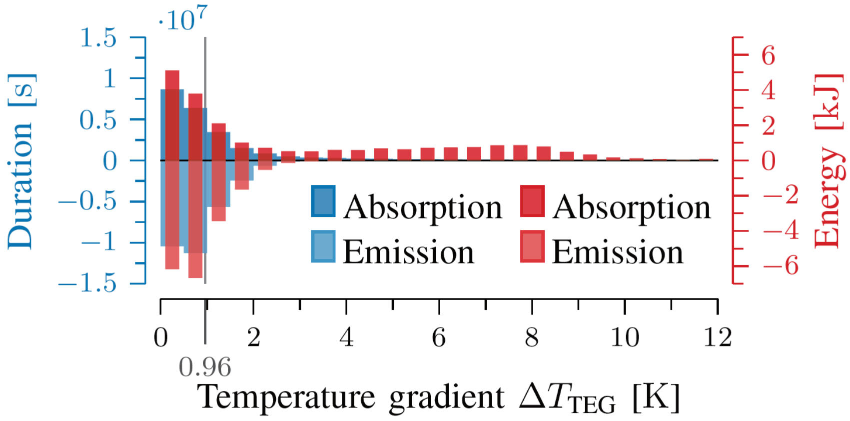


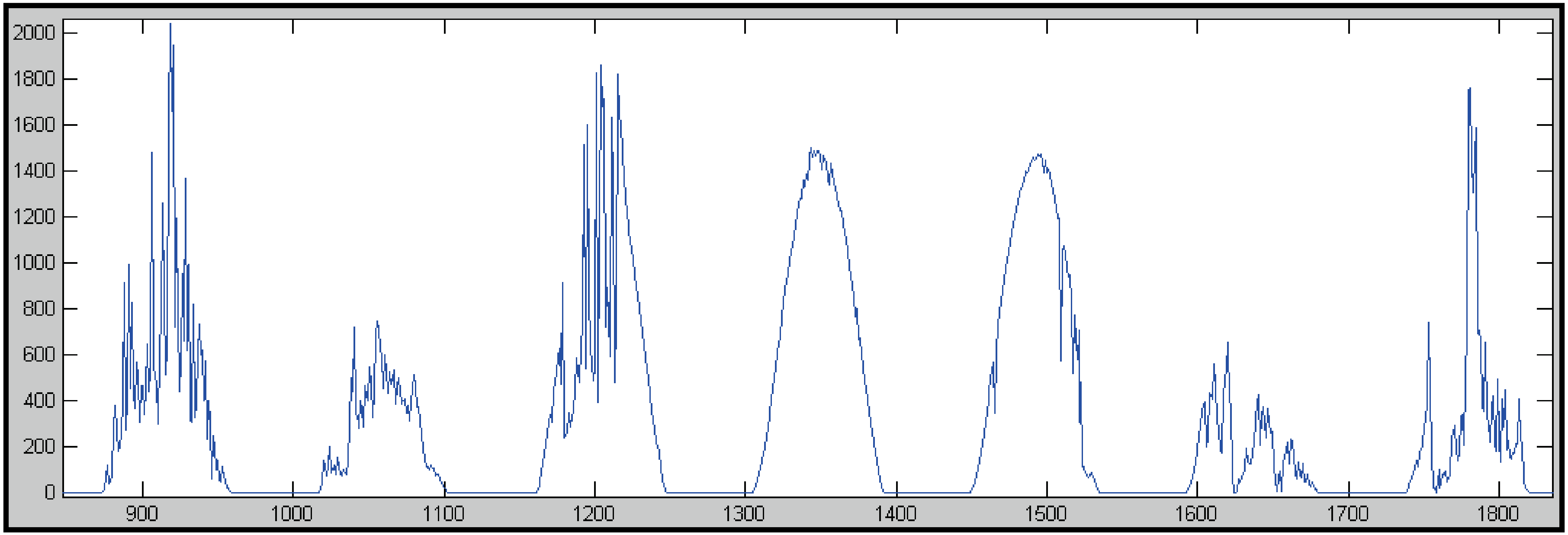
Figure 12. Histogram of temperature gradients and generated energy during 625 days, NW facing sensor node deployment.

Low-Power System Design

MODELING ENERGY USAGE – HARVESTING CONTROL

Harvesting Control: What is Different?

- Conventional energy management:
  - How do we **save** energy ?
- Energy harvesting:
  - When do we **use** energy ?



[Sunergy: June 2006]

Harvesting Control: Problem Definition

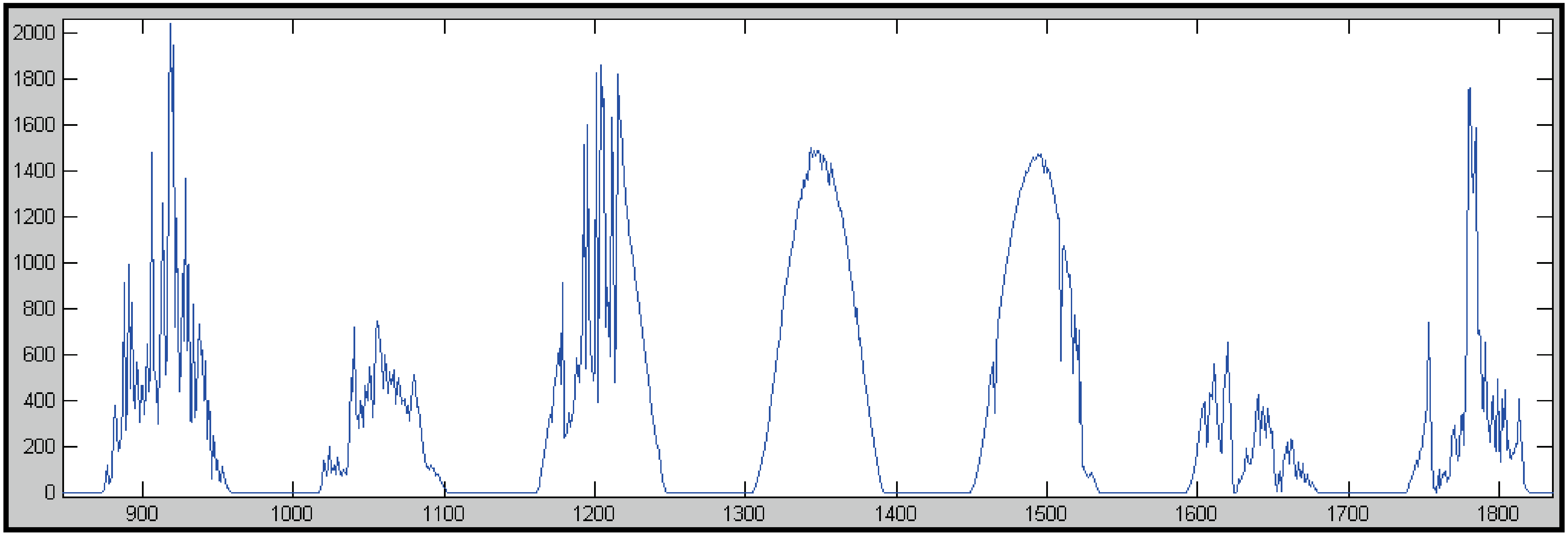
Determine **decisions on the application level** that
optimize the long term system behavior

sensing rate

data throughput

required overhead

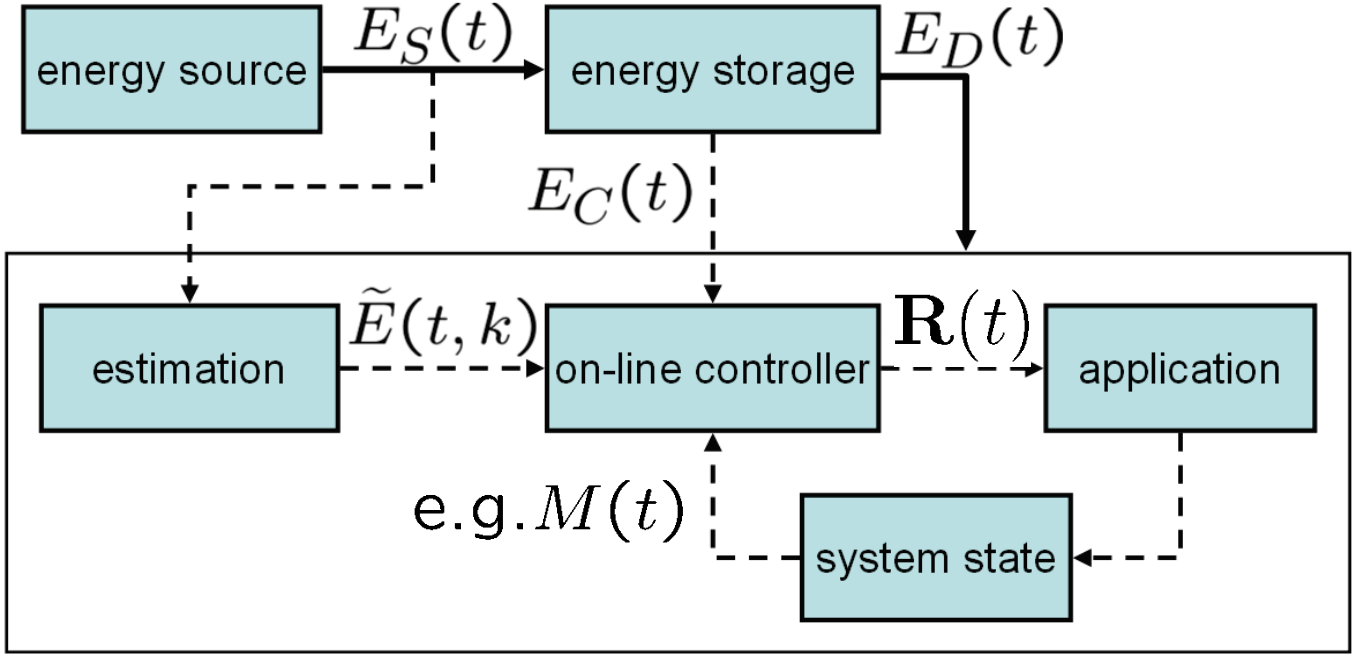
Latency/reactivity



[Sunergy: June 2006]

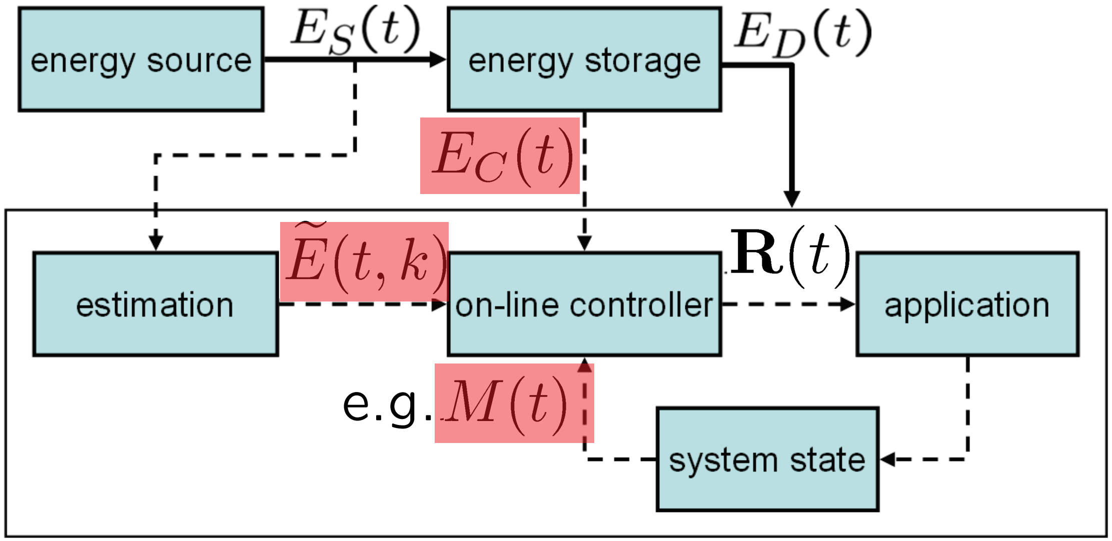
ETH zürich

Harvesting Control: System Model



Optimization: MP-Linear Programming

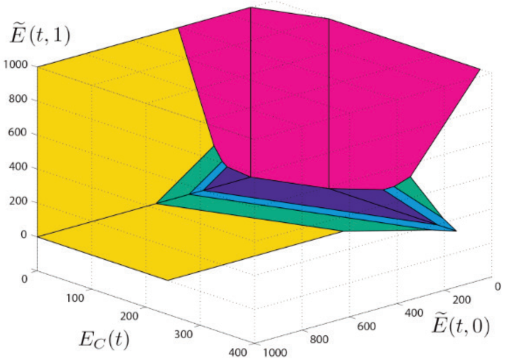
- Efficient run-time implementation by applying multiparametric linear programming
- Idea: Calculate optimal solution of the mp-LP as an explicit function of the state vector

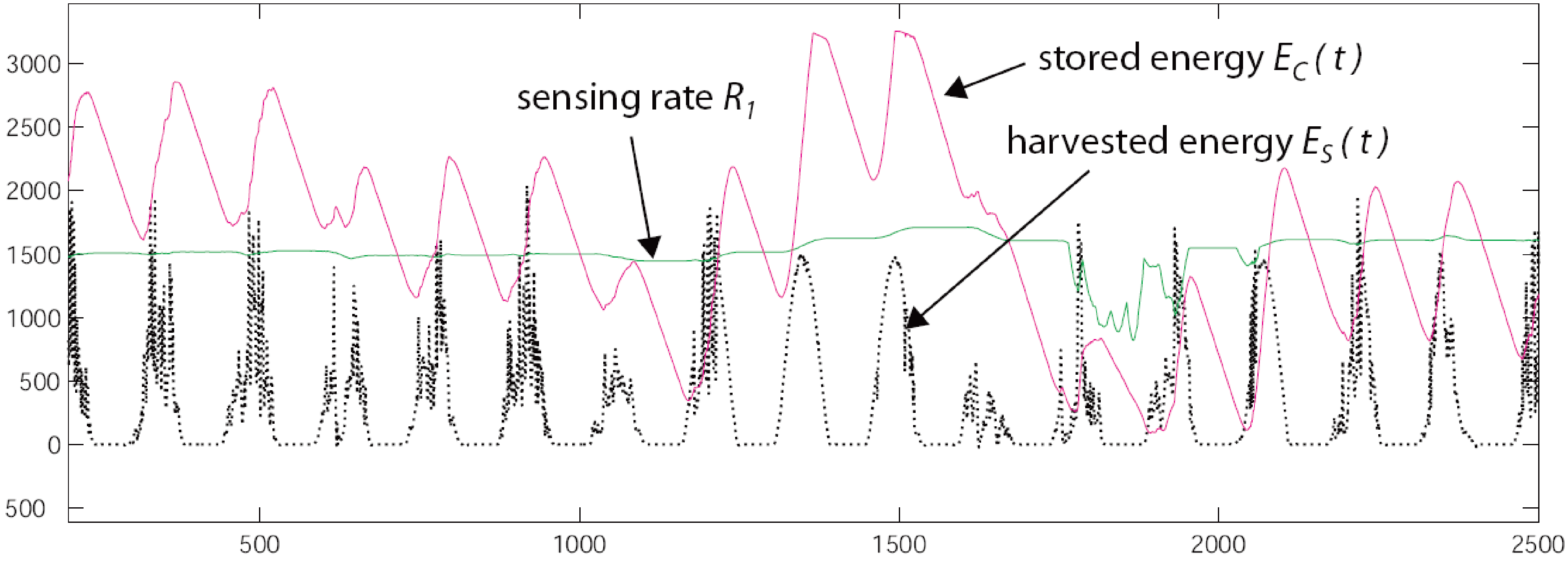


Simulation Results

- Adaptation of sensing rate depending on energy availability

$$\mathbf{H}_i\mathbf{X}(t) \le \mathbf{K}_i, i = 1, \ldots, N_{CR} = 7$$



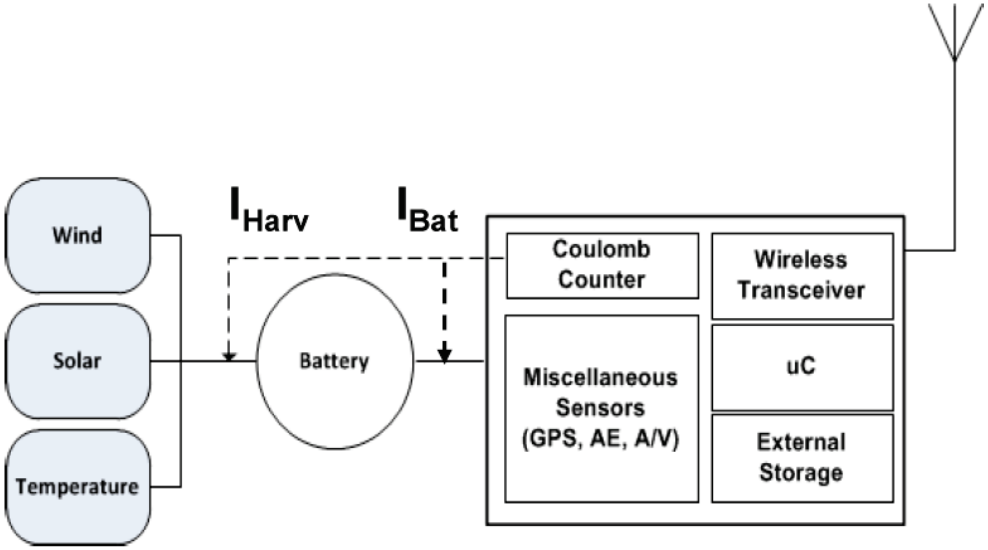


Low-Power System Design

MODELING BATTERY STATE OF CHARGE

Battery State-of Charge Approximation

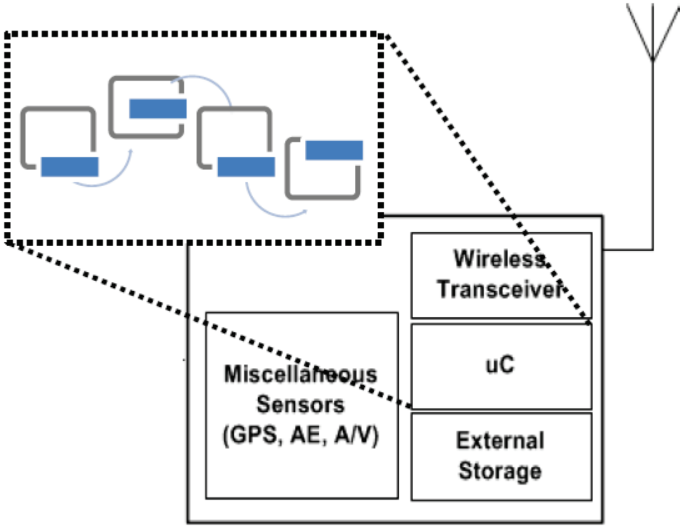
- Hardware
  - Coulomb counting



SOC Approach	Dedicated Hardware	Integration Effort	Account for Battery Inefficiencies
Pure HW	Yes	High	No
Pure SW			
Hybrid CC			
This work			

Battery State-of Charge Approximation

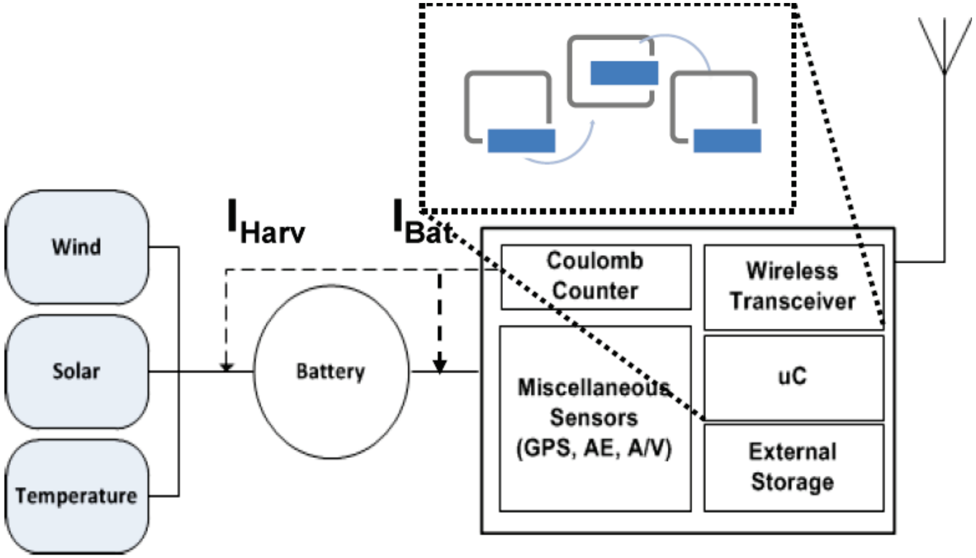
- Hardware
  - Coulomb counting
- Software
  - State monitoring, profiling



SOC Approach	Dedicated Hardware	Integration Effort	Account for Battery Inefficiencies
Pure HW	Yes	High	No
Pure SW	No	Low	No
Hybrid CC			
This work			

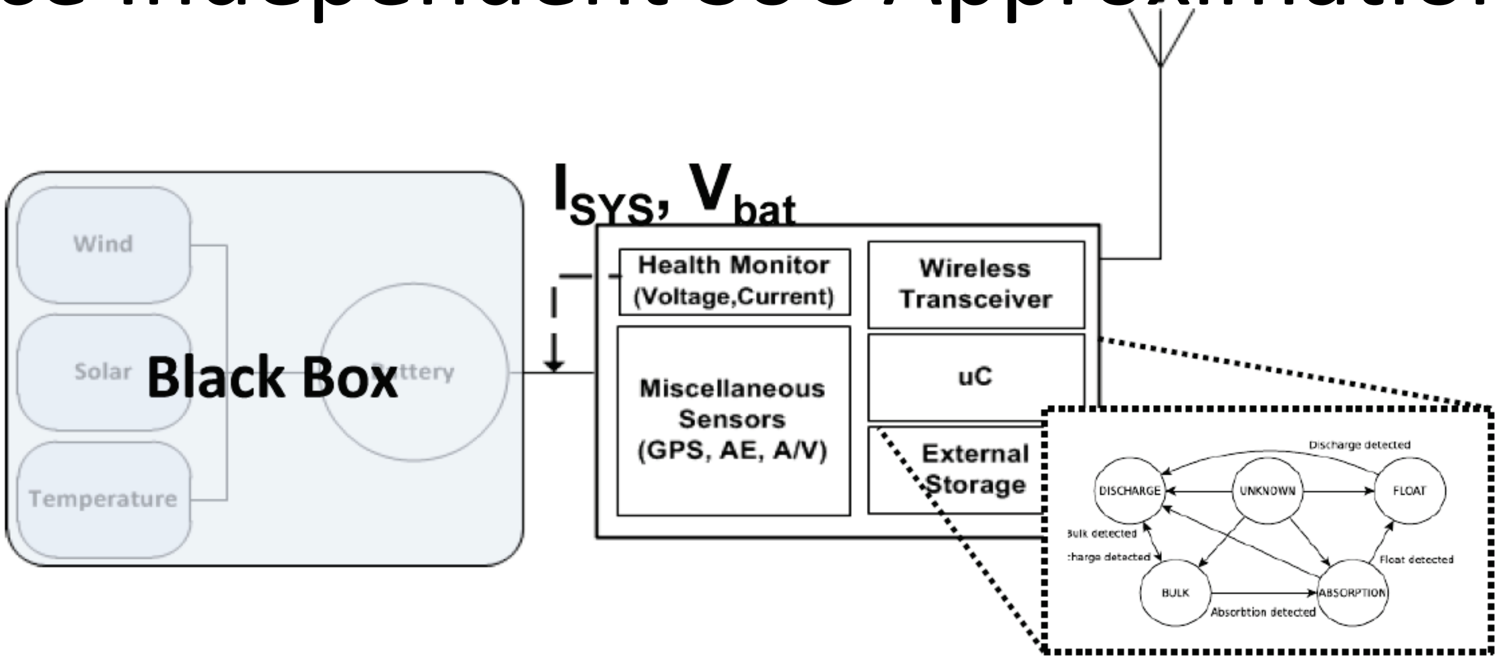
Battery State-of Charge Approximation

- Pure HW
  - Coulomb counting
- Pure SW
  - State monitoring, profiling
- Hybrid HW/SW
  - Bookkeeping



SOC Approach	Dedicated Hardware	Integration Effort	Account for Battery Inefficiencies
Pure HW	Yes	High	No
Pure SW	No	Low	No
Hybrid CC	Yes	High	Yes
This work			

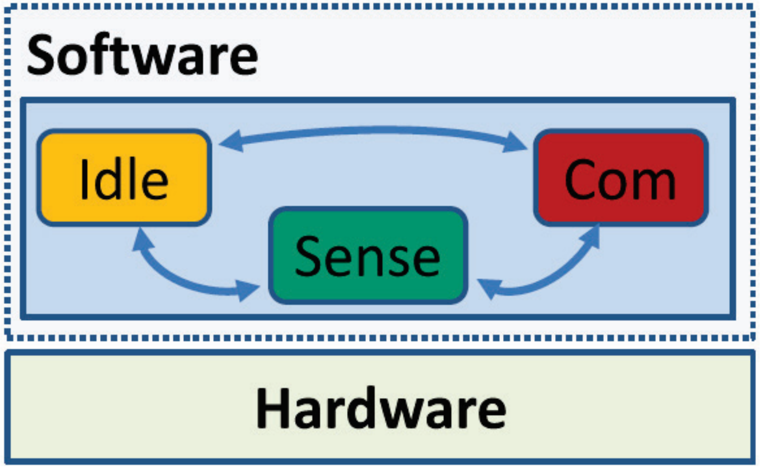
Source Independent SoC Approximation



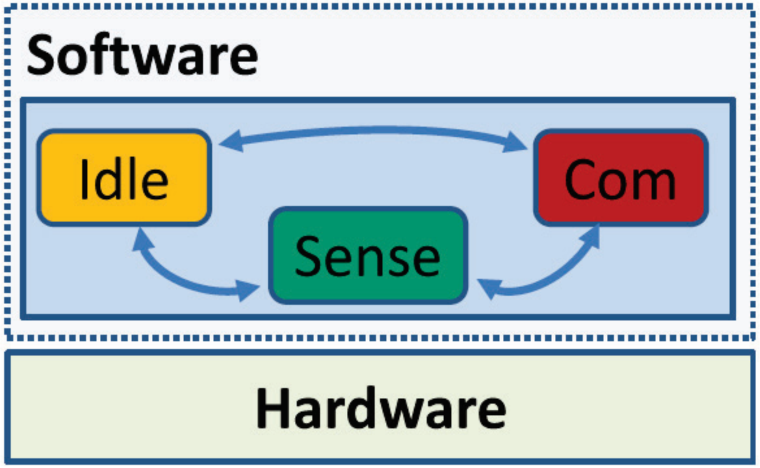
SOC Approach	Dedicated Hardware	Integration Effort	Account for Battery Inefficiencies
Pure HW	Yes	High	No
Pure SW	No	Low	No
Hybrid CC	Yes	High	Yes
This work	No	Low	Yes

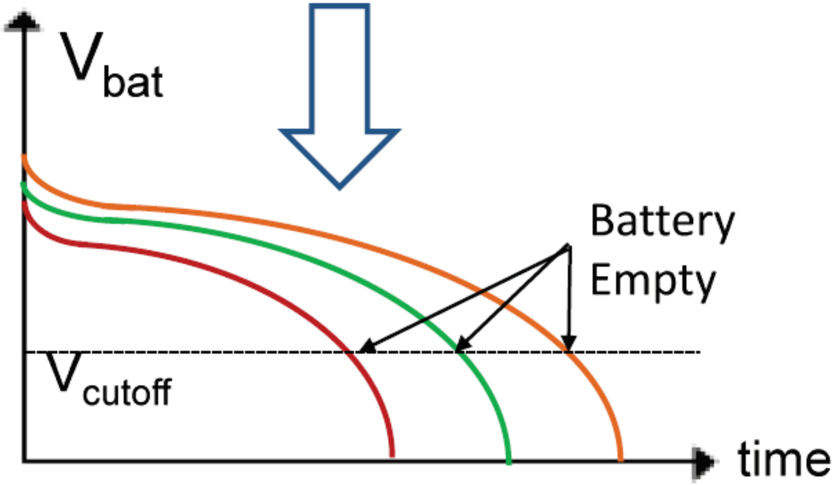
[B. Buchli, D. Aschwanden and J. Beutel: Battery State-of-Charge Approximation for Energy Harvesting Embedded Systems. Lecture Notes on Computer Science. Proc. of 10th European Conference on Wireless Sensor Networks (EWSN 2013), p. 179-196, February 2013.]

Abstract System As State-Machine

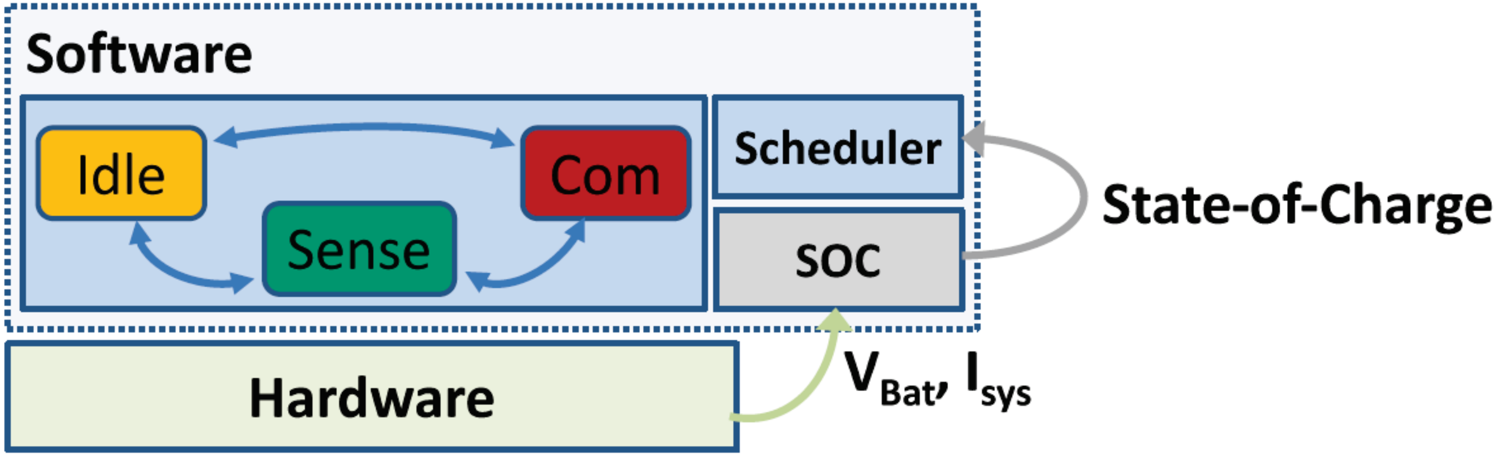


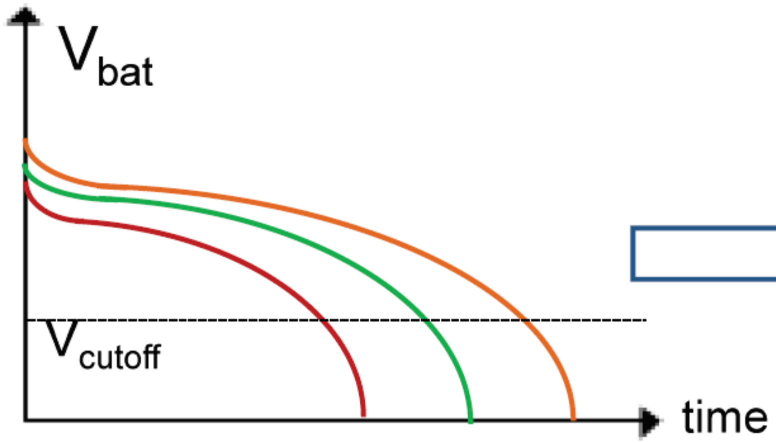
States Exhibit Voltage Profile “Signature”

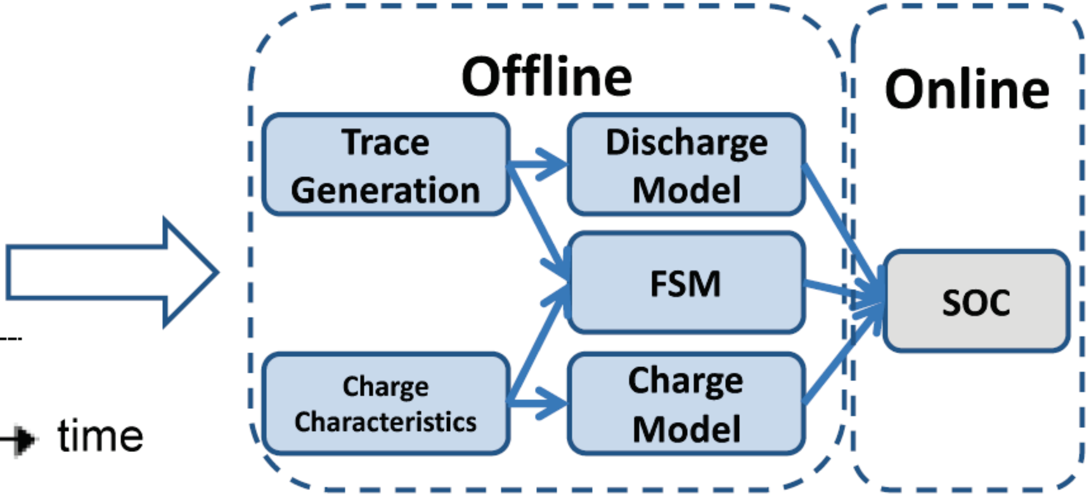




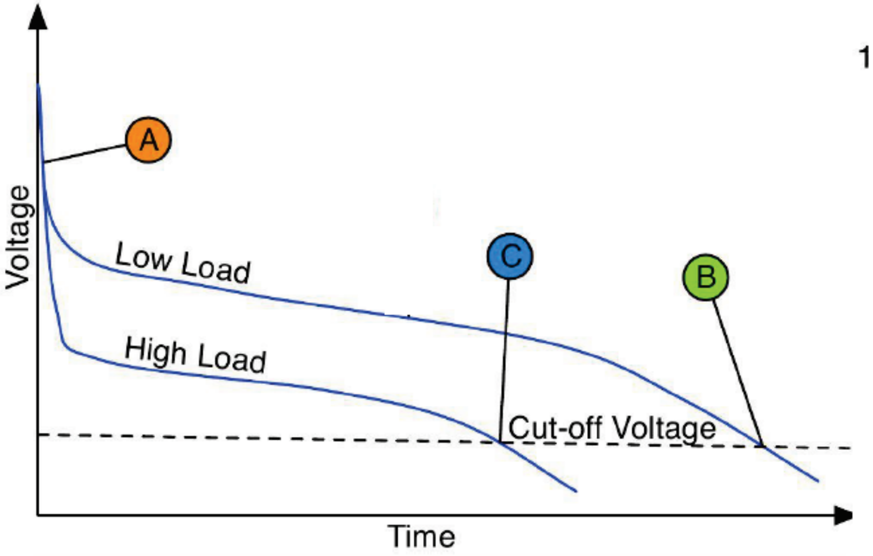
Online State-of-Charge Information for Energy-Aware Scheduling

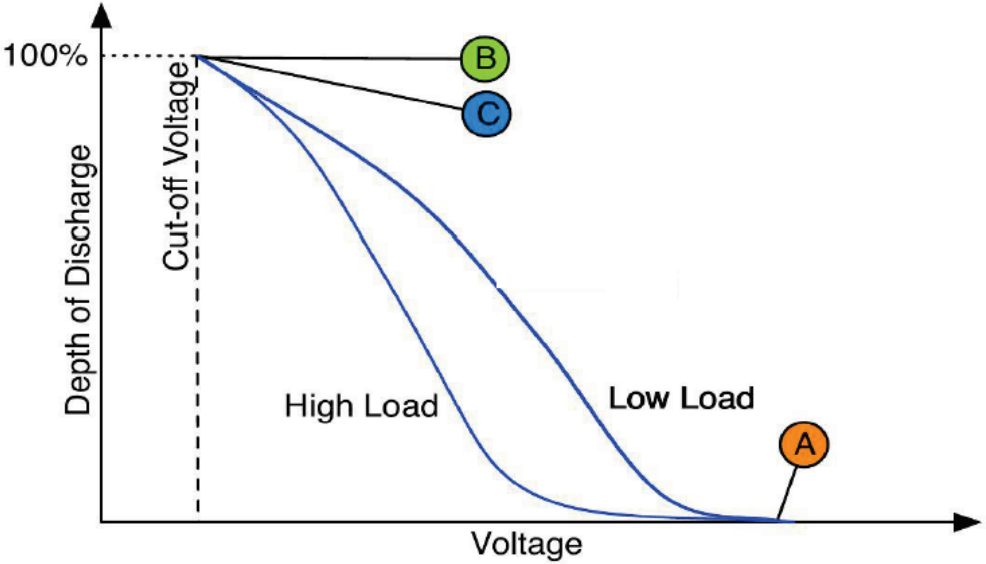


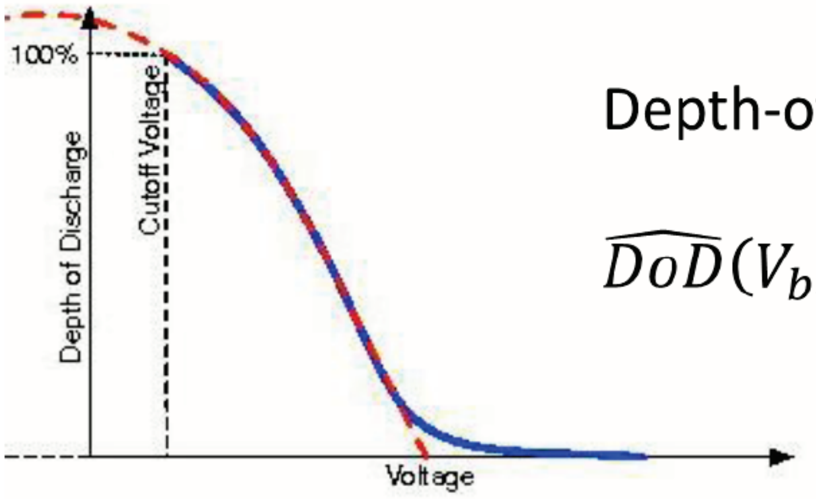




Proposed Approach: Trace Generation and Transformation



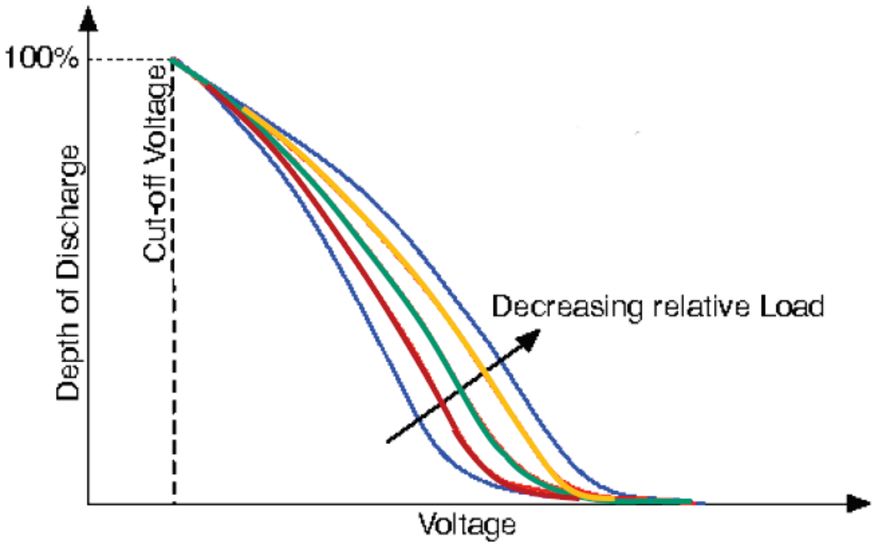


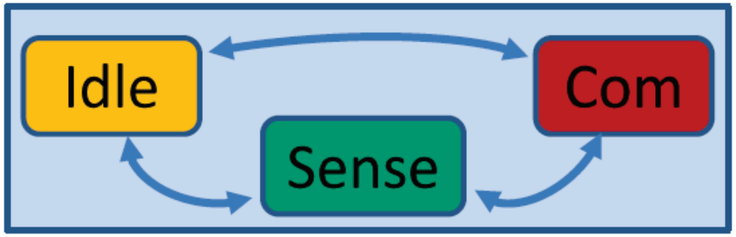


Depth-of-Discharge = $DOD = 1 - \text{SOC}$

$$\widehat{DoD}(V_{bat}) = a_2 * {V_{bat}}^2 + a_1 * V_{bat} + a_0$$

Proposed Approach: Discharge Model



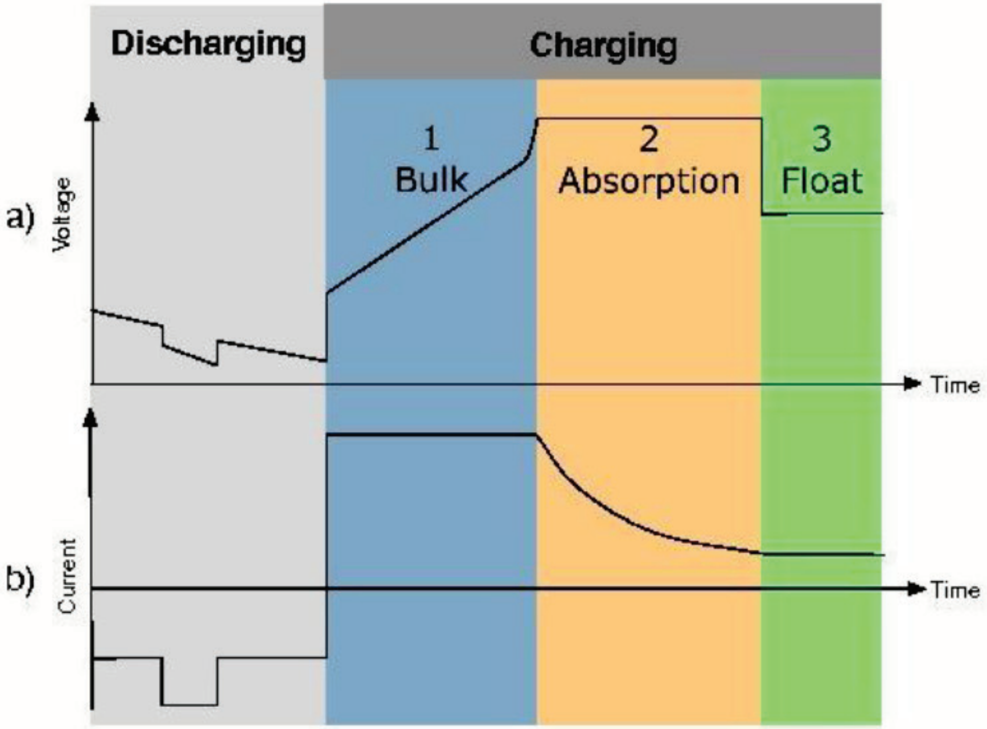


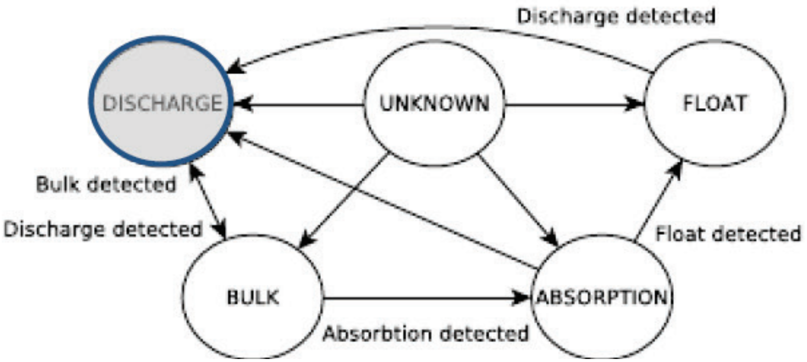
$$Relative\ Load = RL = \frac{Drain\ Current}{Nom.Bat.Cap.}$$

$$\widehat{DoD}(V_{bat}, RL) = a_2(RL) * {V_{bat}}^2 + a_1(RL) * V_{bat} + a_0(RL)$$

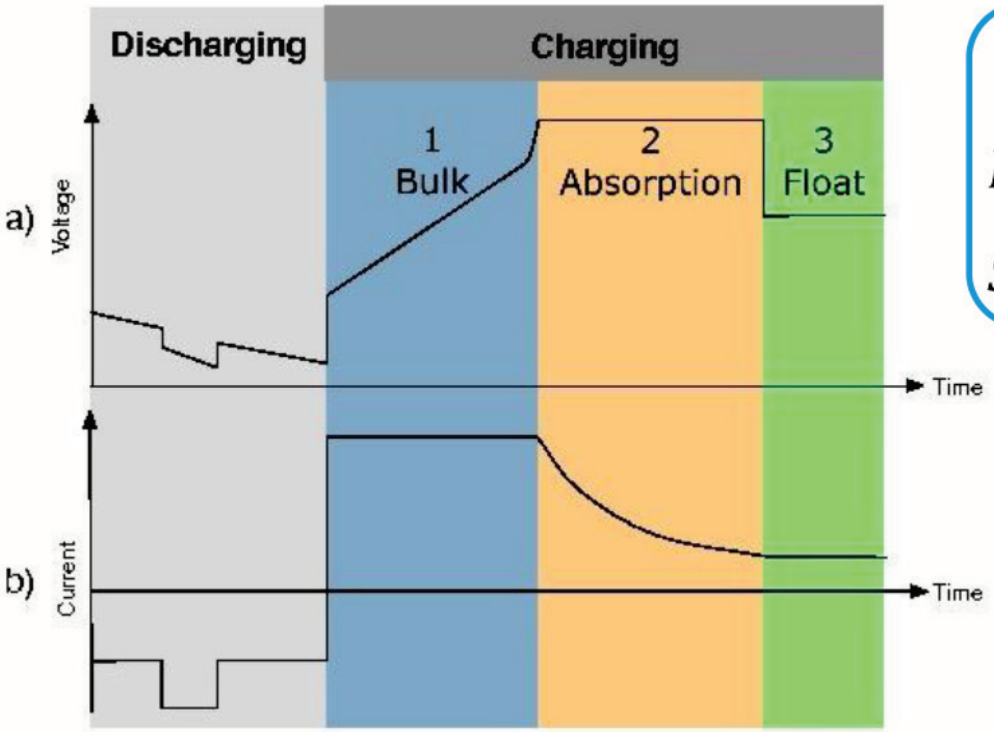
$$a_n(RL) = b_{n,2} * RL^2 + b_{n,1} * RL + b_{n,0}, for\ n = 0,1,2$$

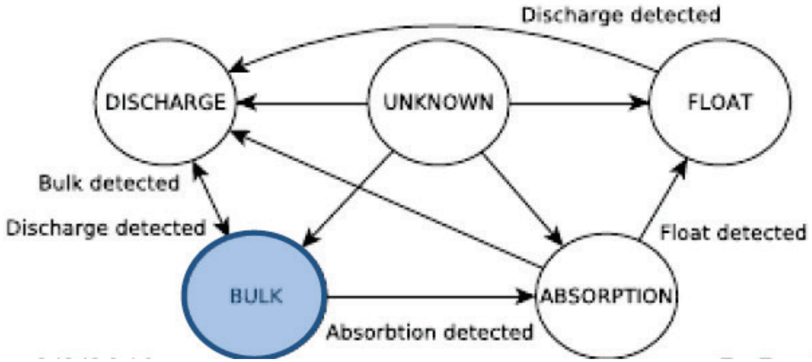
Proposed Approach: Charge Model





Proposed Approach: Charge Model



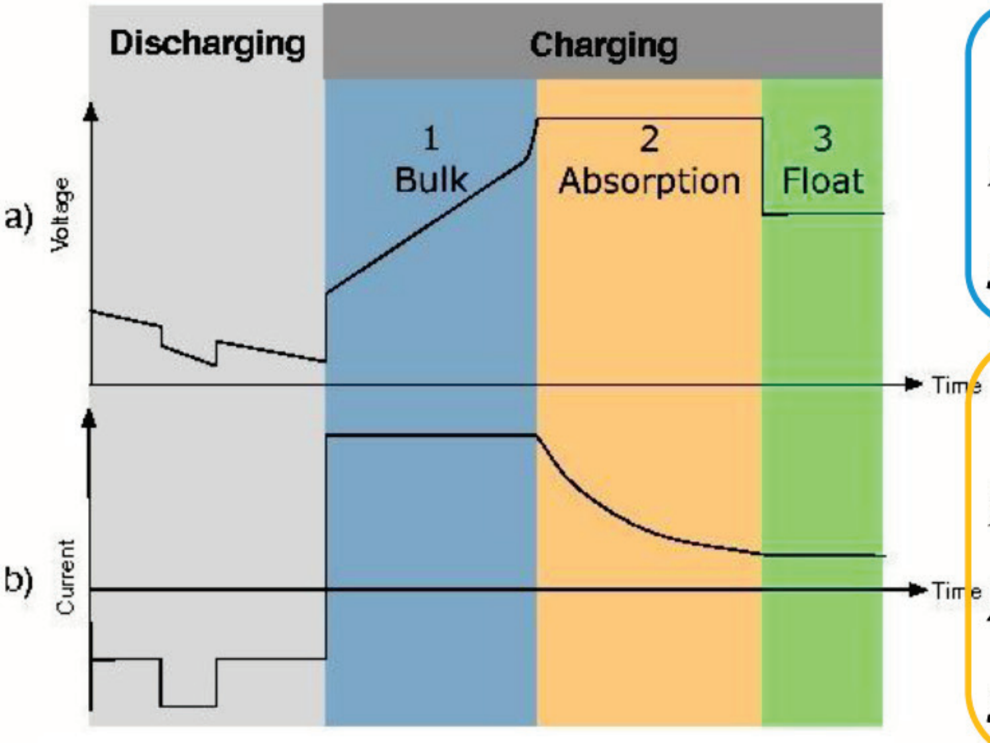


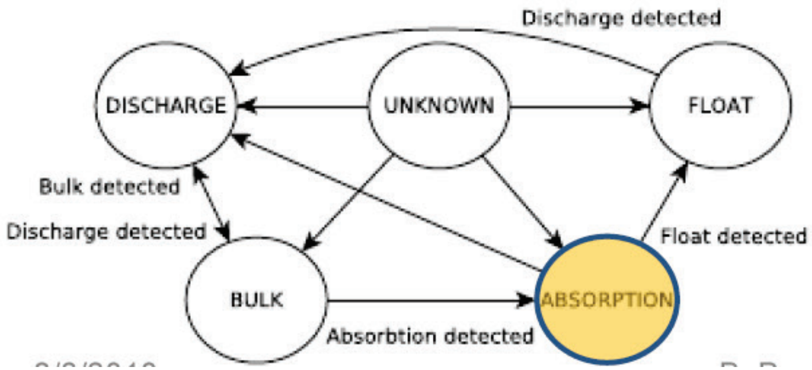
Bulk:

$$\widehat{RC}_{bulk} = c_1 * \frac{\delta V}{\delta t} + c_0$$

$$\widehat{SOC}(\mathrm{t}) = \widehat{SOC}(\mathrm{t} - t_{bulk}) + \widehat{RC}_{bulk} * t_{bulk}$$

Proposed Approach: Charge Model





Bulk:

$$\widehat{RC}_{bulk} = c_1 * \frac{\delta V}{\delta t} + c_0$$

$$\widehat{SOC}(\mathrm{t}) = \widehat{SOC}(\mathrm{t} - t_{bulk}) + \widehat{RC}_{bulk} * t_{bulk}$$

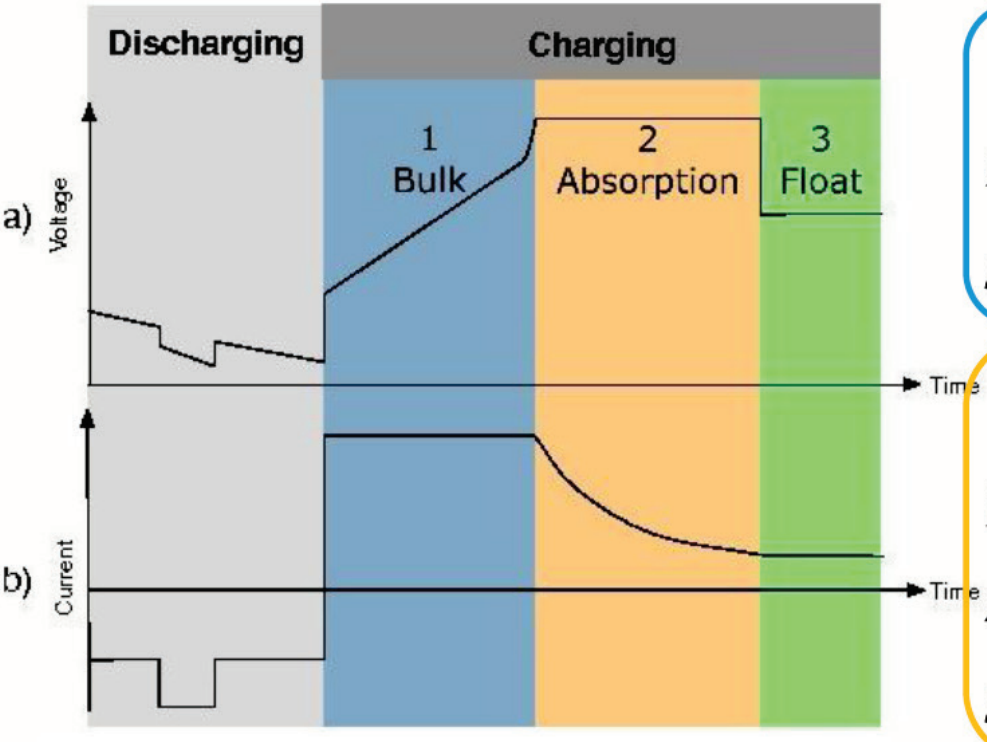
Absorption:

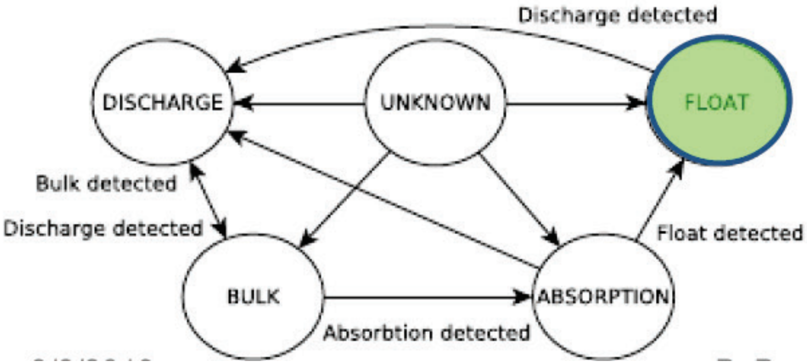
$$\widehat{RC}_{abs}(t) = \widehat{RC}_{bulk} * e^{(\lambda(\widehat{RC}_{bulk}) * t_{abs})}$$

$$\lambda\left(\widehat{RC}_{bulk}\right) = d_1 * \widehat{RC}_{bulk} + d_0$$

$$\widehat{SOC}(\mathrm{t}) = \widehat{SOC}(\mathrm{t} - t_{abs}) + \widehat{RC}_{abs} * t_{abs}$$

Proposed Approach: Charge Model





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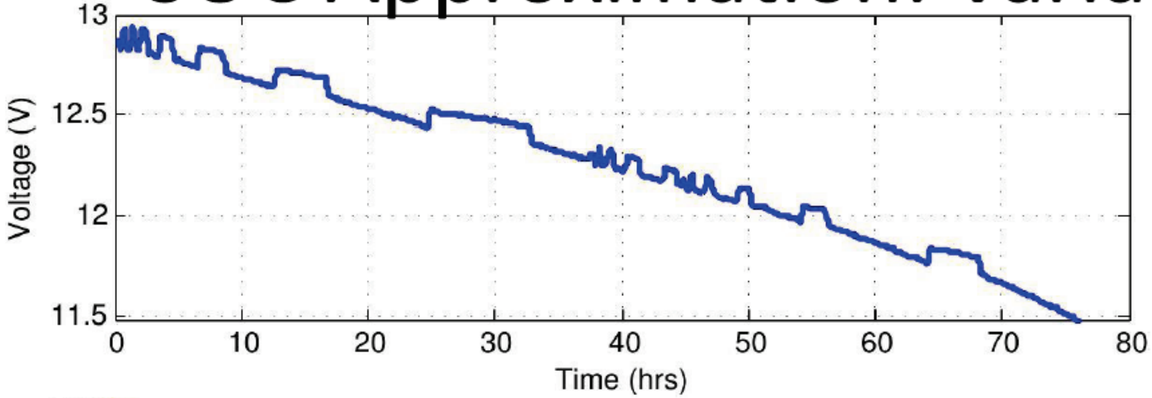
$$\lambda\left(\widehat{RC}_{bulk}\right) = d_1 * \widehat{RC}_{bulk} + d_0$$

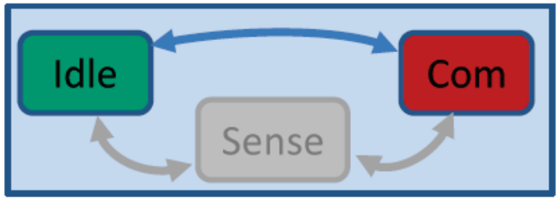
$$\widehat{SOC}(\mathrm{t}) = \widehat{SOC}(\mathrm{t} - t_{abs}) + \widehat{RC}_{abs} * t_{abs}$$

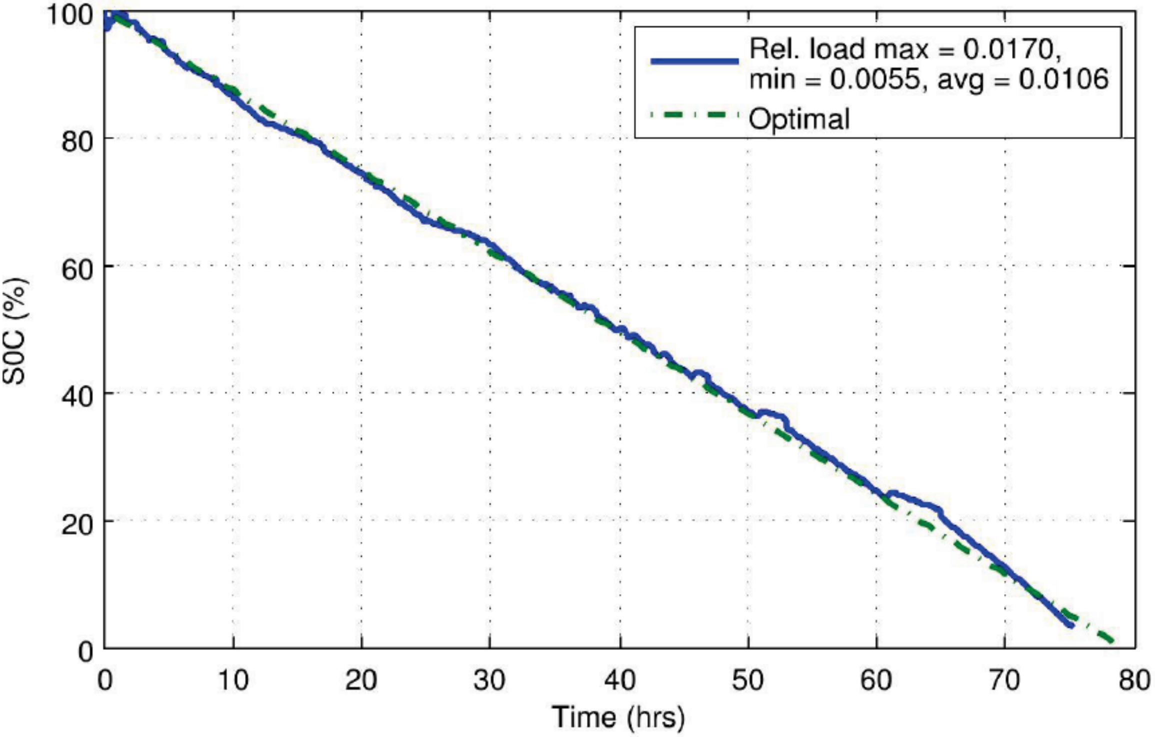
Float:

$$\widehat{SOC}(\mathrm{t}) = 100\%$$

SOC Approximation: Variable Load (BAT 3)







SOC estimation error (%):

Max	Min	Mean	Var.	Std.
4.98	-0.79	3.02	4.53	2.13

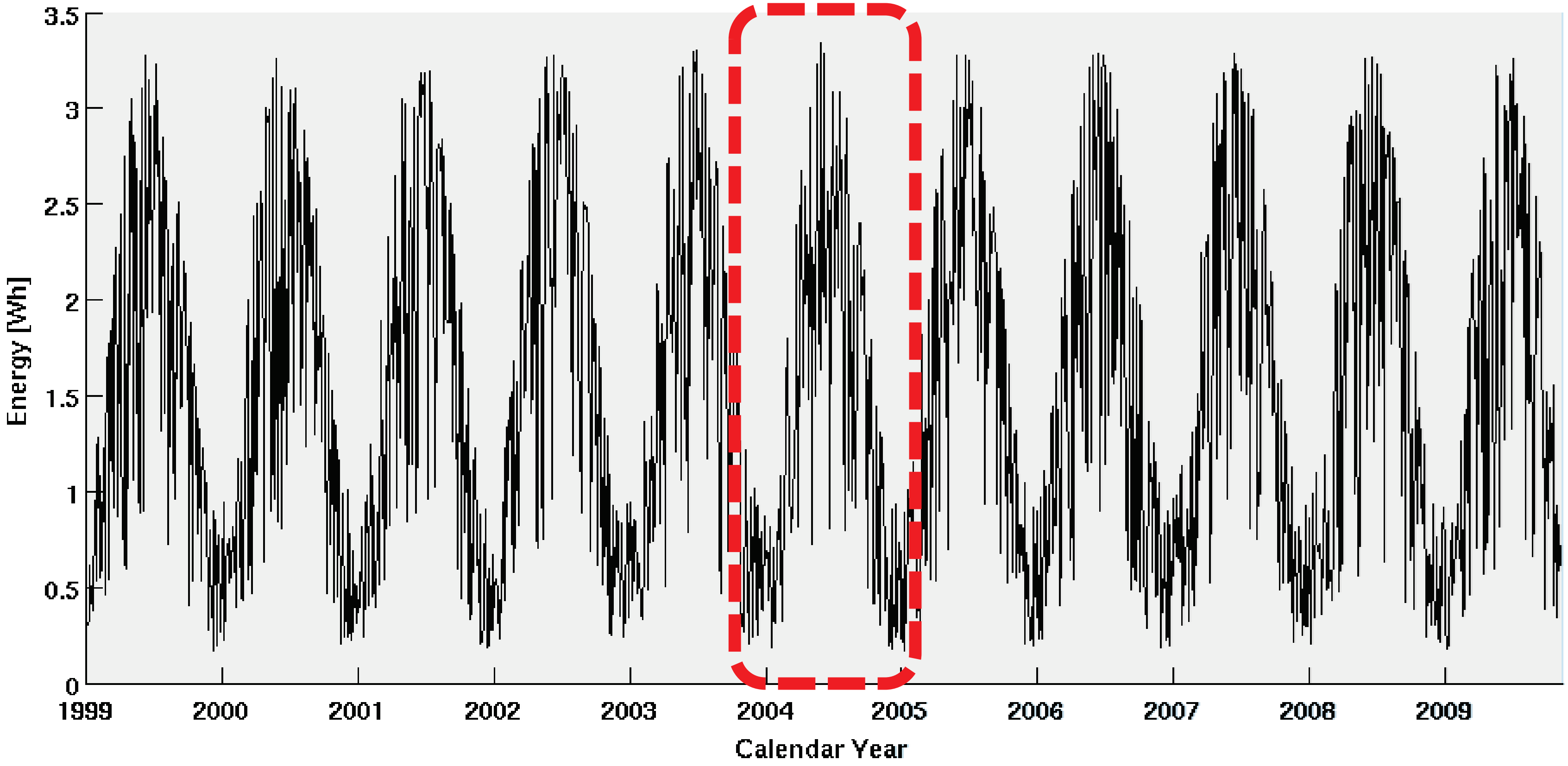
$$Error = SOC_{model} - SOC_{Opt}$$

$$f_s = \frac{1}{60\ sec}$$

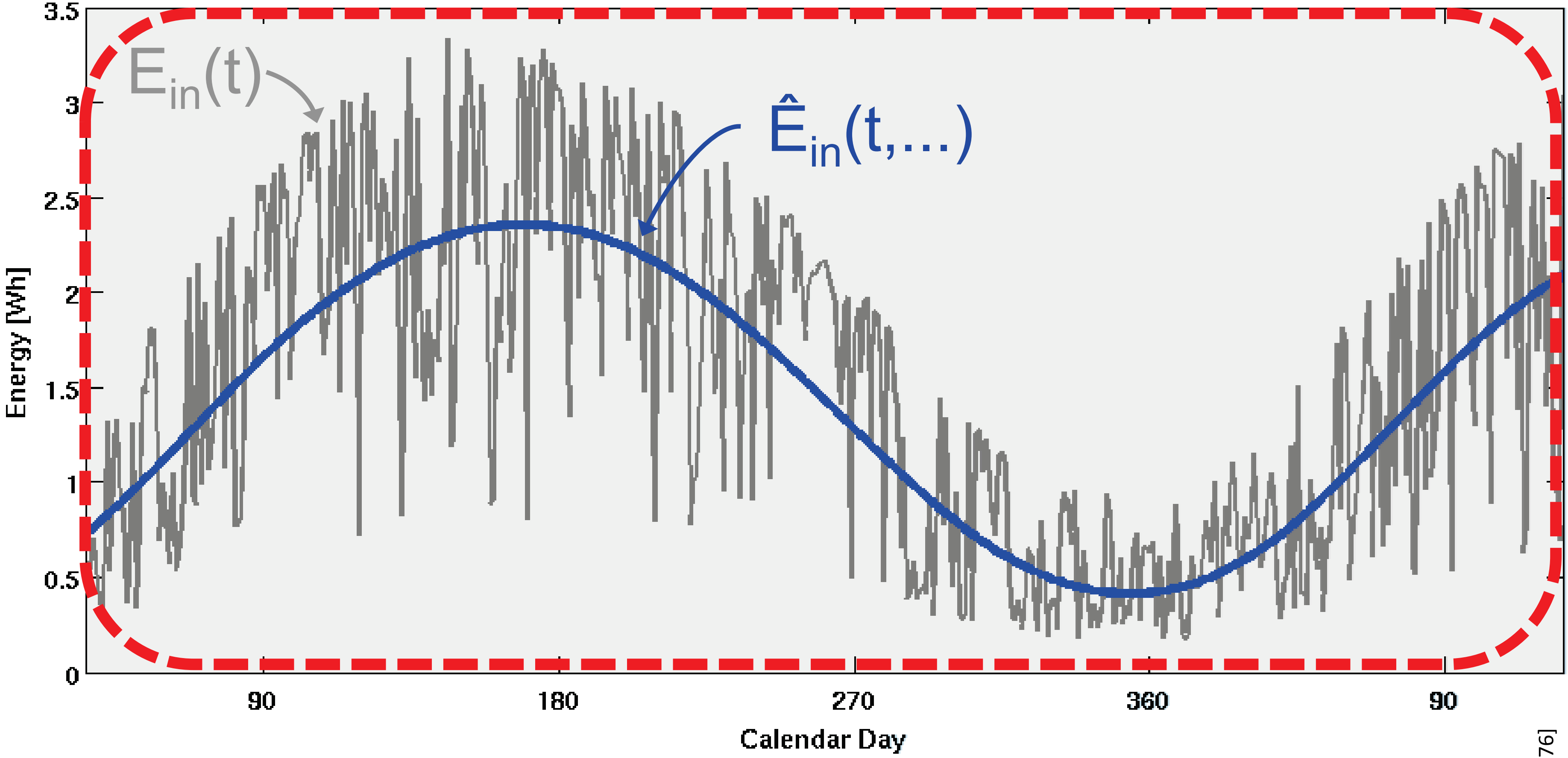
Low-Power System Design

LONG-TERM ENERGY NEUTRAL OPERATION – CAPACITY PLANNING

High Day-to-Day
Relatively Low Year-to-Year Variability

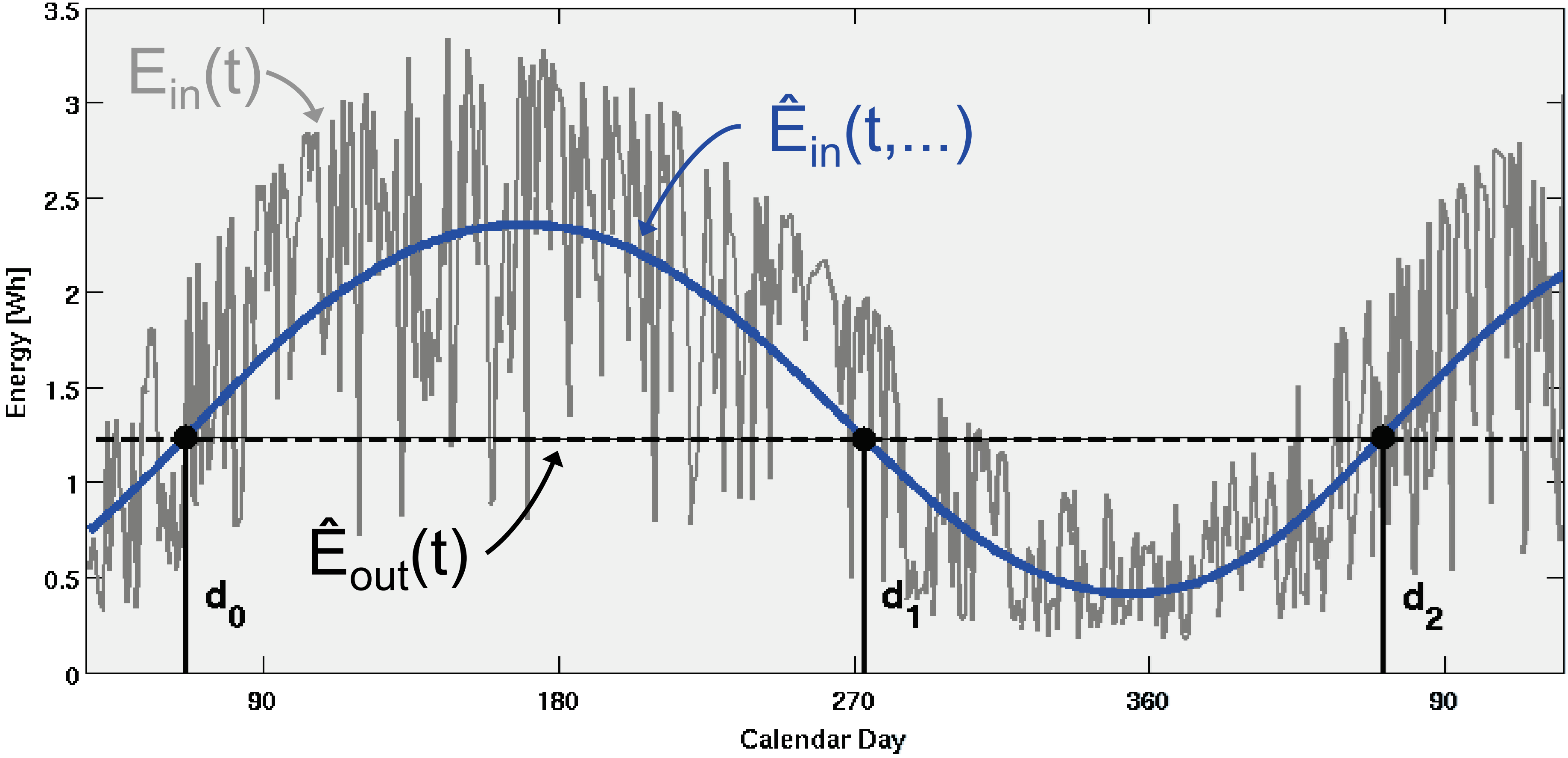


Approximation by Astronomical Model

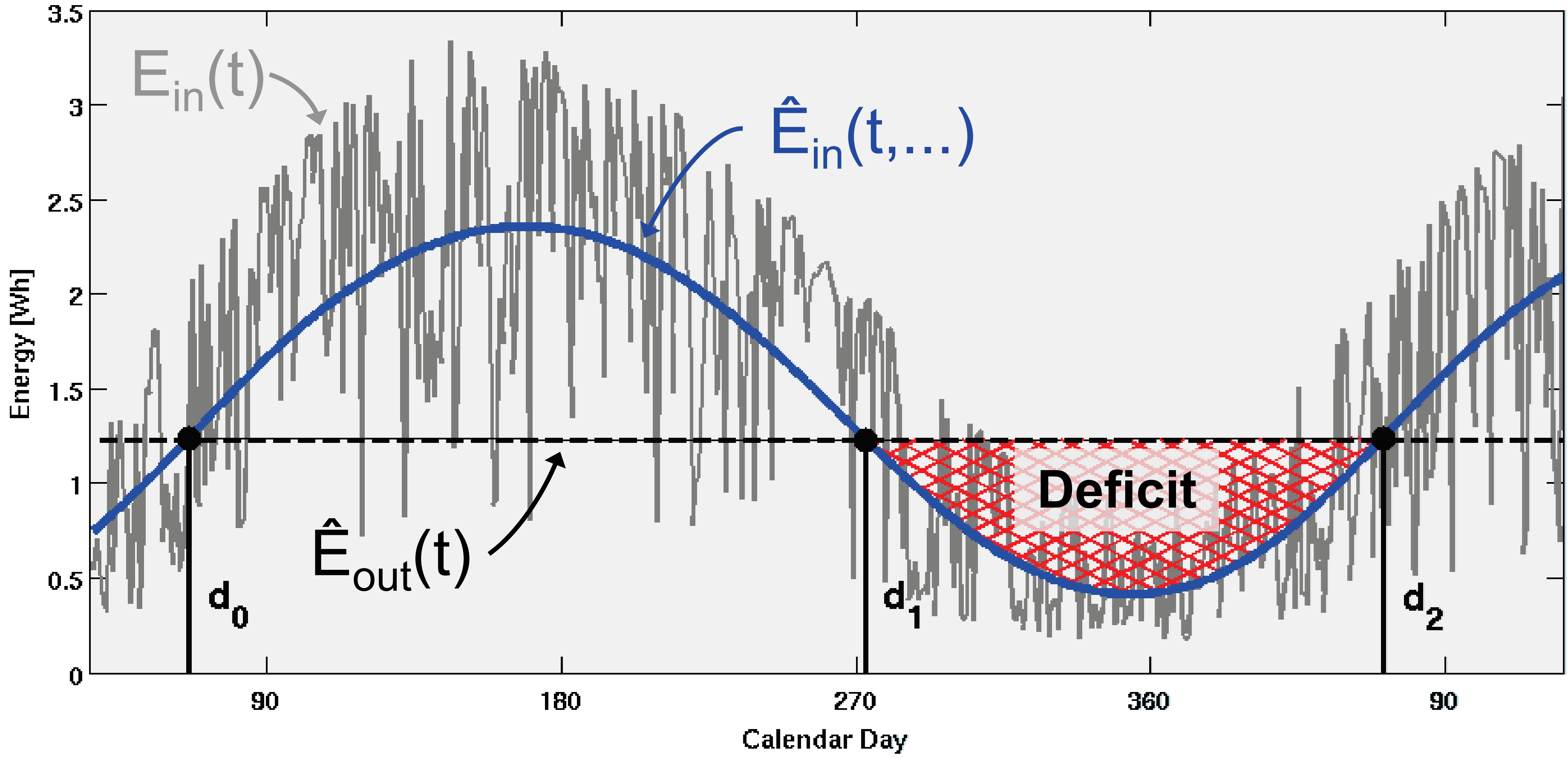


[Dave '76]

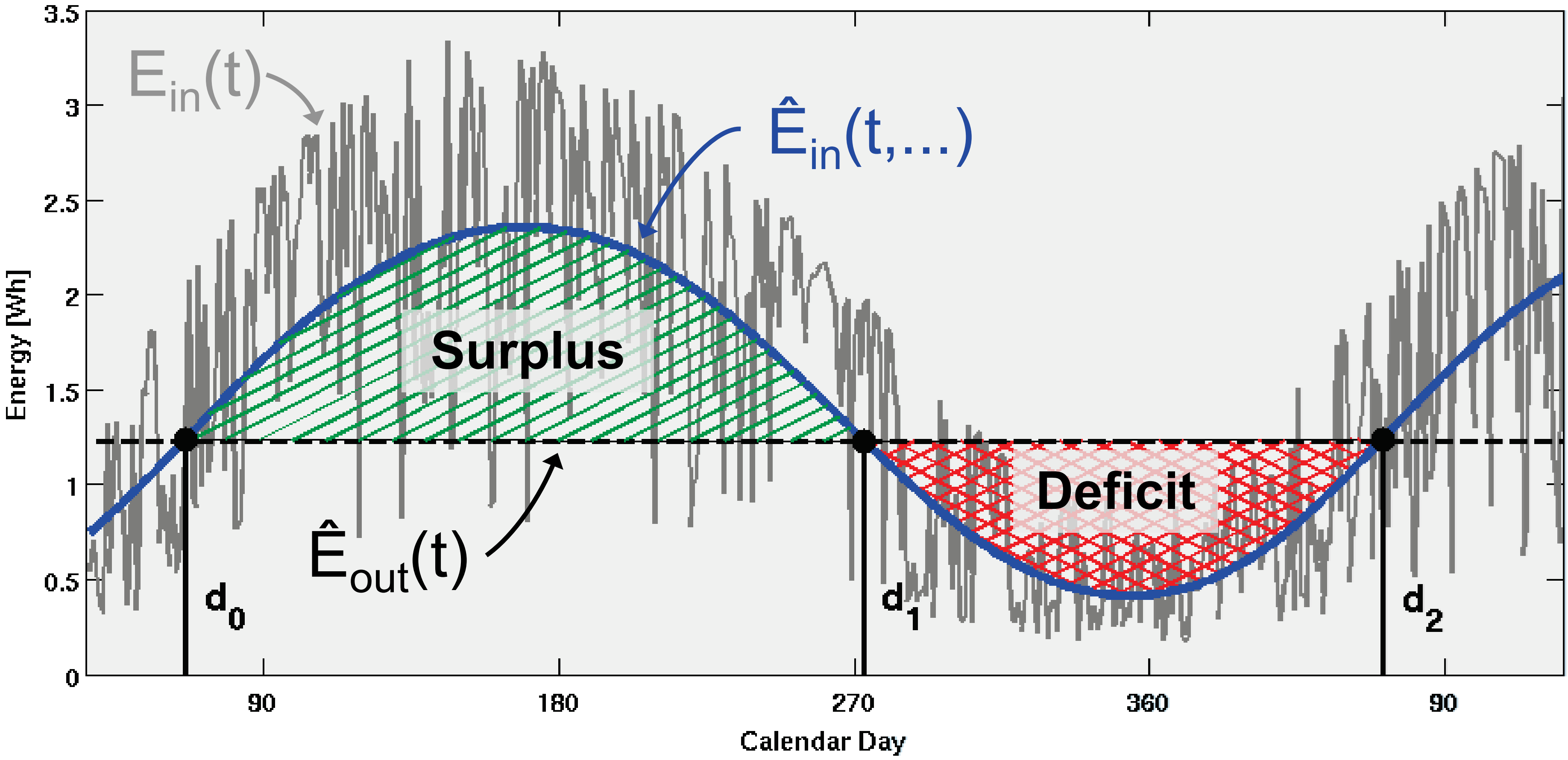
Energy Profile Partitions into Surplus and Deficit



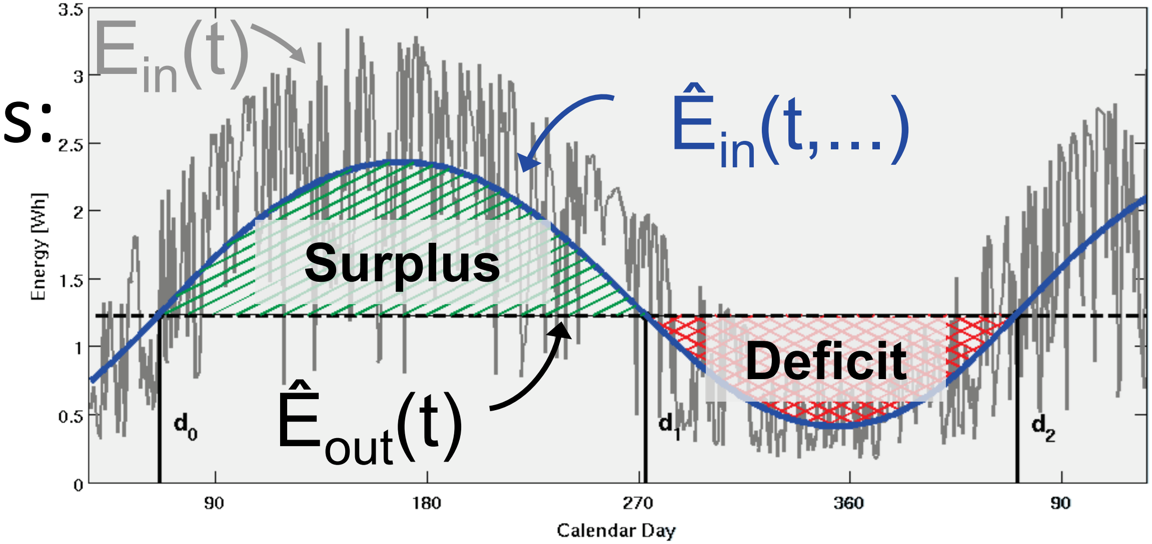
Period of Continuous Deficit Defines Minimum Required Battery Capacity



Period of Energy Surplus Defines Maximum Battery Capacity Supported by Solar Panel



Capacity planning for Uninterrupted Long-Term Operation



Periods of continuous:

- surplus: d_0 to d_1
- deficit: d_1 to d_2

Battery capacity:

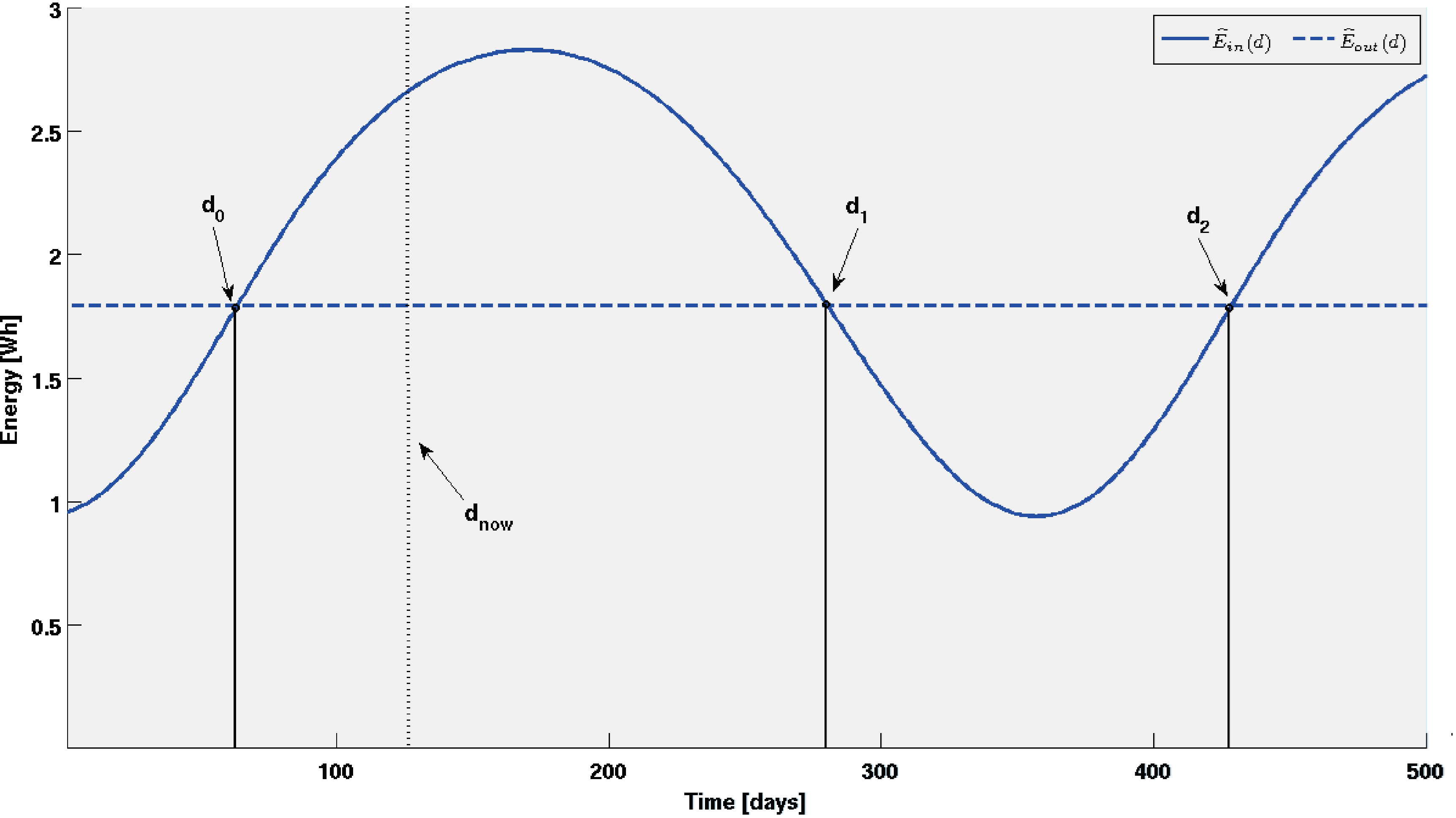
$$B_{\text{nom}} \geq \sum_{t=d_1}^{d_2} \left(\hat{E}_{out}(t) - \hat{E}_{in}(\bullet) \right)$$

And panel size such that: $\sum_{t=d_0}^{d_1} \hat{E}_{in}(\bullet) \geq B_{\text{nom}} + \sum_{t=d_0}^{d_1} \hat{E}_{out}(t)$

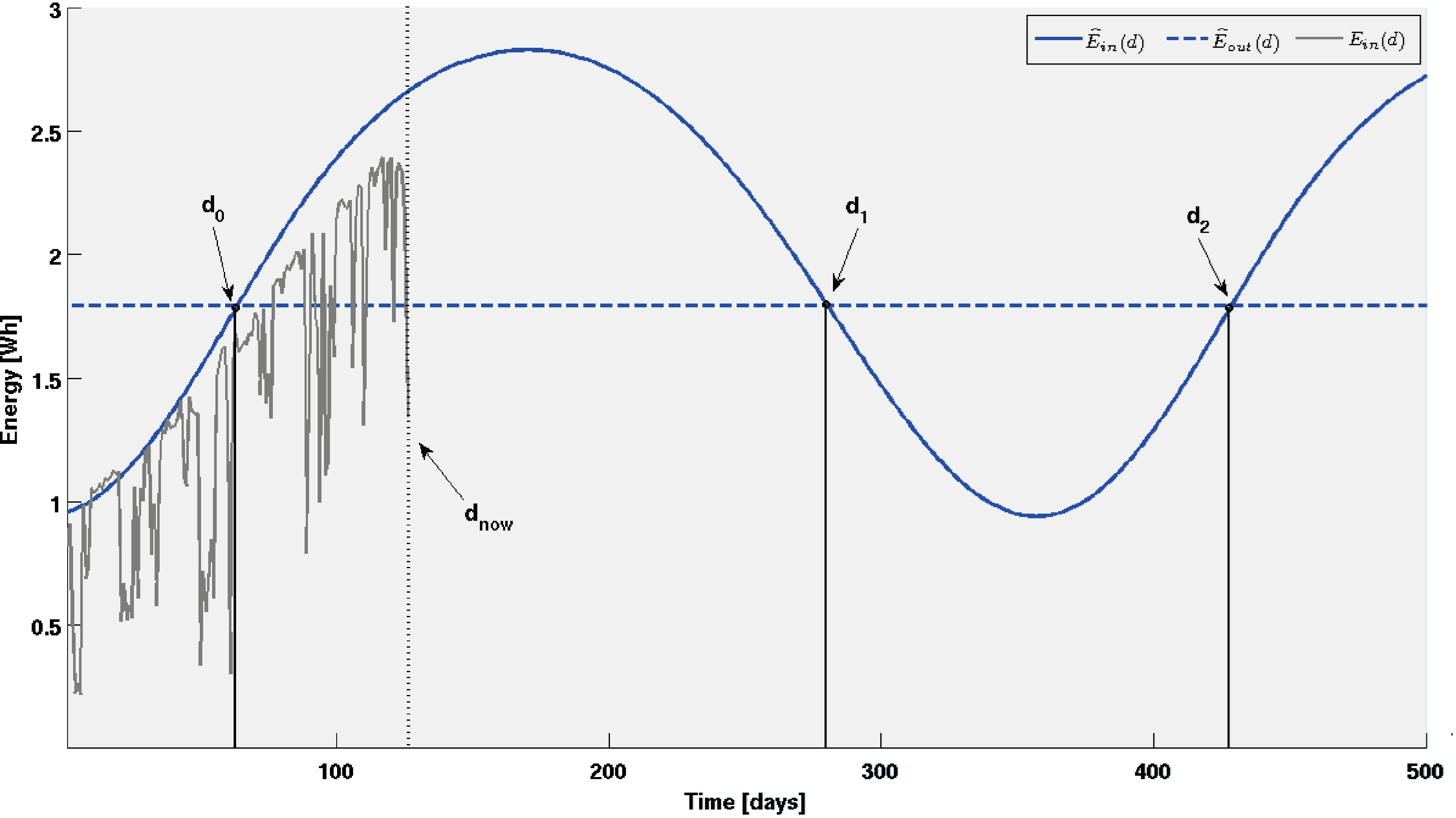
Low-Power System Design

LONG-TERM ENERGY NEUTRAL OPERATION – DYNAMIC POWER MANAGEMENT

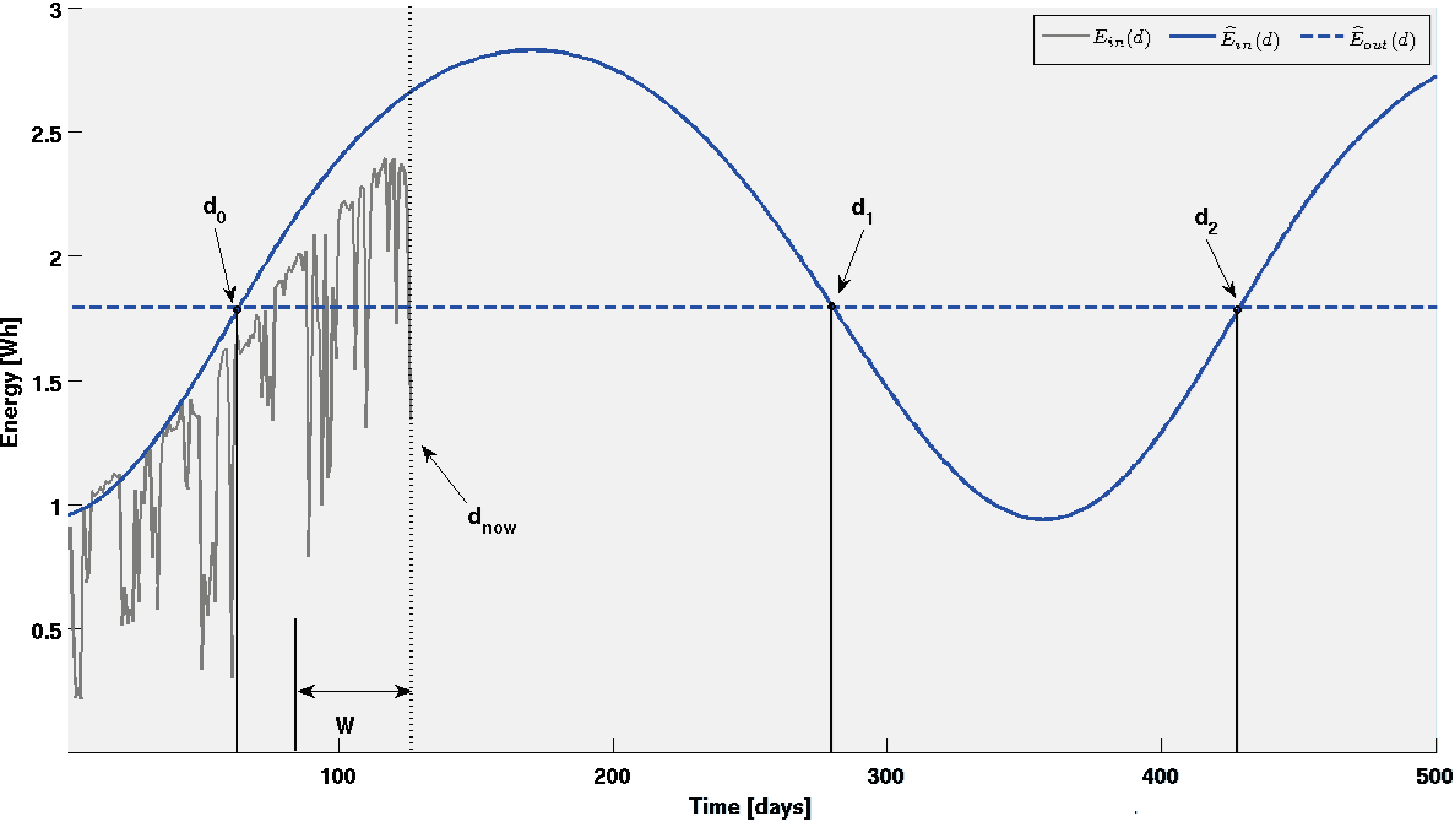
DPM knows Energy Input Profile Used for Capacity Planning



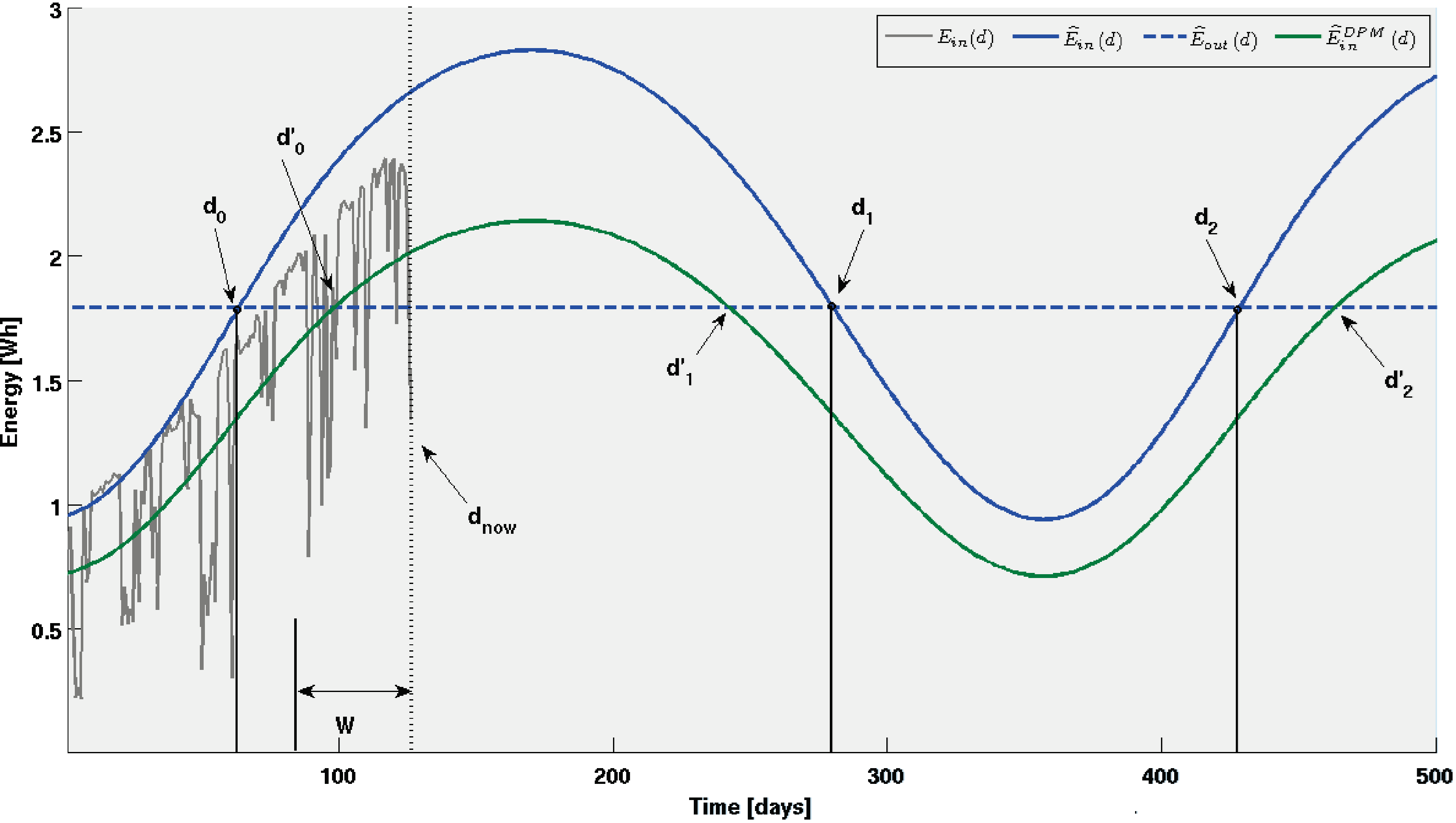
Performance Level Adjustment According to Actual Conditions



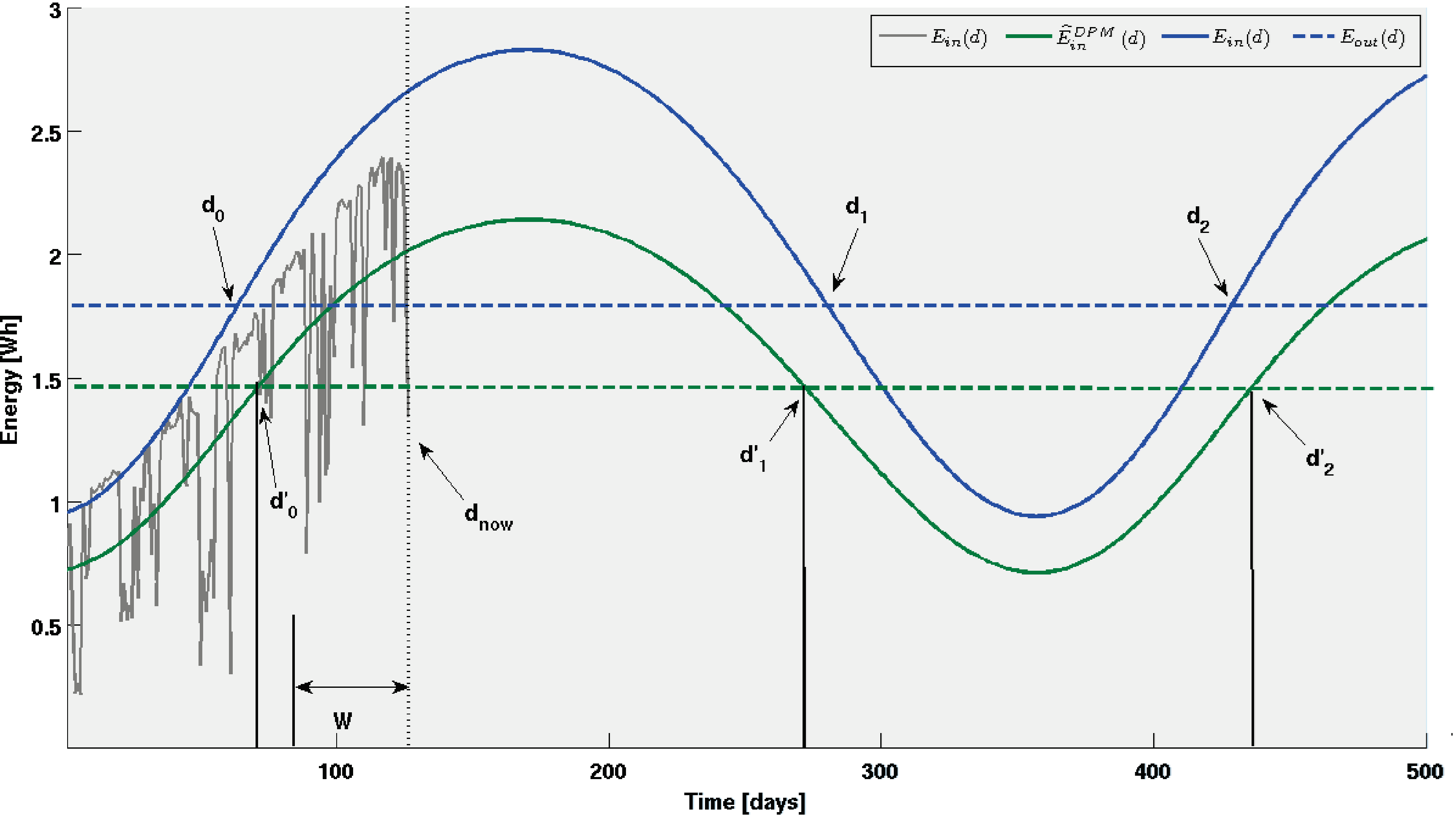
Step 1: Approximate Energy Availability Using History Window and Offline Model



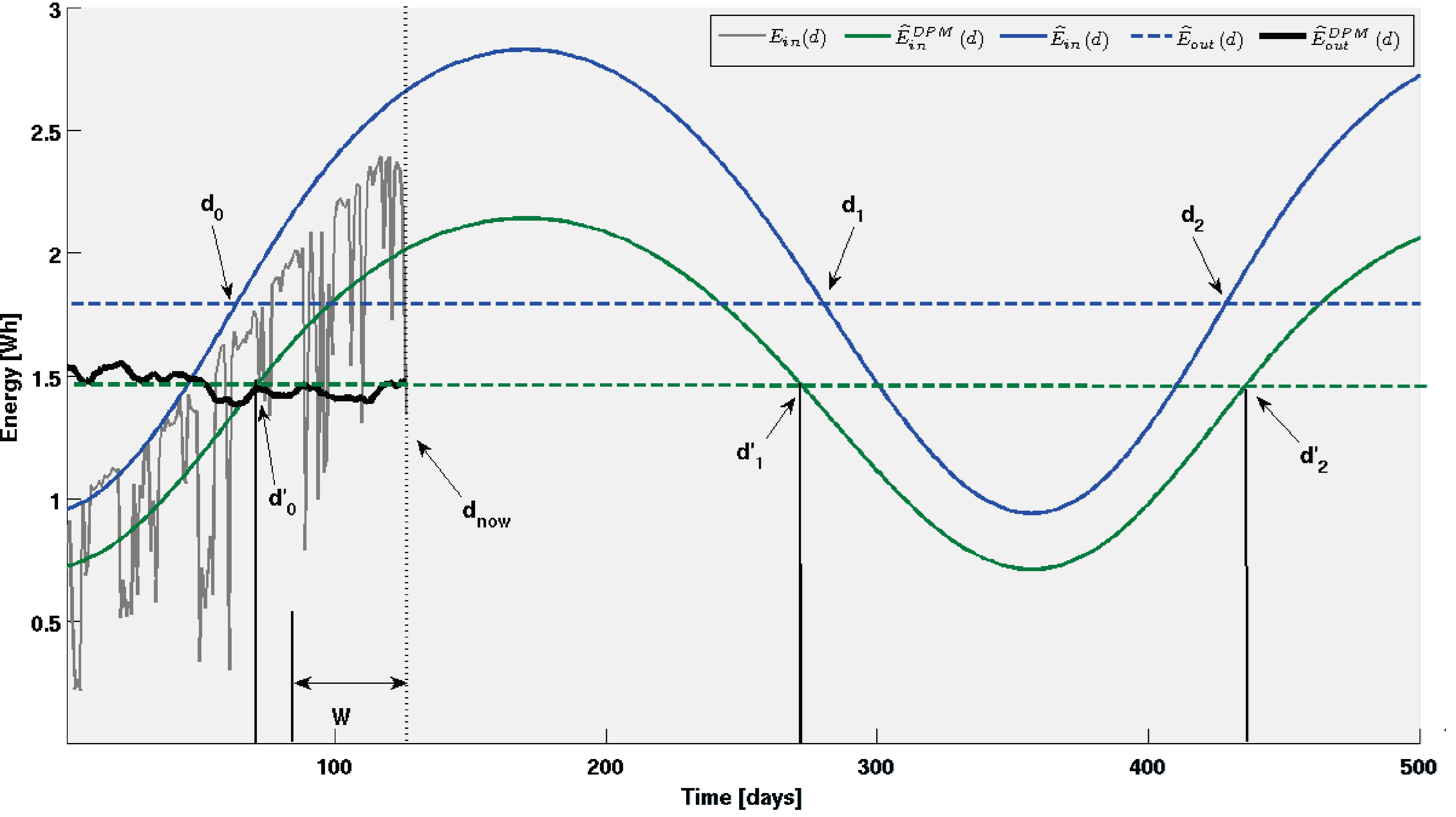
Step 2: Find Long-Term Performance Level



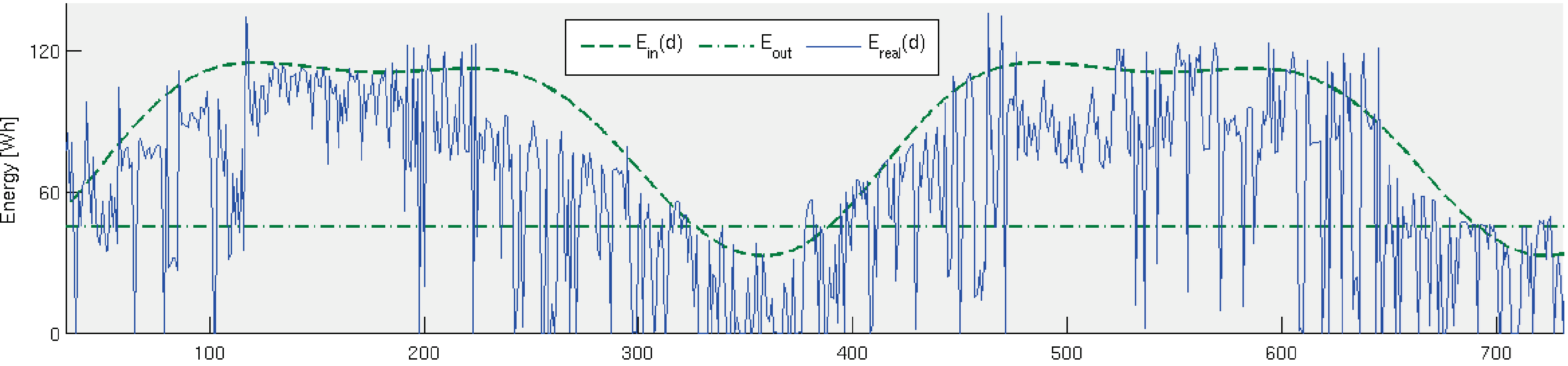
Step 2: Find Long-Term Performance Level



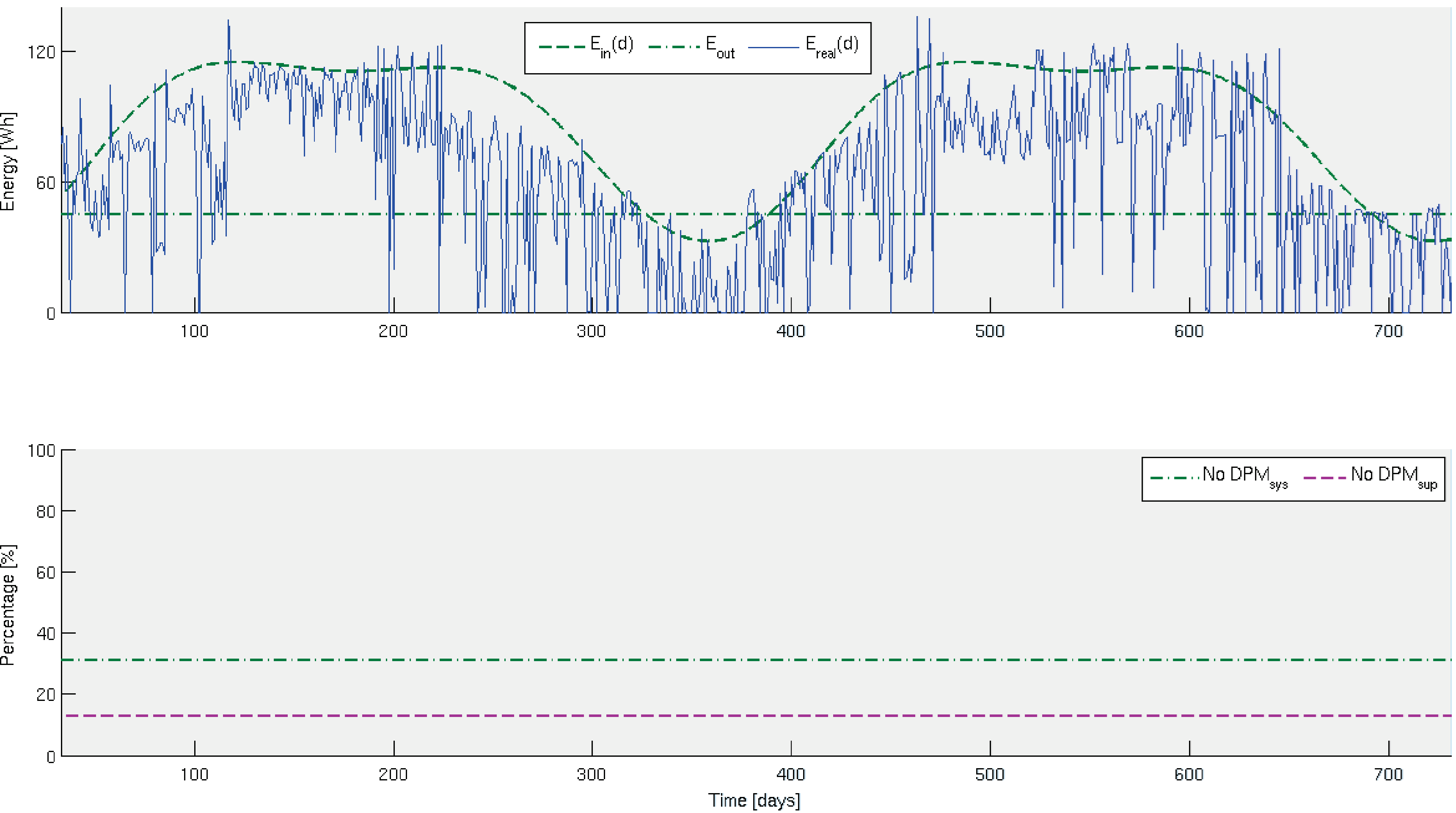
DPM Ensures Long-Term Energy Neutrality



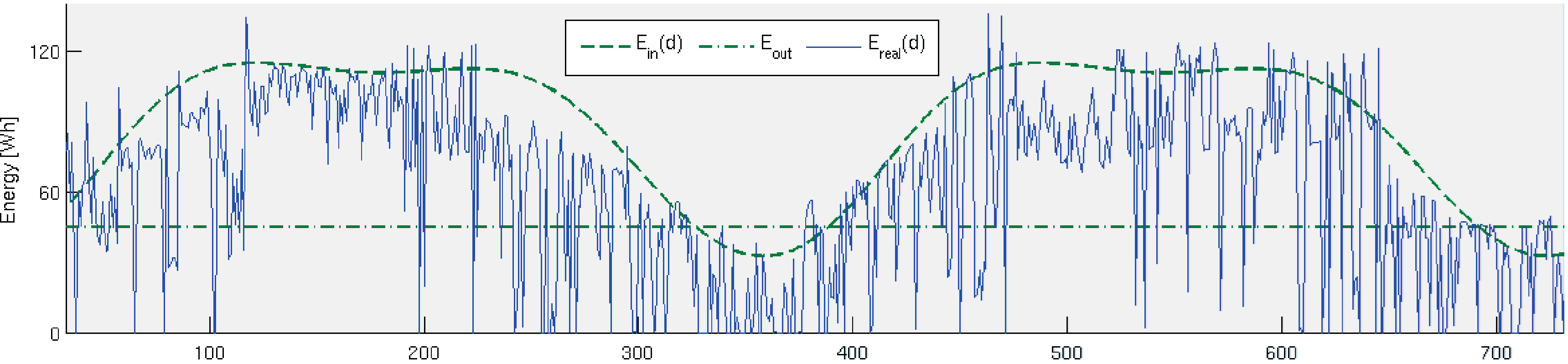
Caveat: Energy Availability Model Overestimates True Conditions

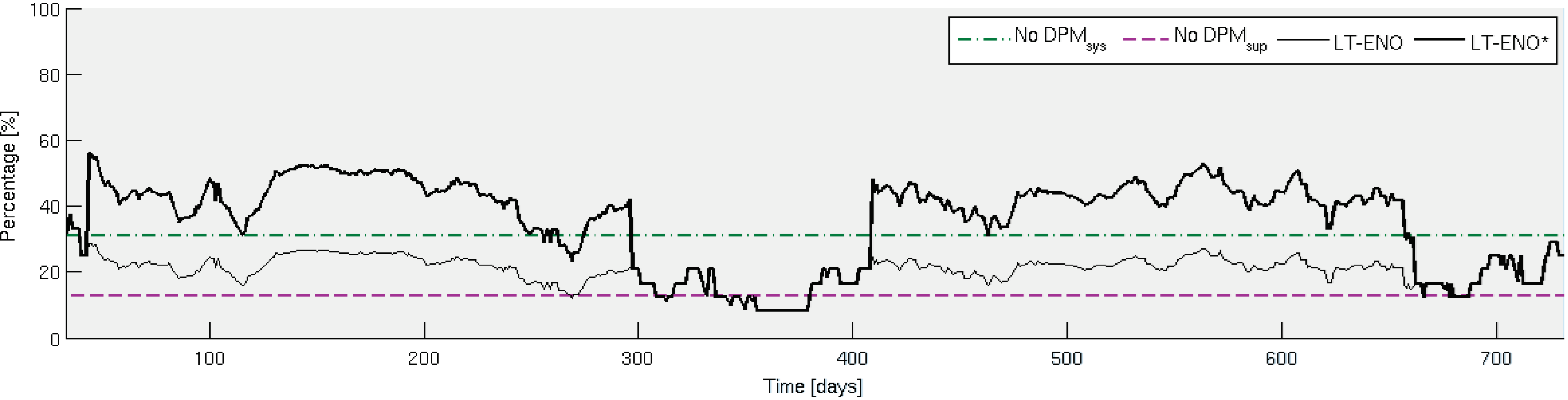


Supported Performance Level According Model/True Conditions (no DPM)

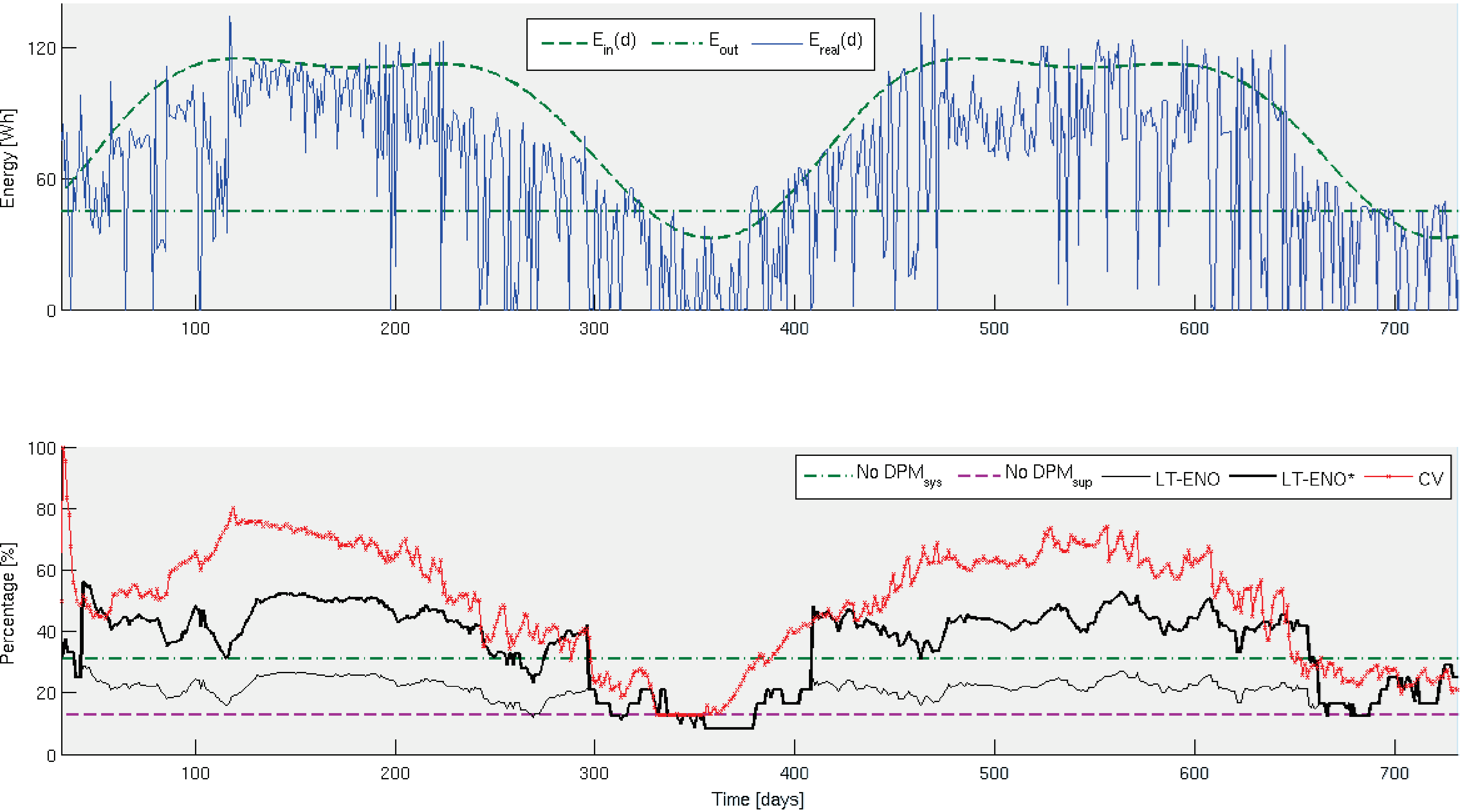


Long-Term Energy Neutral DPM





Clairvoyant Energy Predictor



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

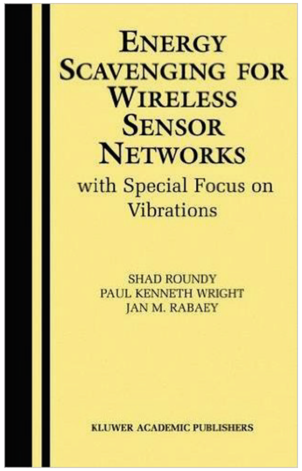
- LP architectures are increasingly designed with power subsystem in mind

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

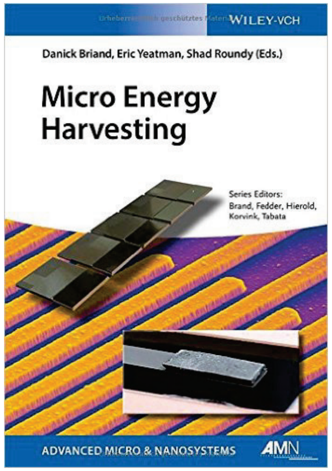
- Roundy, S., Wright PK, Rabaey JM 2003. *Energy Scavenging for Wireless Sensor Networks*, Kluwer Academic Publishers, Boston MA.
- Briand, D., Yeatman, E., Roundy, S., (Eds.). (2015). *Micro Energy Harvesting (Advanced Micro and Nanosystems)* . John Wiley & Sons.



ENERGY SCAVENGING FOR WIRELESS SENSOR NETWORKS
with Special Focus on Vibrations

SHAD ROUNDY
PAUL KENNETH WRIGHT
JAN M. RABAEY

KLUWER ACADEMIC PUBLISHERS



WILEY-VCH

Danick Briand, Eric Yeatman, Shad Roundy (Eds.)

Micro Energy Harvesting

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