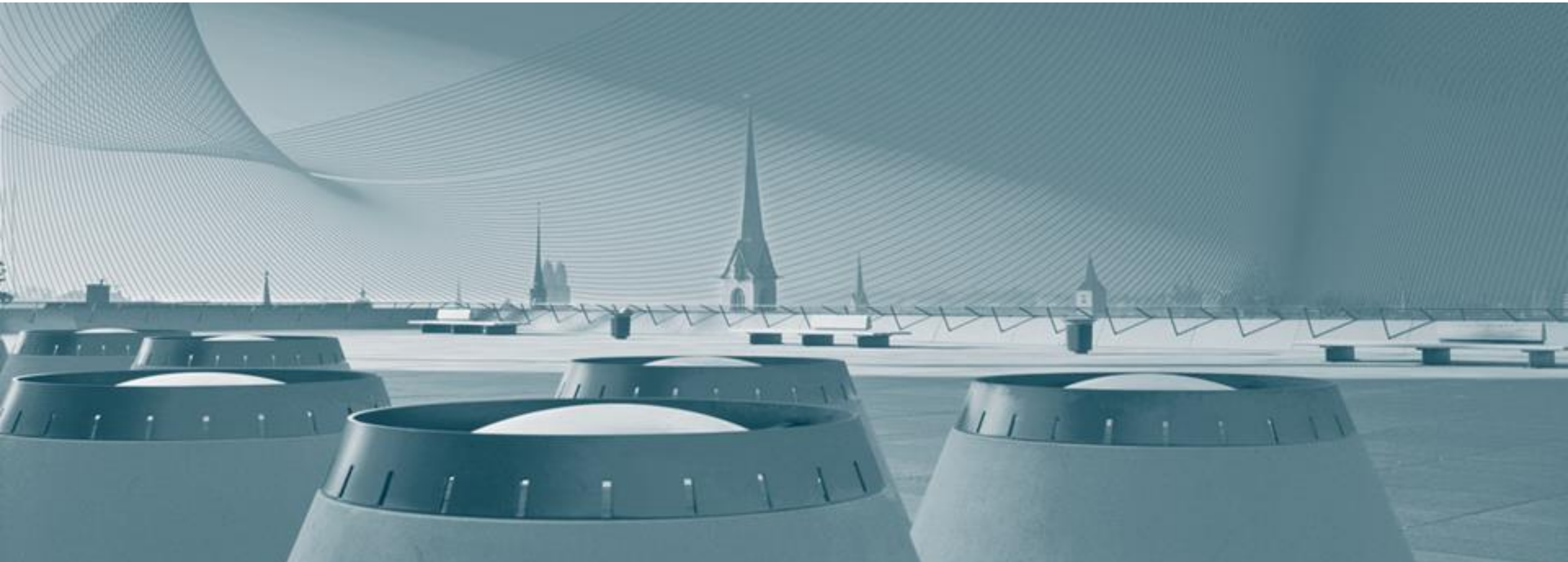
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Harvesting Energy from the Human Body

Moritz Thielen, PhD Student, Micro and Nanosystems
Seminar on Frontiers in Energy Research
2014-04-09



Outlook

Energy autonomous systems

Consumer electronics, biomedical, Body Sensor Networks

Sources of Energy from the human body

Movement, biochemical, heat

Energy harvesters

Electromagnetic, piezoelectric, electrochemical, thermoelectric

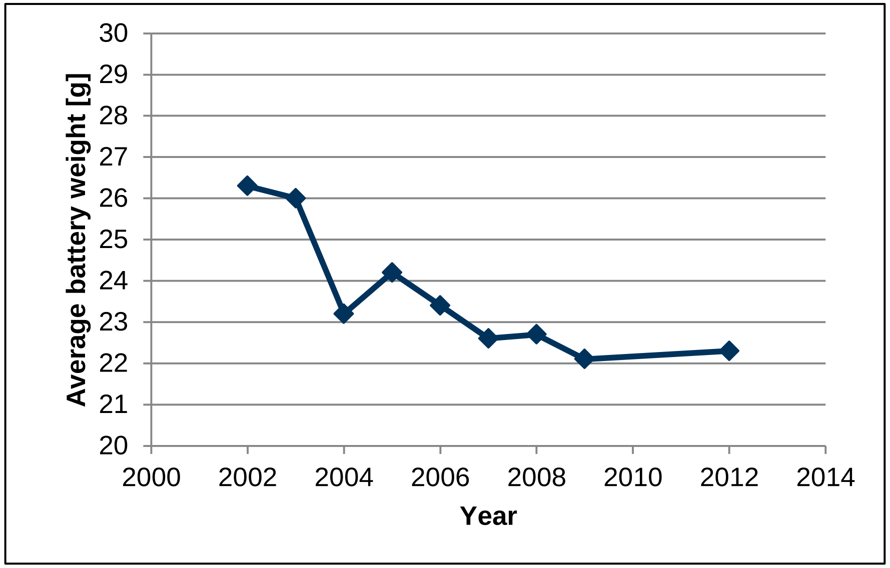
Body Powered Sense Project

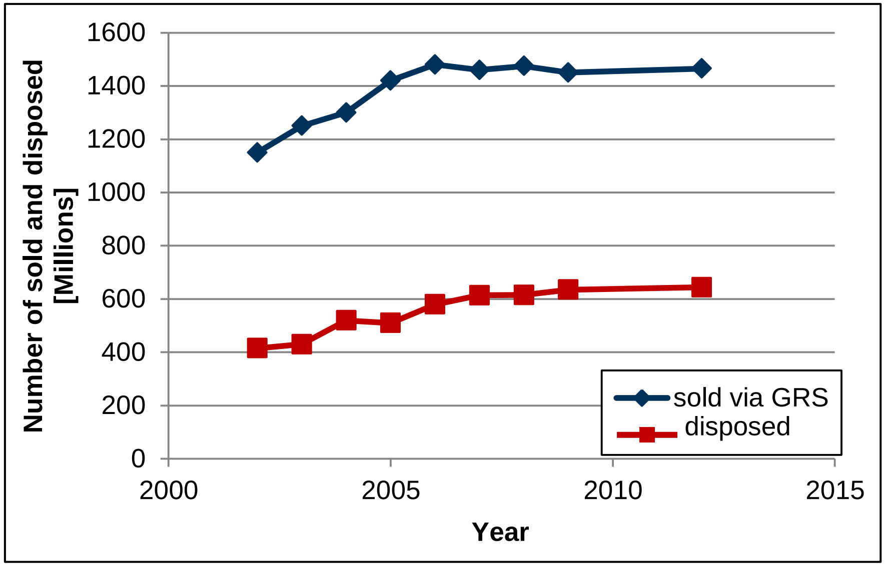
Overview, simulation, prototype, future research

Some numbers about batteries

Battery consumption and disposal in Germany

All data taken from 'Stiftung gemeinsames Ruecknahmesystemf fuer Batterien' (GRS)





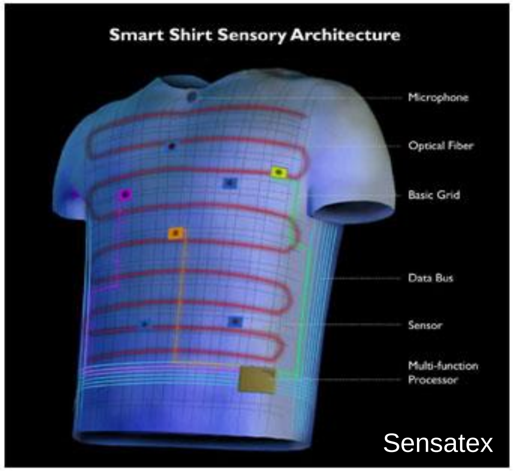
In 2012 the discrepancy between sold and disposed batteries via GRS was **18.423 tons!**

Battery dependent systems in and on the human body

Consumer

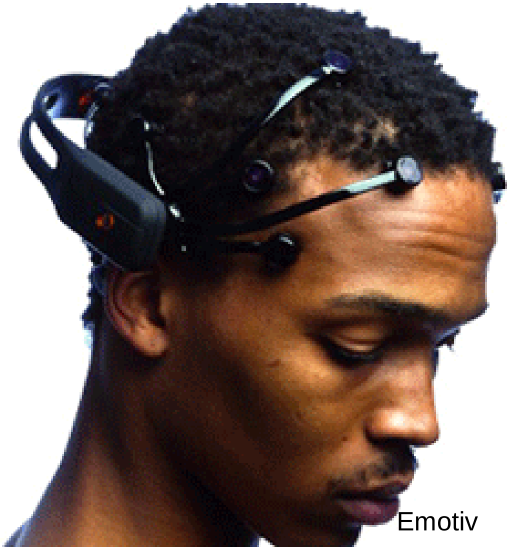
Nike

Seiko



Sensatex

Biopotentials



Emotiv

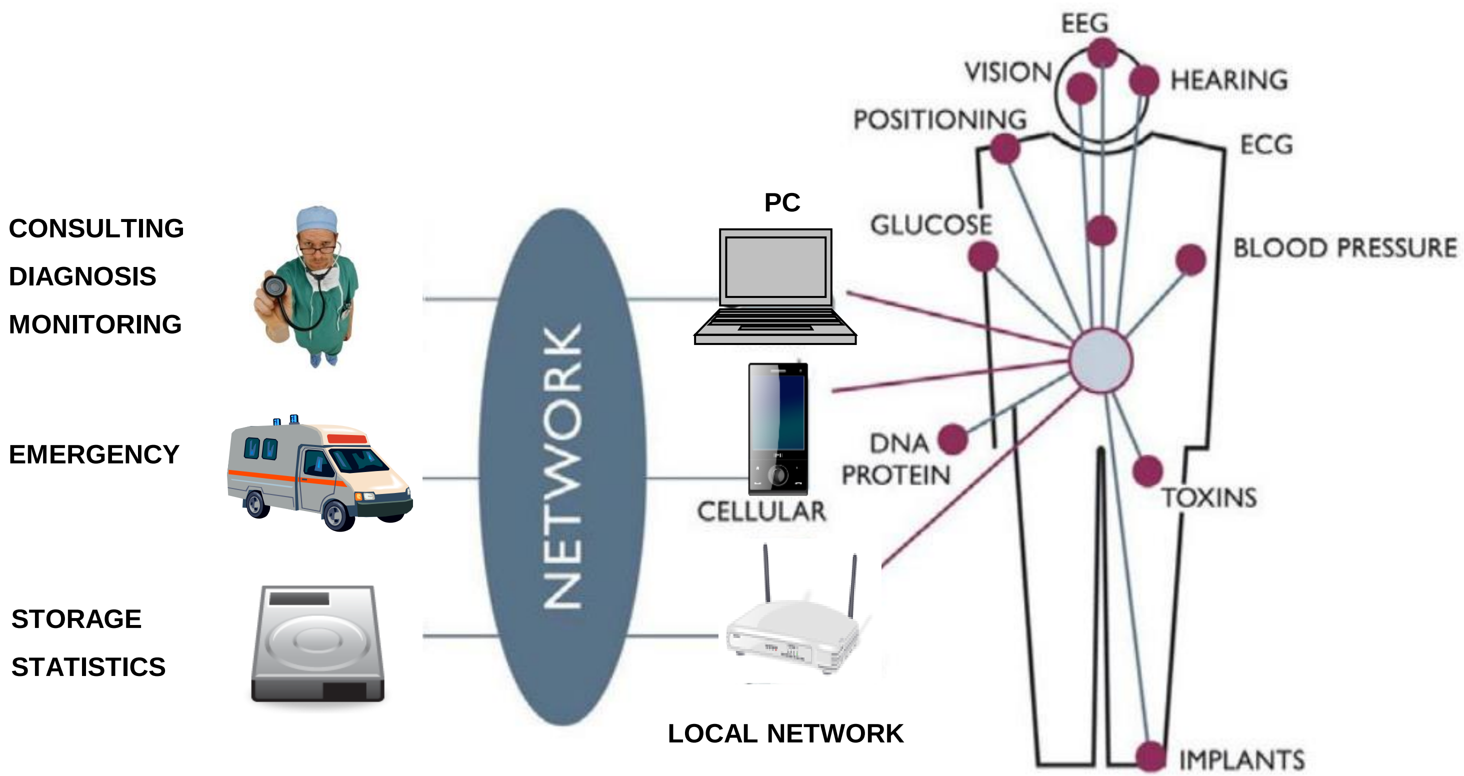
Polar

Implants

Biotronik

wikimedia

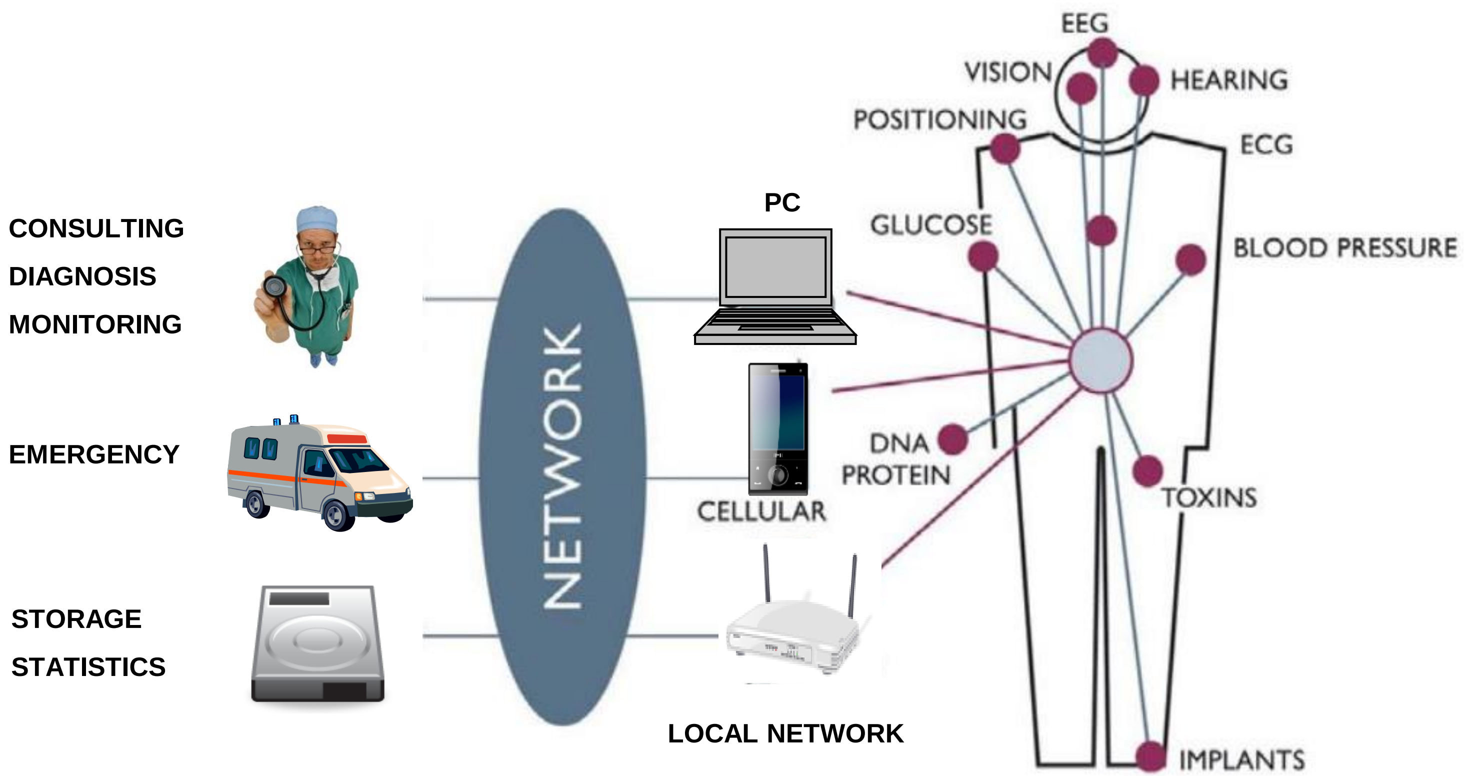
Future: Body Sensor Networks (BSN or BAN)



adapted from: Gyselinckx et al. IEEE Int.Circ.Conf. 2005

Attributes: Continuous use 24/7, portable and unobtrusive, **Anytime, Anywhere, Anybody**

Future: Body Sensor Networks (BSN or BAN)



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Attributes: Continuous use 24/7, portable and unobtrusive, **Anytime, Anywhere, Anybody**

Would it not be nice to power such a systems without batteries?

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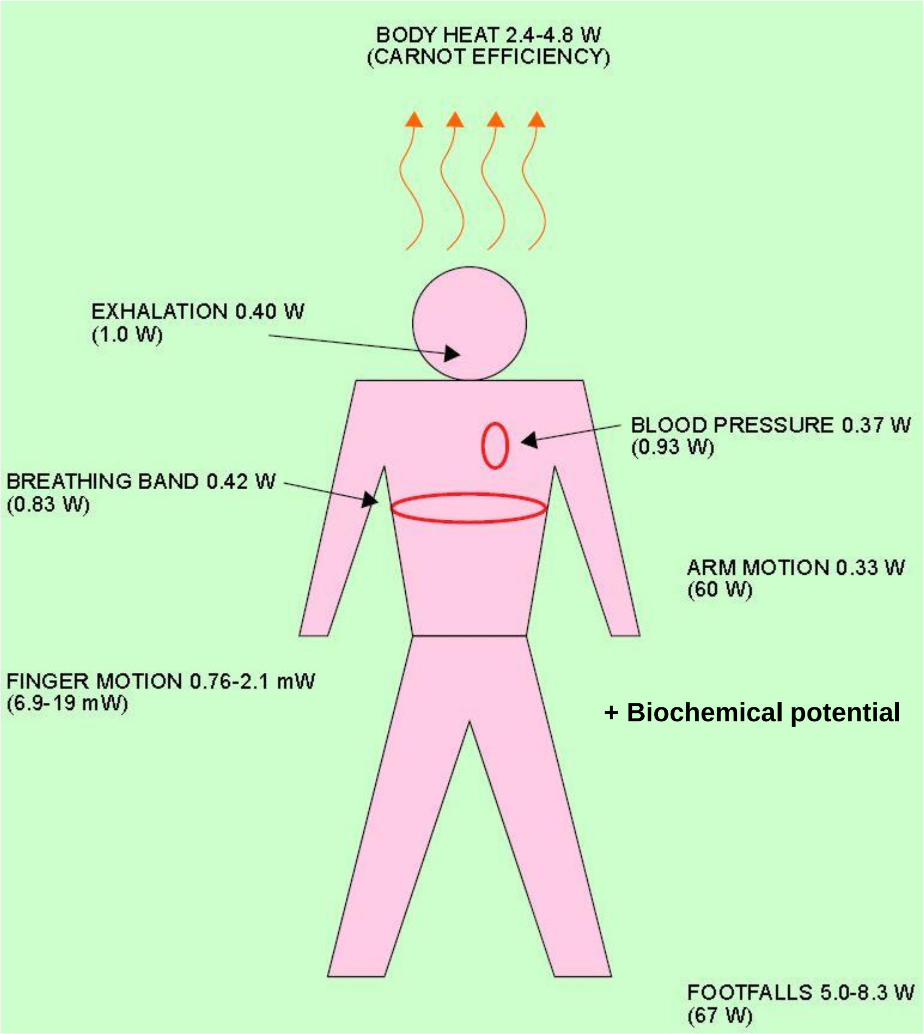
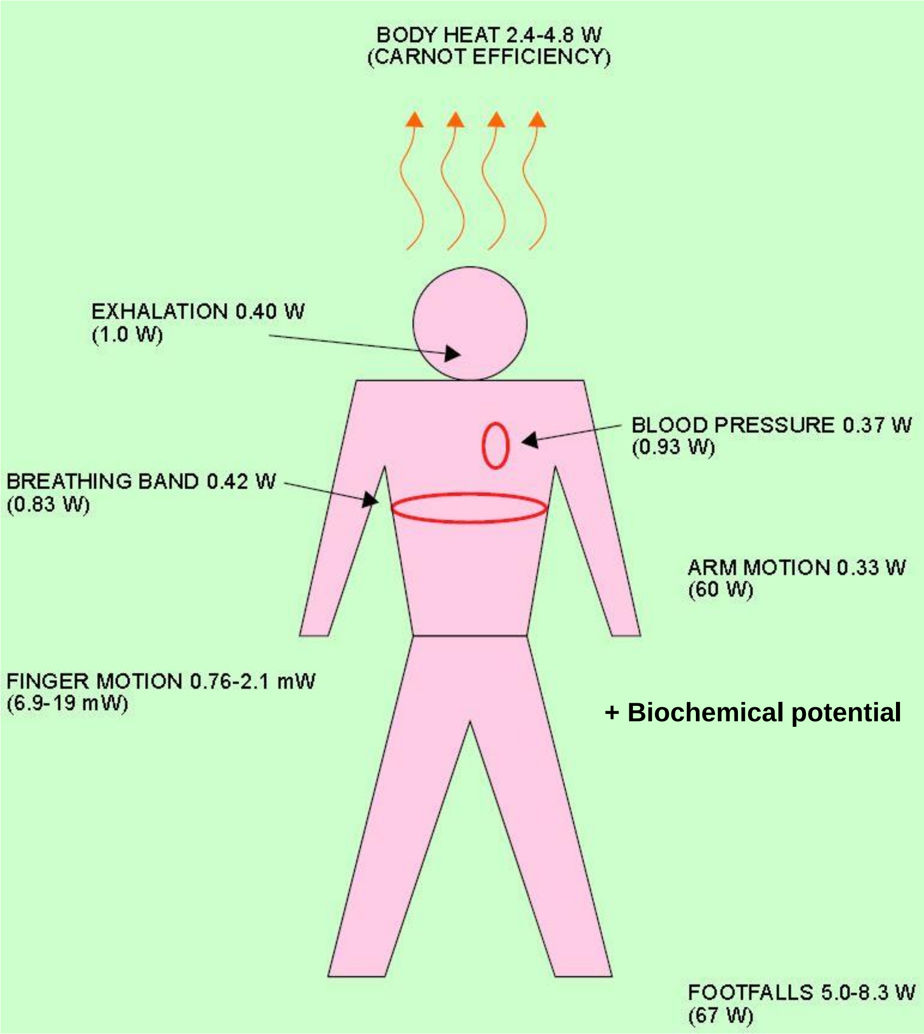
Energy provided by the human body



Starner. "Human-powered wearable computing." *IBM systems Journal* 35.3.4 (1996): 618-629.

Energy provided by the human body



Starner. "Human-powered wearable computing." *IBM systems Journal* 35.3.4 (1996): 618-629.

How can we access this energy?

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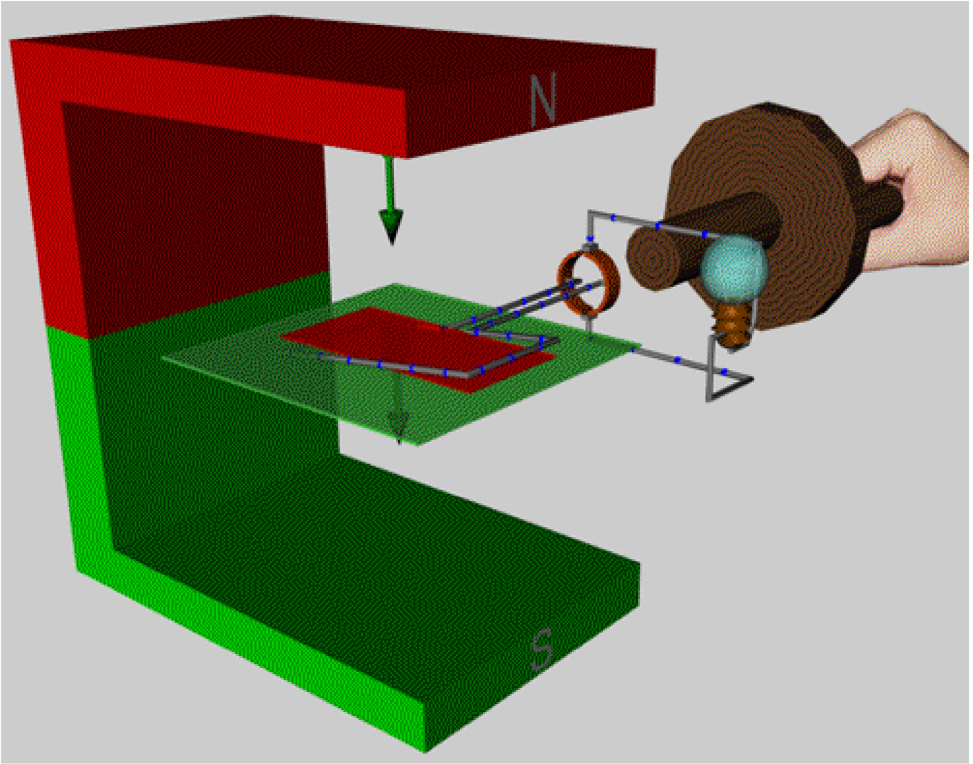
Electromagnetic harvesters

Working principle



$$V_G = EMF * \omega_G$$

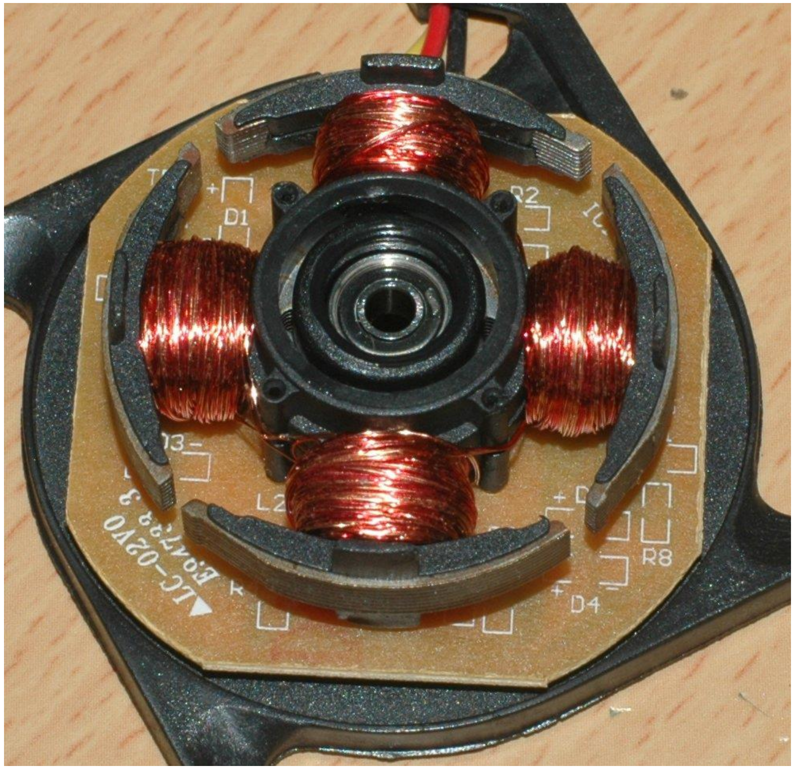
$$\eta_G = \frac{R_L}{R_L + R_G}$$

with: EMF = electromotive force constant, R = electrical resistance,

ω = angular velocity and

η = efficiency

Rotary brushless generator

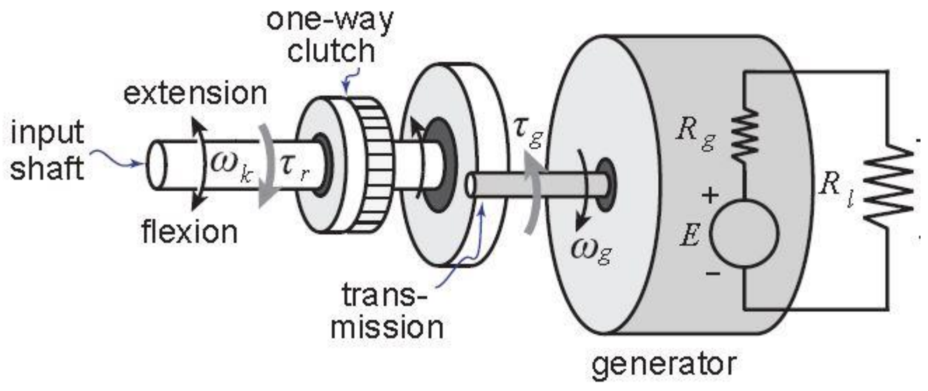


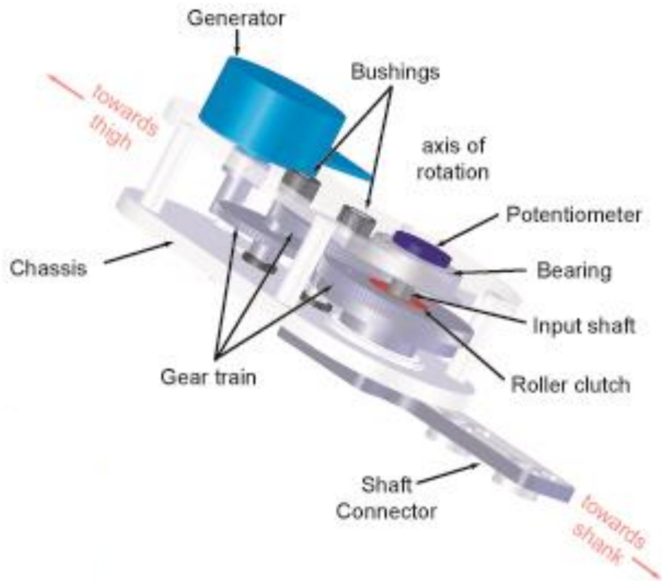
Images: wikimedia

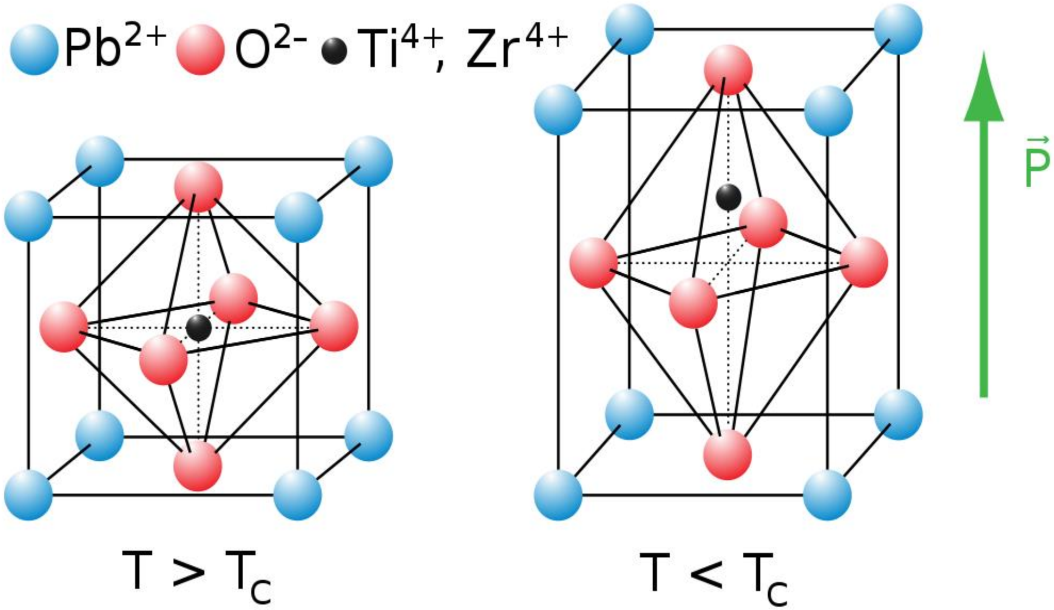
Knee mounted energy harvesting device

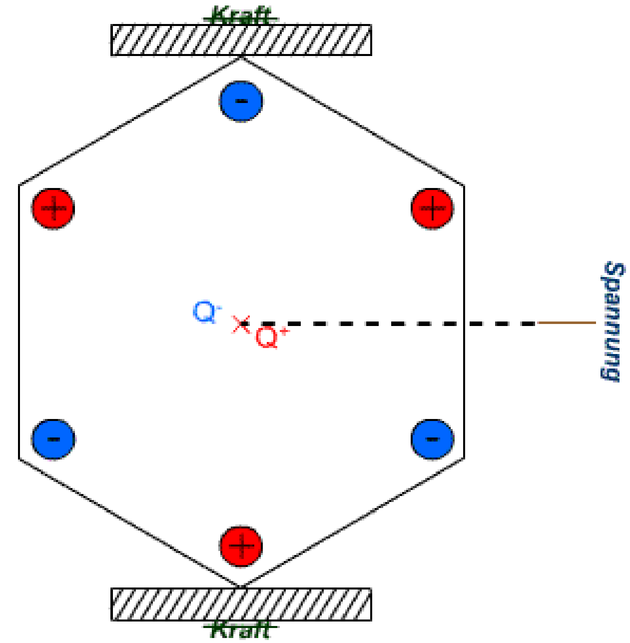
Li et al. J NeuroEng and Rehab, 6:22, 2009

Power generation:	4.8 ± 0.8 W at 1.5 m/s
Size/Weight:	NA/ 1.6 kg
Body location:	Knee
Applications:	Prosthesis (e.g. C-leg), Body Sensor Networks Military









Piezoelectric coupling coefficient:

$$k = \sqrt{\frac{\mathit{electrical\ energy\ stored}}{\mathit{mechanical\ energy\ applied}}} = d \cdot \sqrt{\frac{Y}{e}}$$

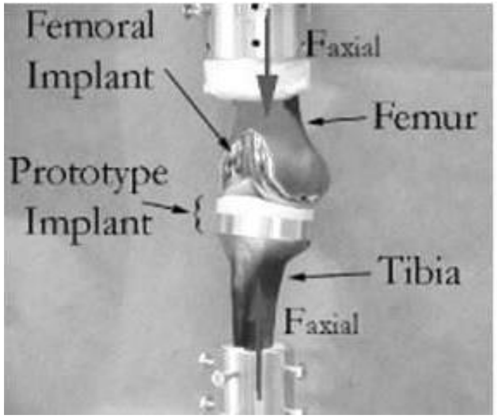
with: d = strain coefficient, Y = Young's modulus,

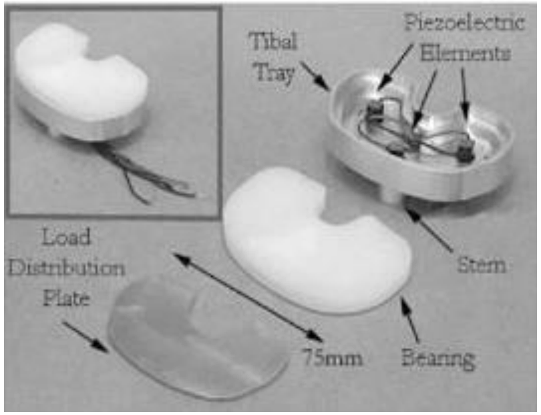
e = dielectric constant

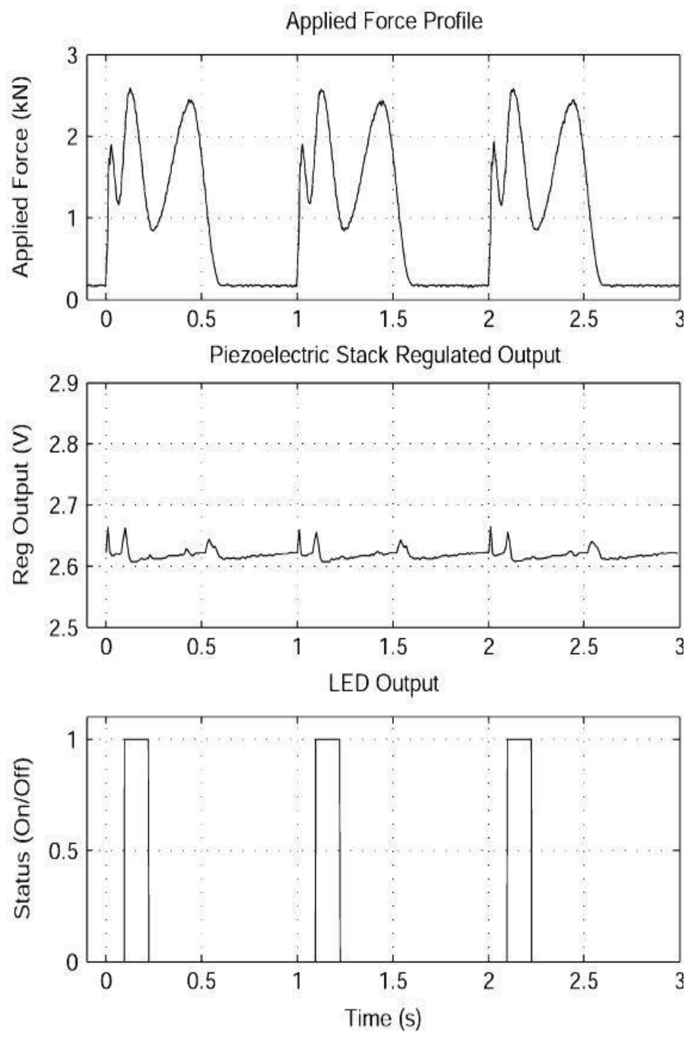
Power generation within orthopedic implants

Platt et al. IEEE/ASME Transaction on Mechatronics 10(4). 2005

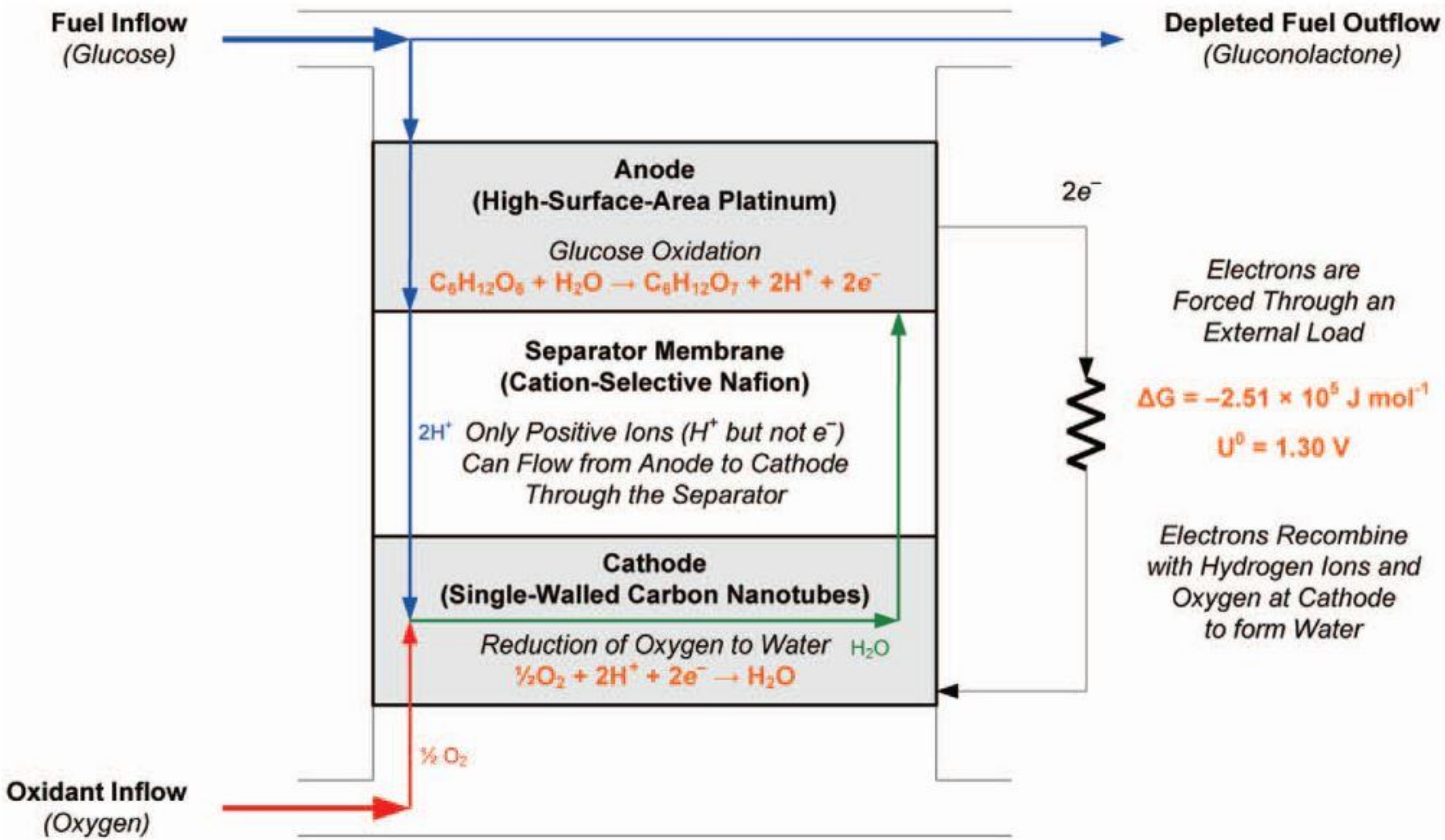
Power generation:	4.8 mW (raw), 850 µW (regulated)
Size/Weight:	10x10x20 mm / NA
Body location:	Knee implant
Applications:	In vivo diagnostics (duty cycle, forces, wear, etc.), Muscle stimulation







Electrochemical harvesters

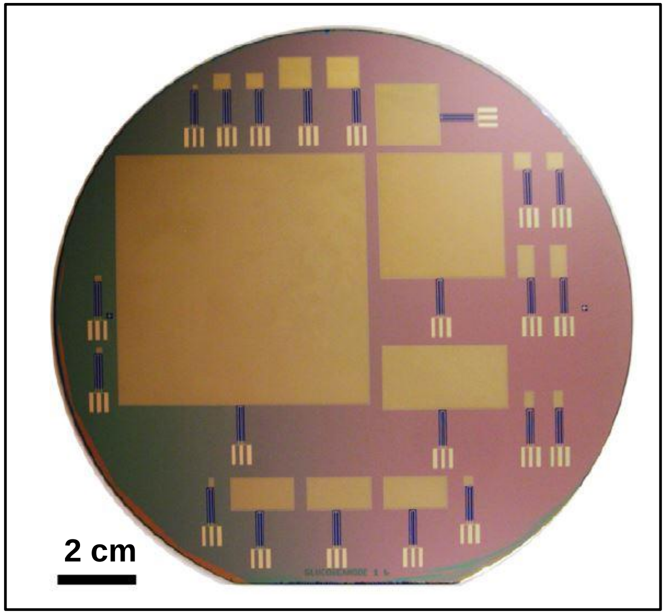


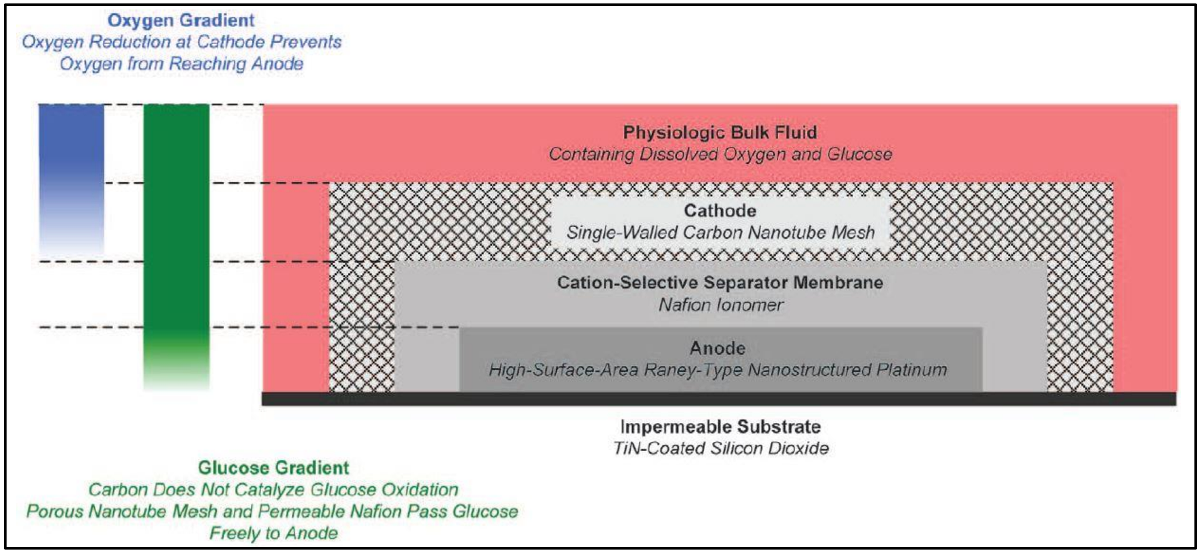
Rapoport et al. PLoS ONE, 7-6-e38436, 2012

Implantable glucose fuel cell

Rapoport et al. PLoS ONE, 7-6-e38436, 2012

Power generation:	3.4 - 180 uW/cm2,
Size/Weight:	scalable up to 40 cm2
Body location:	Head, chest (possible)
Applications:	Brain computer interfaces, pacemaker, drug delivery, hearing aids
Notes:	Not implanted in humans yet encapsulation issues





Thermoelectric harvesters

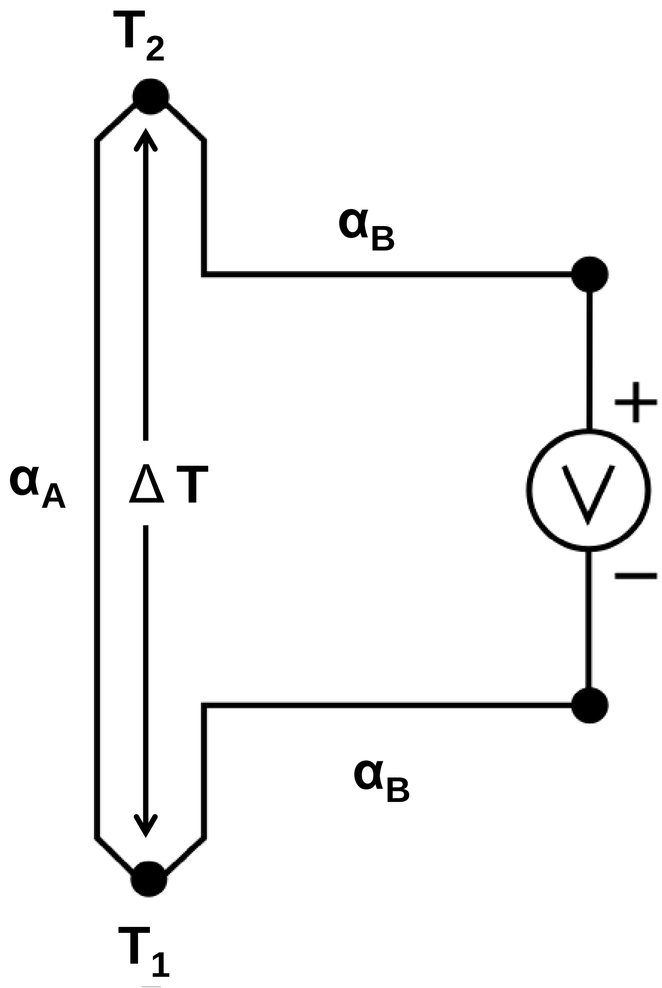
Seebeck effect (1928): A combination of different physical phenomena

- Thermodiffusion
- Diffusion coefficient / mobility
- Phonon drag
- Charge accumulation → E-field

Seebeck coefficient: α [V/K]

$$V = (\alpha_B - \alpha_A) * (T_2 - T_1) = \alpha_m \Delta T_G$$

Temperature gradient → Electric potential



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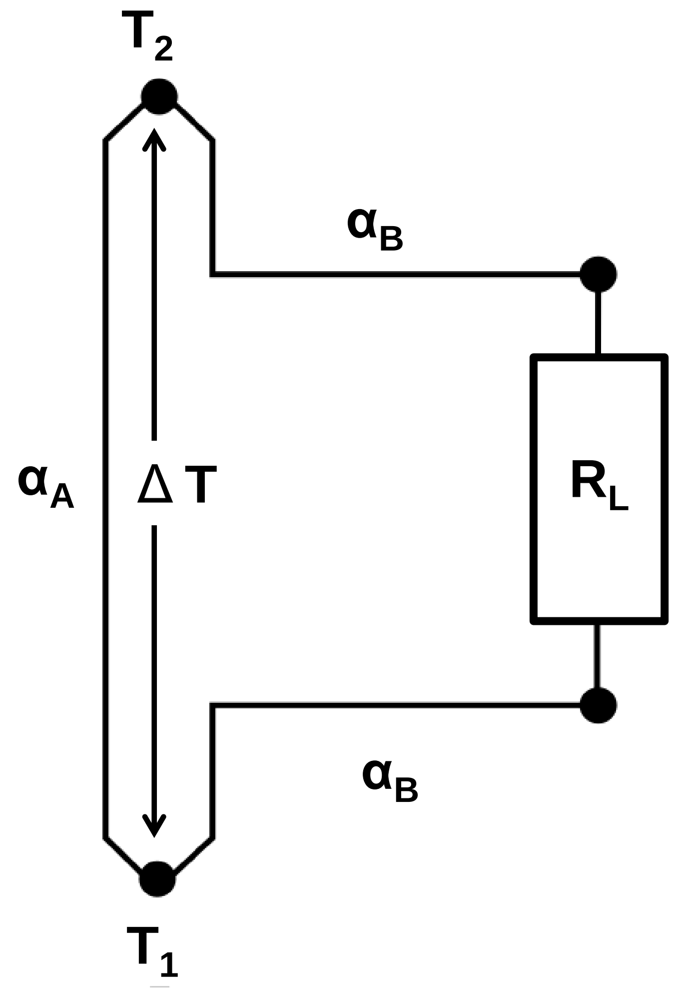
Seebeck coefficient: α [V/K]

$$V = (\alpha_B - \alpha_A) * (T_2 - T_1) = \alpha_m \Delta T_G$$

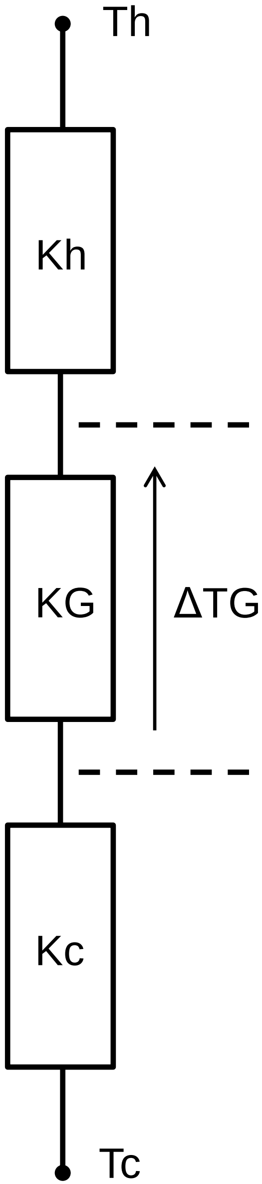
$$P_{out} = V * I = \frac{V^2}{4\,RL}$$

for an electrically matched load ($R_G = R_L$)

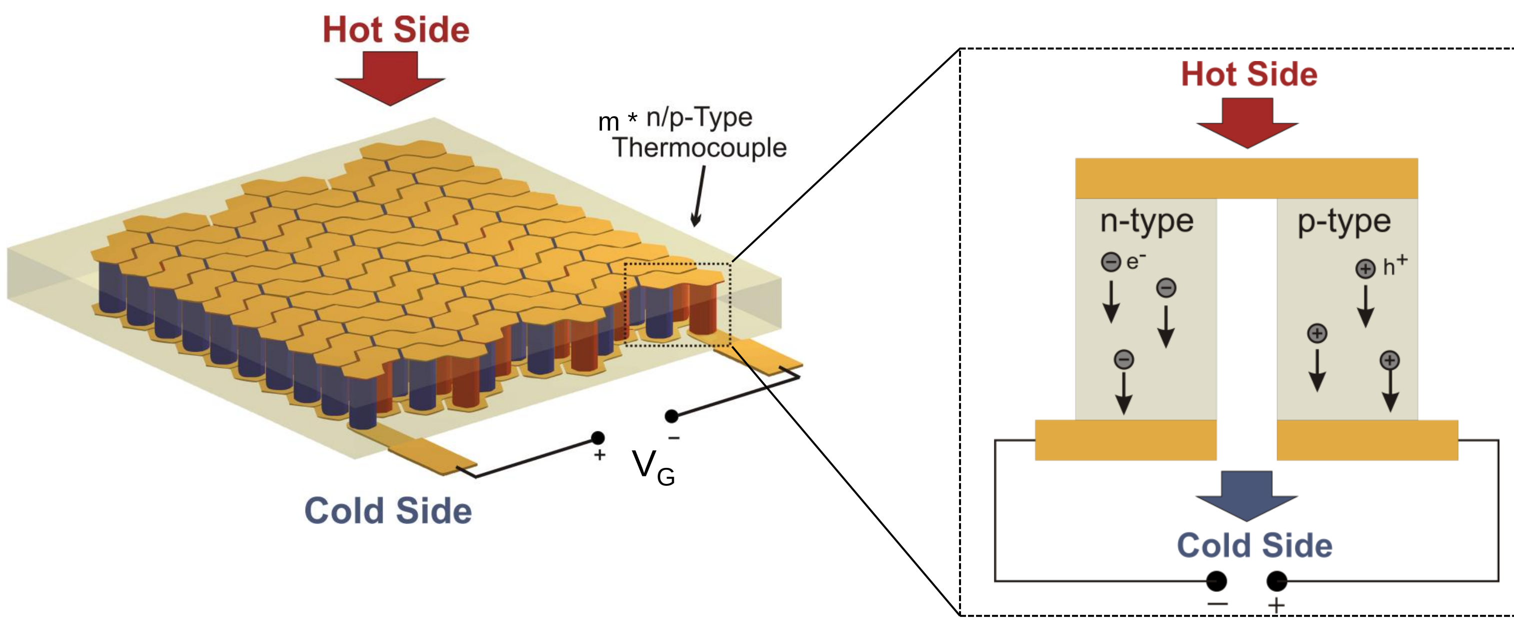
Temperature gradient → Electric potential



Thermoelectric generator (TEG)

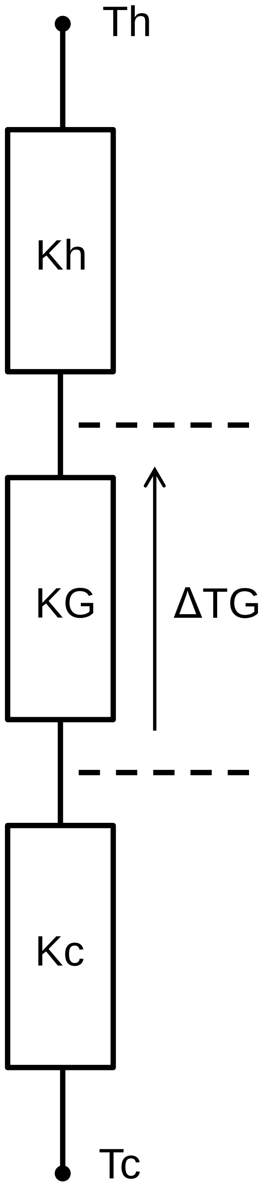


$$V_G = m * \alpha_m \Delta T_G$$



Attributes: Robust, no moving parts, small and light-weight, cheap

Thermoelectric generator (TEG)



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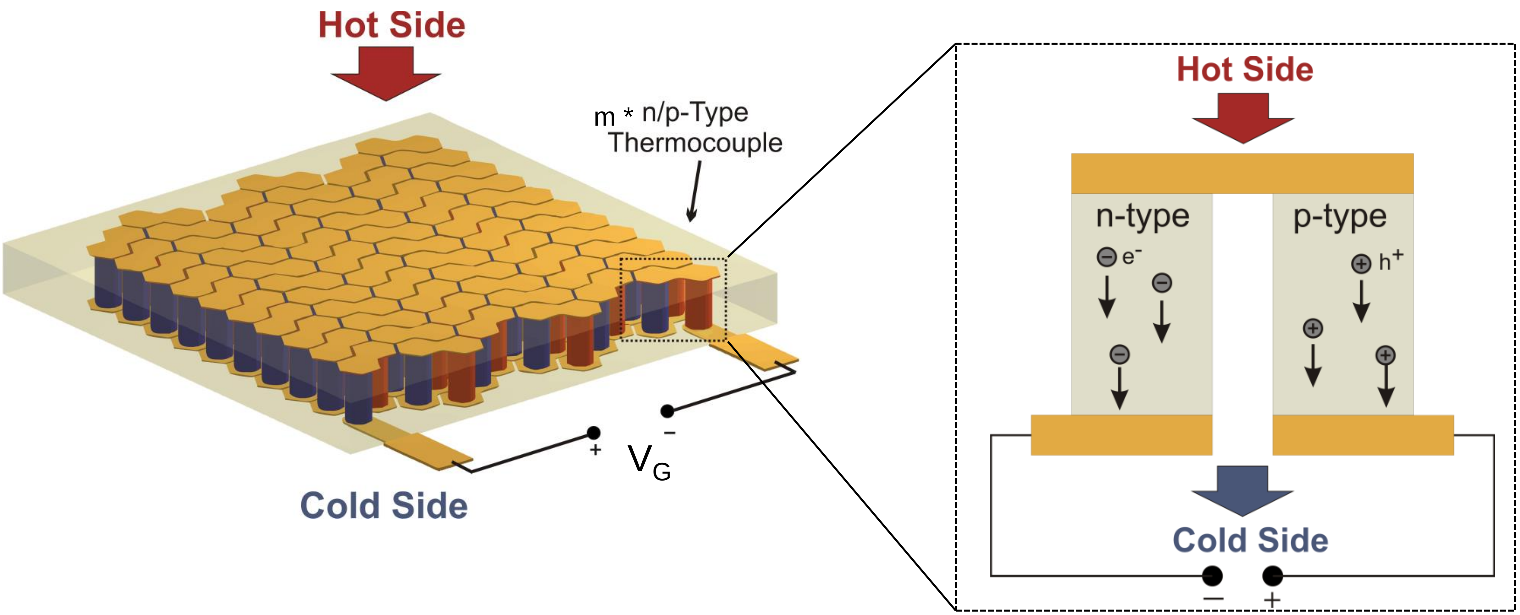
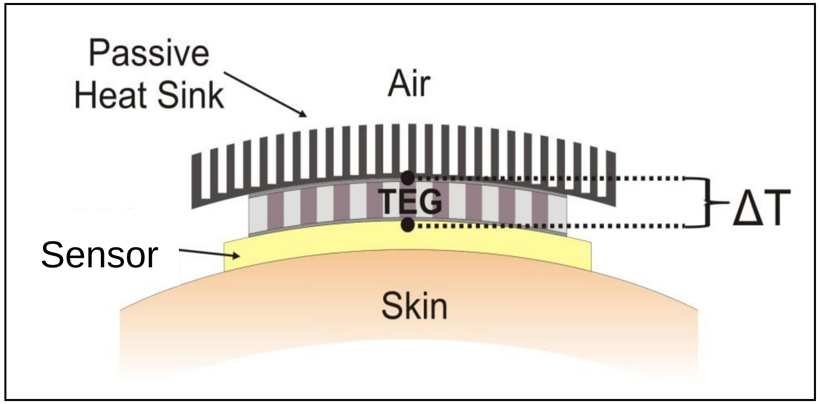


Attributes: Robust, no moving parts, small and light-weight, cheap

So where is the catch? → Efficiency (1-10%), interfacing

Thermoelectric harvesting from the human body

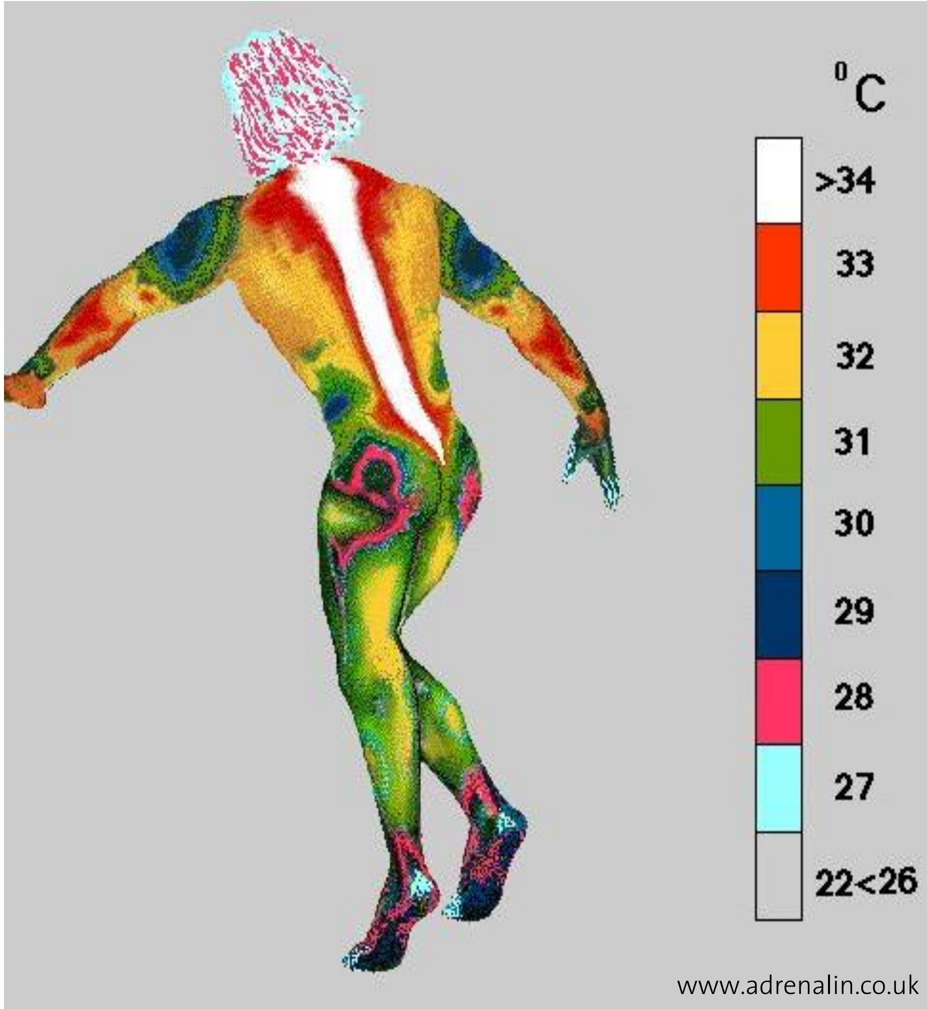


Characteristics:

- Poor thermal coupling
- low ΔT (~ 1 K)

Challenges:

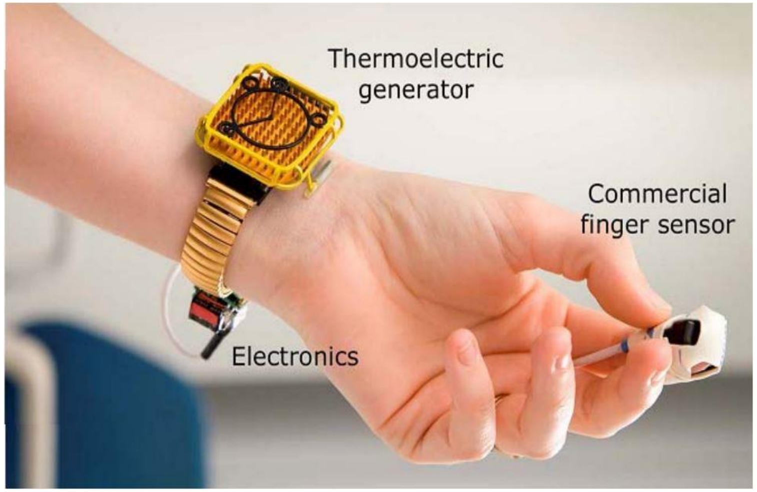
- Thermal matching with skin and air
- Cooling of the skin
- Wearability, comfort, usability

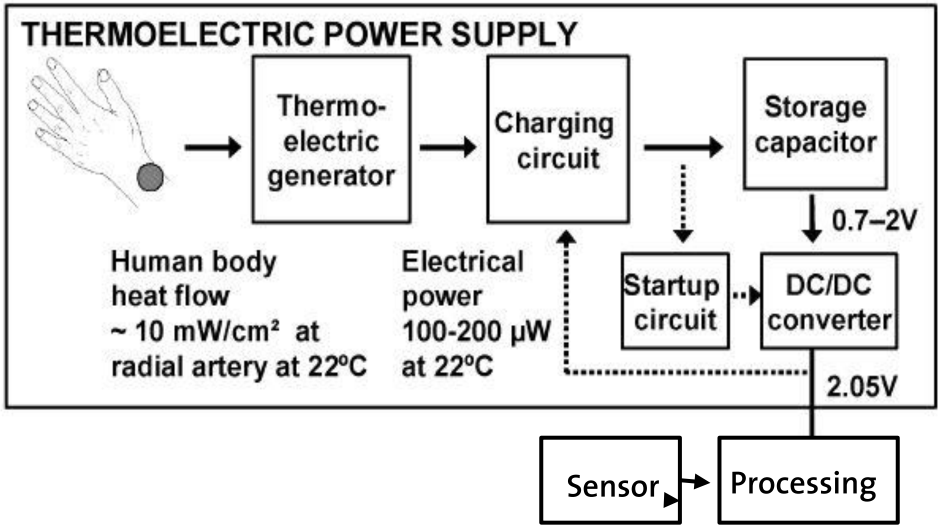


Blood oxymeter

Torf et al. Sens. Trans. J. 80(6). 2007

Sensor type:	Blood oxygen content
Power consumption:	89 µW for 15 s interval
Body location:	Wrist, radial artery
Notes:	Commercial finger sensor
	Custom electronics (CMOS)
	13 cm^2 heat sink

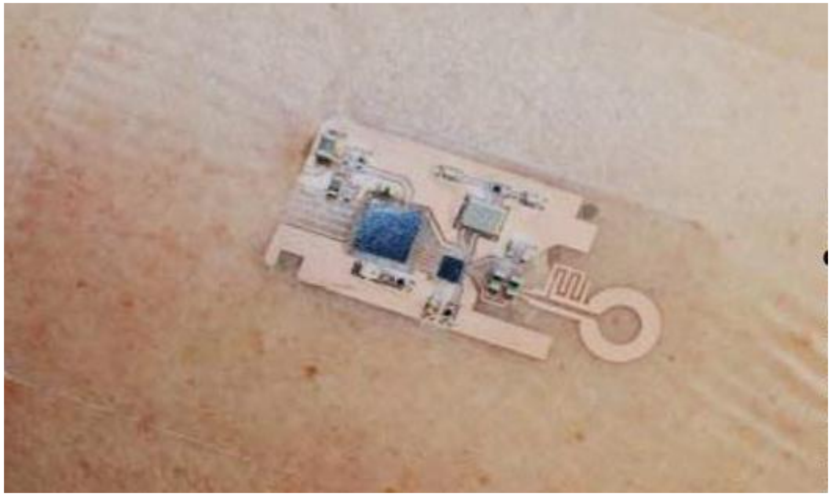




Vision: Wireless sensor node in a flexible band aid

Van Hoof. Cohesi Workshop. 2012

Sensor type:	EEG, ECG, UV, etc.
Power consumption:	not stated
Energy harvesting by:	TEG, PV + supercapacitor
Body location:	Any skin surface
Desired features:	Thin / light weight
	Flexible / stretchable
	Low cost, Disposable / Biodegradable



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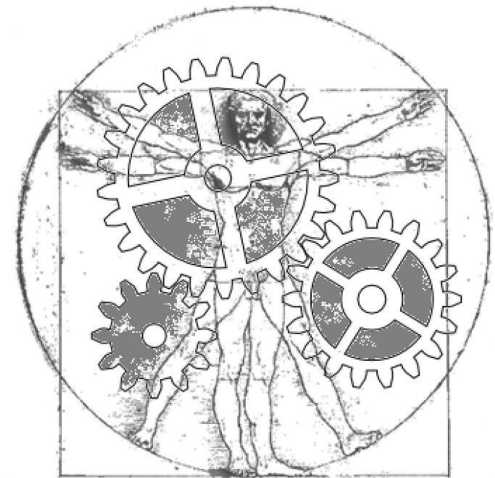
Body Powered Sense Project

nano-tera.ch

- Project objective: **Wearable zero-power IT can be effectively applied in medical devices**

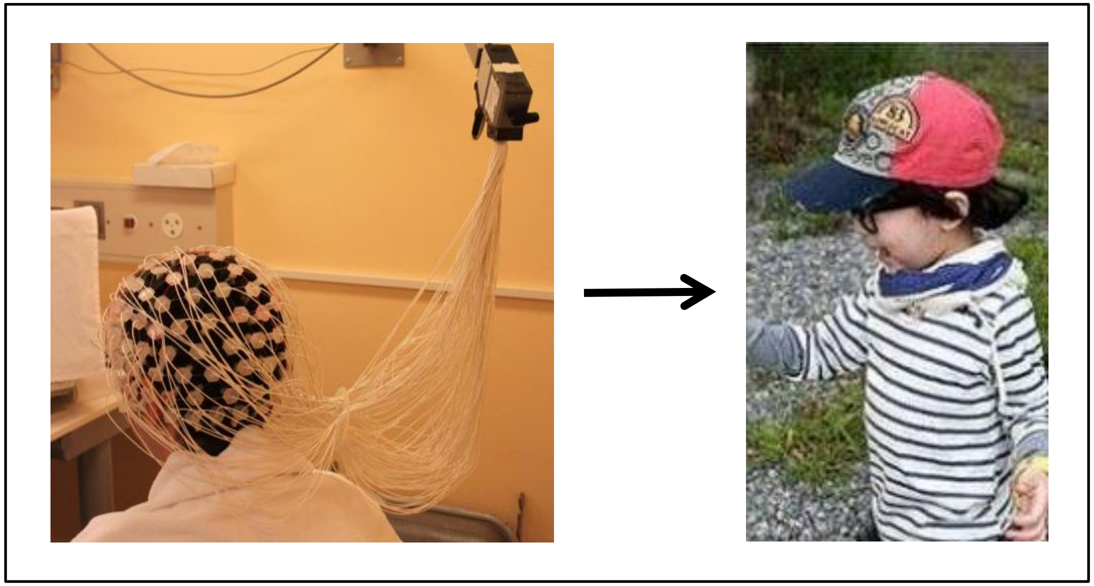


http://BodyPoweredSenSE.ch

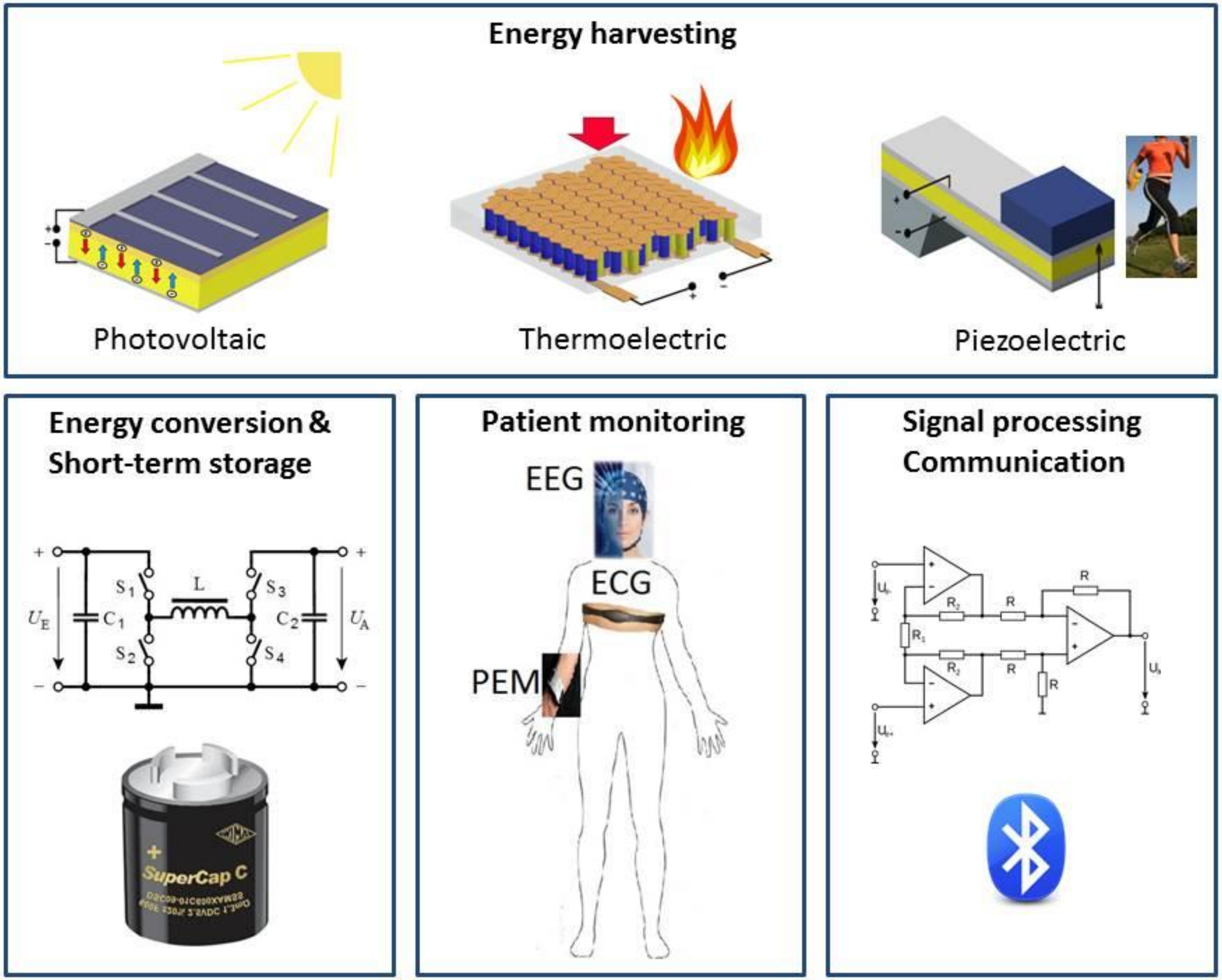
- Specific applications
  - **Alzheimer's detection** in high risk adults
  - **Epilepsy** seizure **diognosis** in children
  - **Long-term** (10 d) measurement outside the lab

- Project partners

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
ETH zürich
CHUV Centre hospitalier universitaire vaudois
KINDERSPITAL ZÜRICH
EXPLORIS from intuition to precision
ByElement Solutions

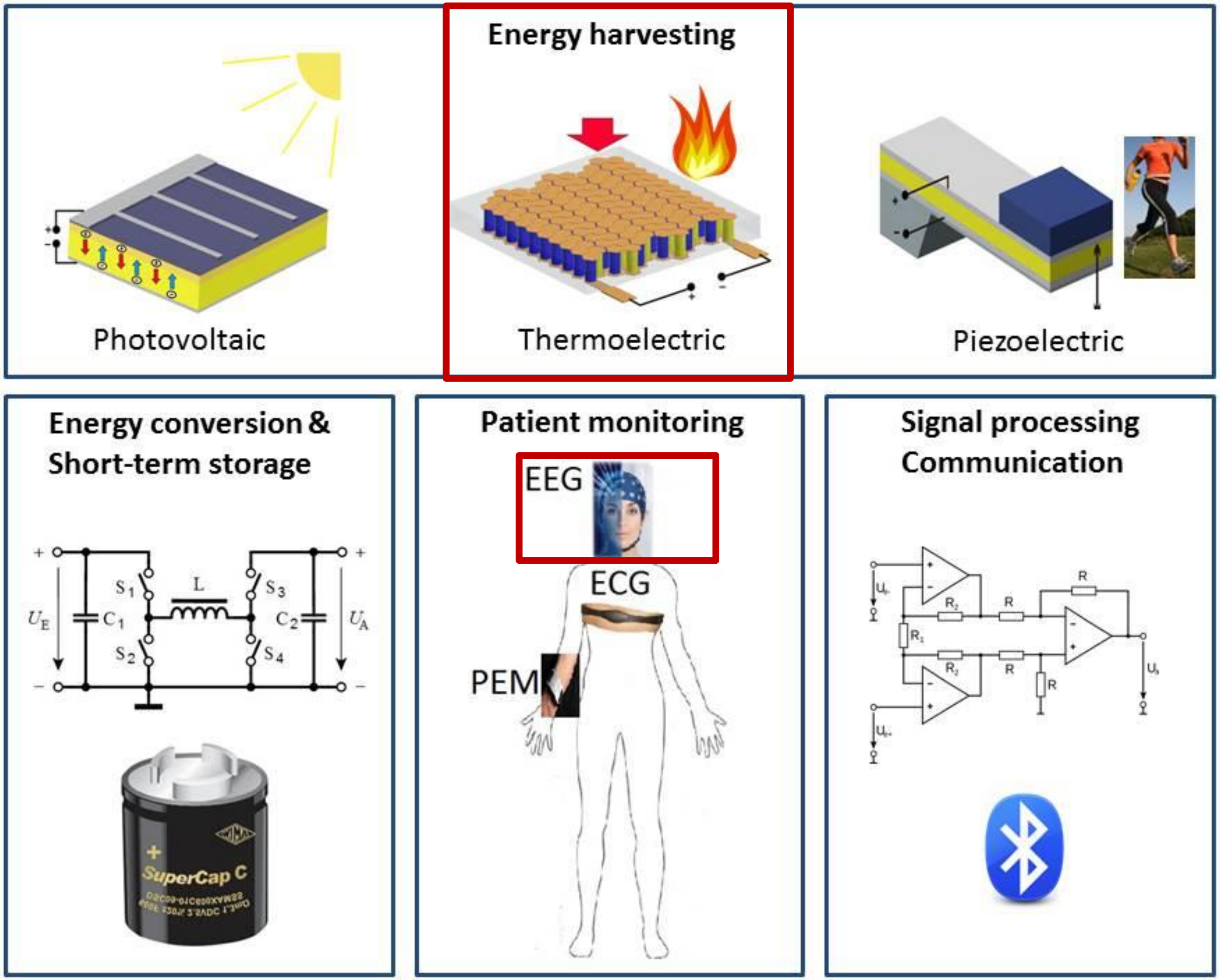


BPS Project



Energy harvesting
Photovoltaic
Thermoelectric
Piezoelectric
Energy conversion &
Short-term storage
L
S1
S2
S3
S4
C1
C2
UE
UA
SuperCap C
Patient monitoring
EEG
ECG
PEM
Signal processing
Communication
R

BPS Project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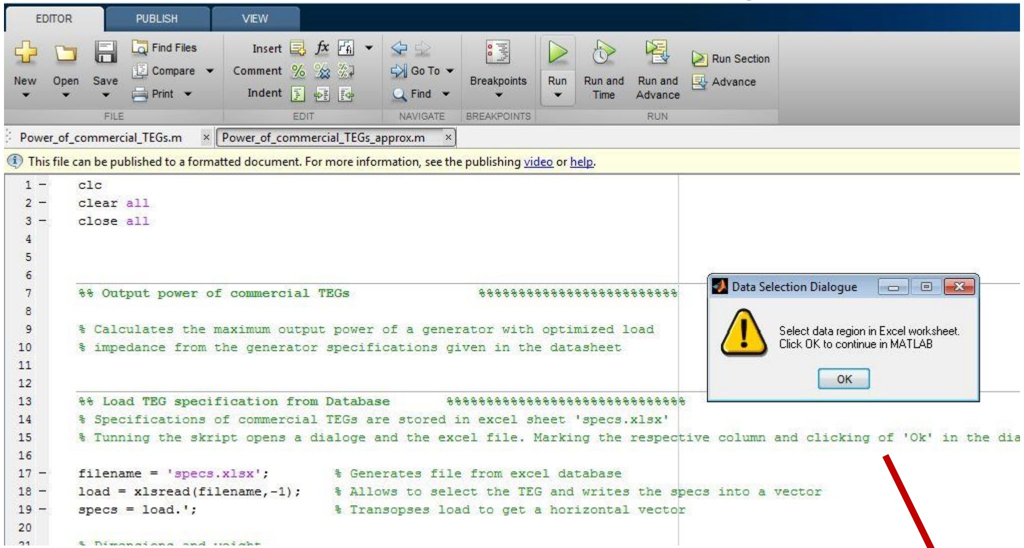
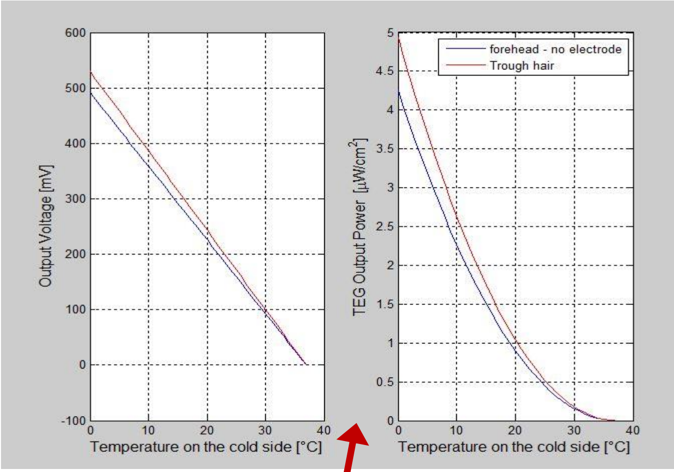
Simulation of expected characteristics

1. Simulation based on numerical solving of heat balance



3. Calculation of output based on TEG specs and boundary conditions



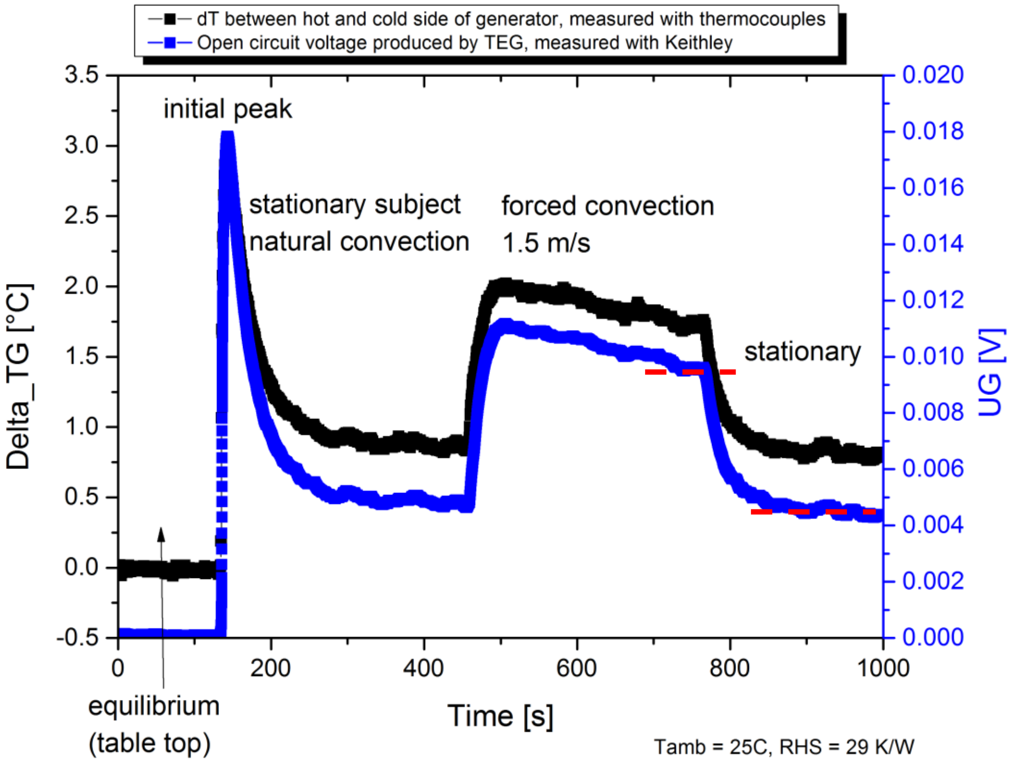
2. Loading of TEG specifications from database

specs [Read-Only]

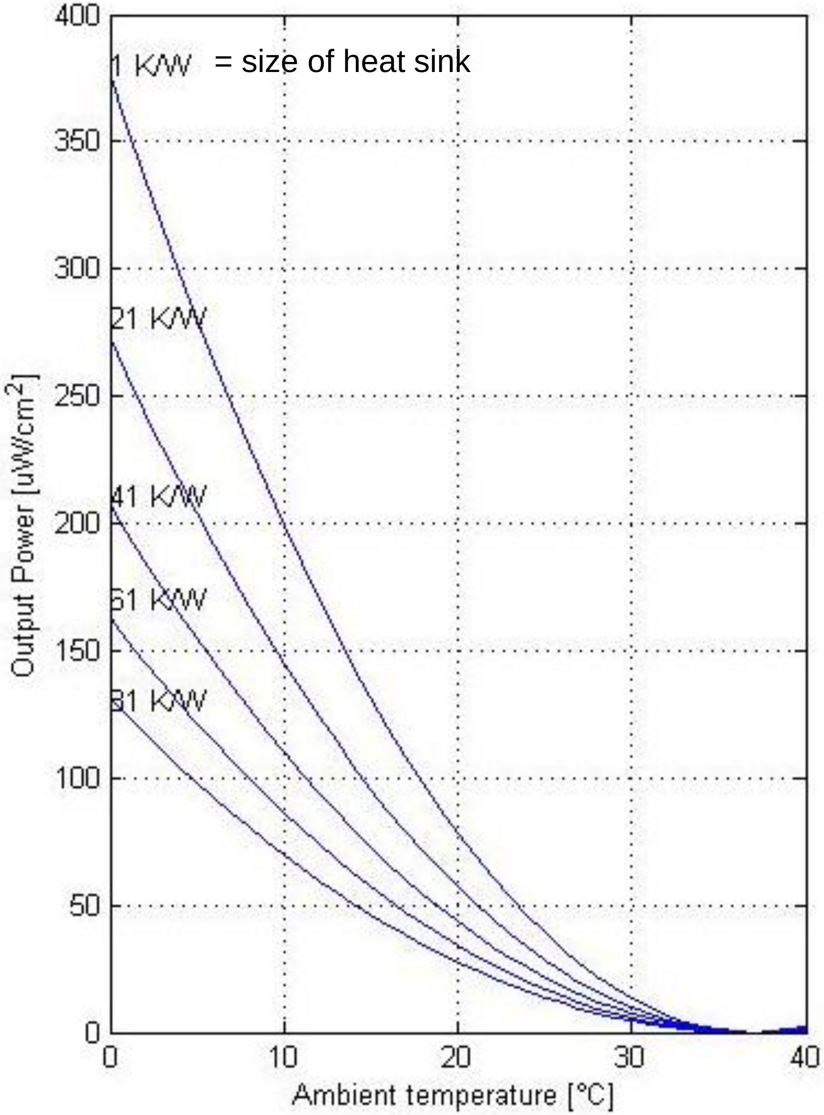
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	**Manufacturer**	**Thermalforce**	**Thermalforce**	**Lairdtech**	**Nextreme**	**Micropelt**	**Micropelt**	**greenTEG**	**Quick-cool (con**	**Hi-Z**	**Hi-Z**	**Hi-Z**	**Hi-Z**	**EURECA**	**EURECA**
2	Model	TEG 017-150-29	TEG 127-175-26	OT20	HV 56	MPG-D751	MPG-D655	gTEG A	QC-32-0.6-1.2	HZ-2	HZ-9	HZ-14	HZ-20	TEG1-9.1-9.9-0.	TEG1-30-30-2.1
3	**Dimensions and Weight**														
4	Length (m)	0.0150	0.0300	0.0123	0.0031	0.0042	0.0033	0.0071	0.0080	0.0290	0.0627	0.0627	0.0750	0.0091	0.0300
5	Width (m)	0.0150	0.0300	0.0062	0.0033	0.0034	0.0025	0.0071	0.0080	0.0290	0.0627	0.0627	0.0750	0.0115	0.0300
6	Height (m)	0.0037	0.0038		0.0006	1.0900	0.0011	0.0010	0.0026	0.0043	0.0066	0.0051	0.0051	2.3000	0.0036
7	Area (cm^2)	2.2500	9.0000	0.7626	0.1023	0.1429	0.0823	0.5041	0.6400	8.4100	39.3129	39.3129	56.2500	1.0465	9.0000
8	Volume (cm^3)	0.8325	3.4200	0.0000	0.0058	15.5764	0.0091	0.0504	0.1664	3.6247	26.0645	19.9710	28.5750	240.6950	3.2400
9	Weigth (g)	10.0	12.0		0.6	1.0	1.0	1.0	2.5	13.5	105.0	82.0	115.0	1.0	15.0
10	**Generator**														
11	Electric resistance (Ohm)	0.2300	1.3600	1.6200	11.2600	300.0000	170.0000	353.0000	2.7000	1.8400	0.6400	0.1000	0.3000	8.8500	3.4100
12	Seebeck coefficient (V/K)	0.000235	0.000465			0.000259	0.000277	0.000169		0.000316	0.000316	0.000316	0.000316		
13	Thermal resistance (K/W)	29.4000	1.4290		13.1000	12.5000	22.0000	42.0000						30.0300	3.2050
14	Number of thermocouples ()	17	127			540	288	142	32	97	97	49	71		
15	Generator net seebeck voltag	0.004000	0.059000	0.000000	0.000000	0.139860	0.079776	0.023998	0.000000	0.030652	0.030652	0.015484	0.022436	0.027000	0.053700
16	Figure of merit														
17															
18	To load generator parameters into Matlab, select column and			click 'ok'											
19	Datasheet values at 300 K														
20	Calculated from datasheet														

Low R_{el} generator evaluation

Dynamic measurement of single generator



Static simulation (ideal electrical matching)



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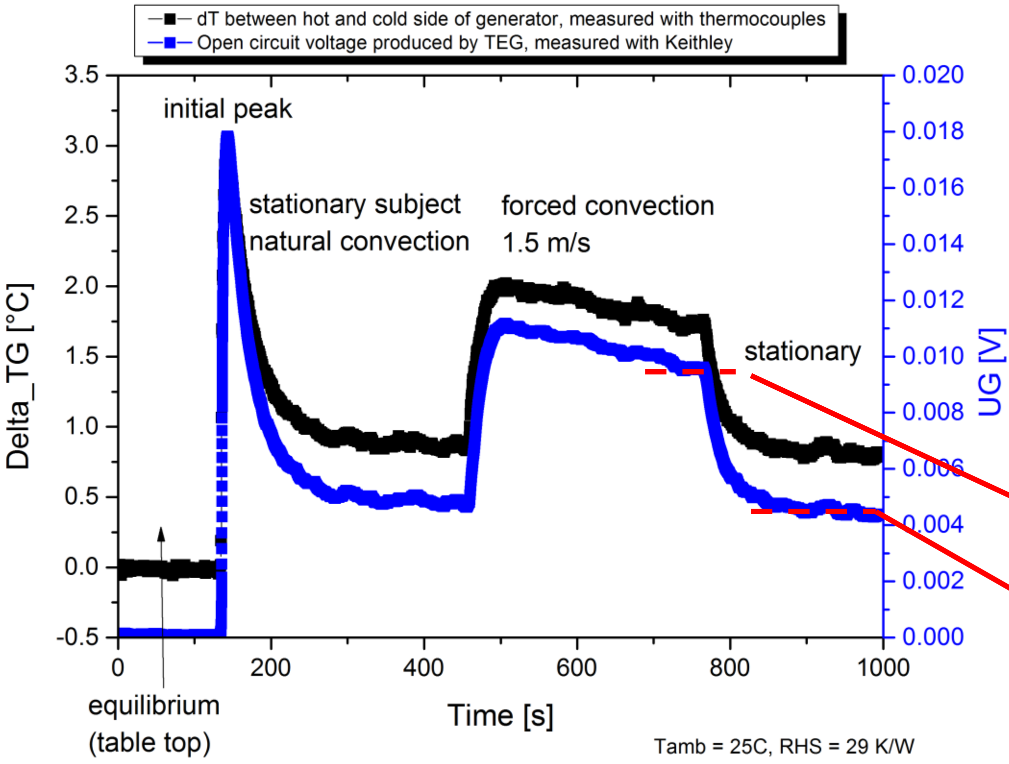

Promising for compact power supply.

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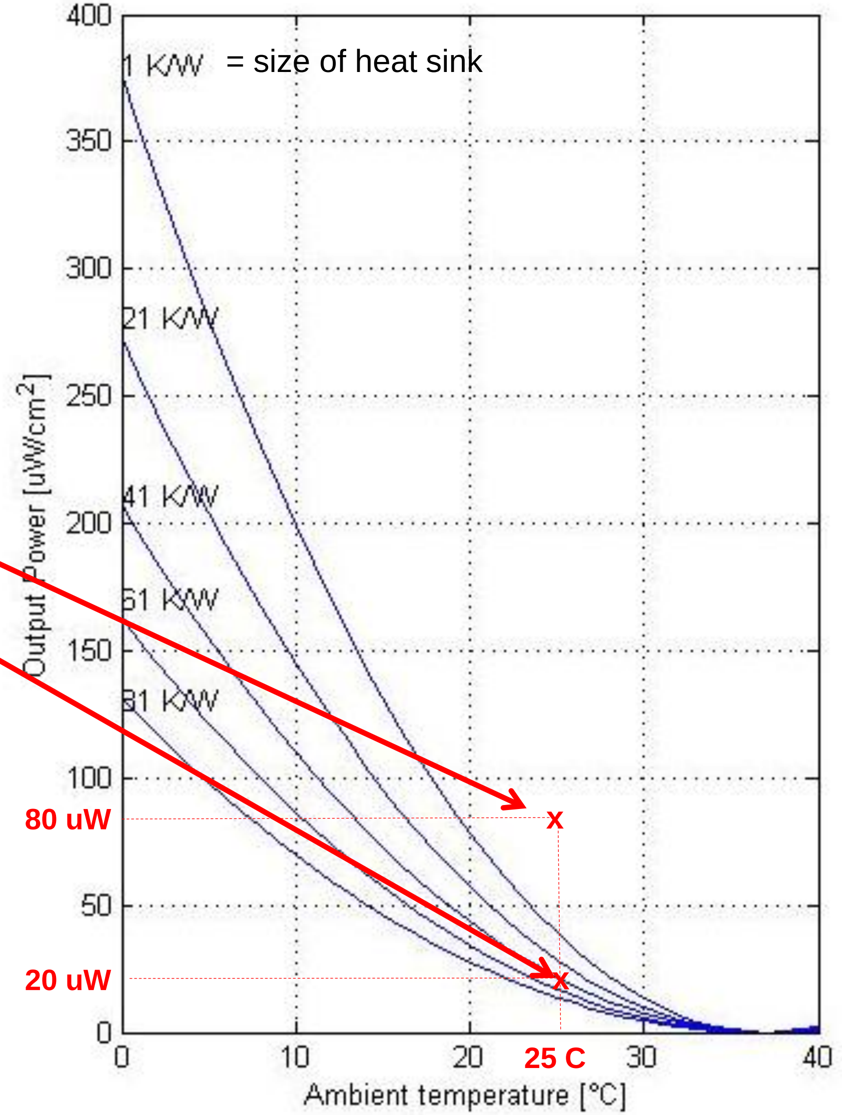

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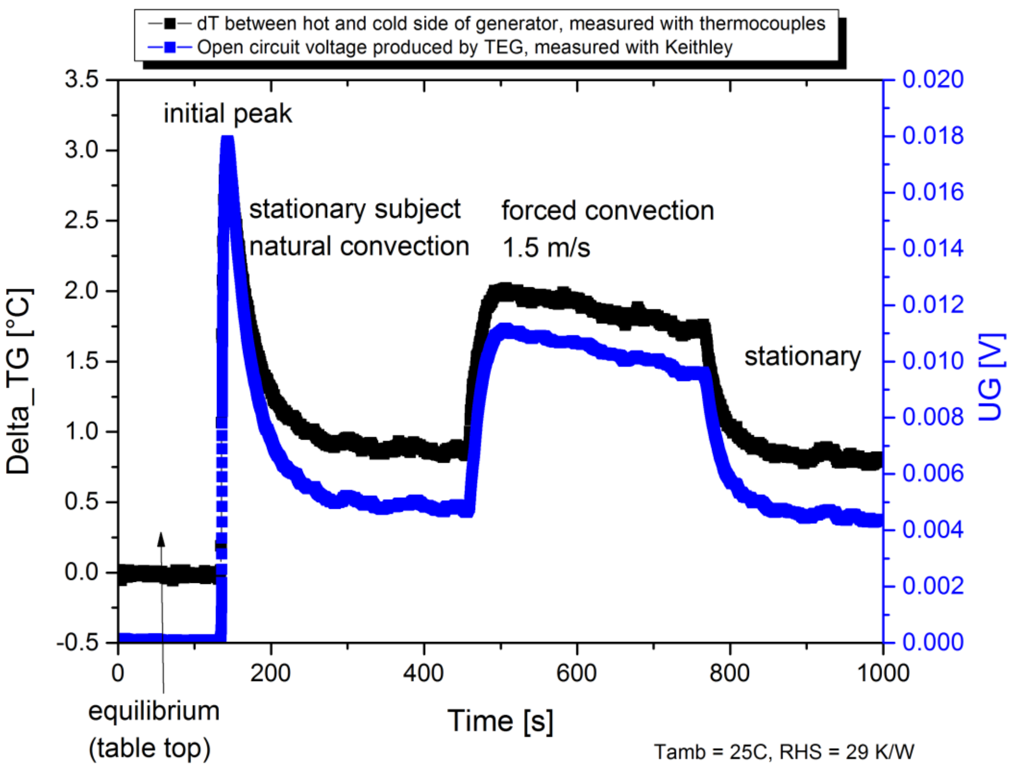

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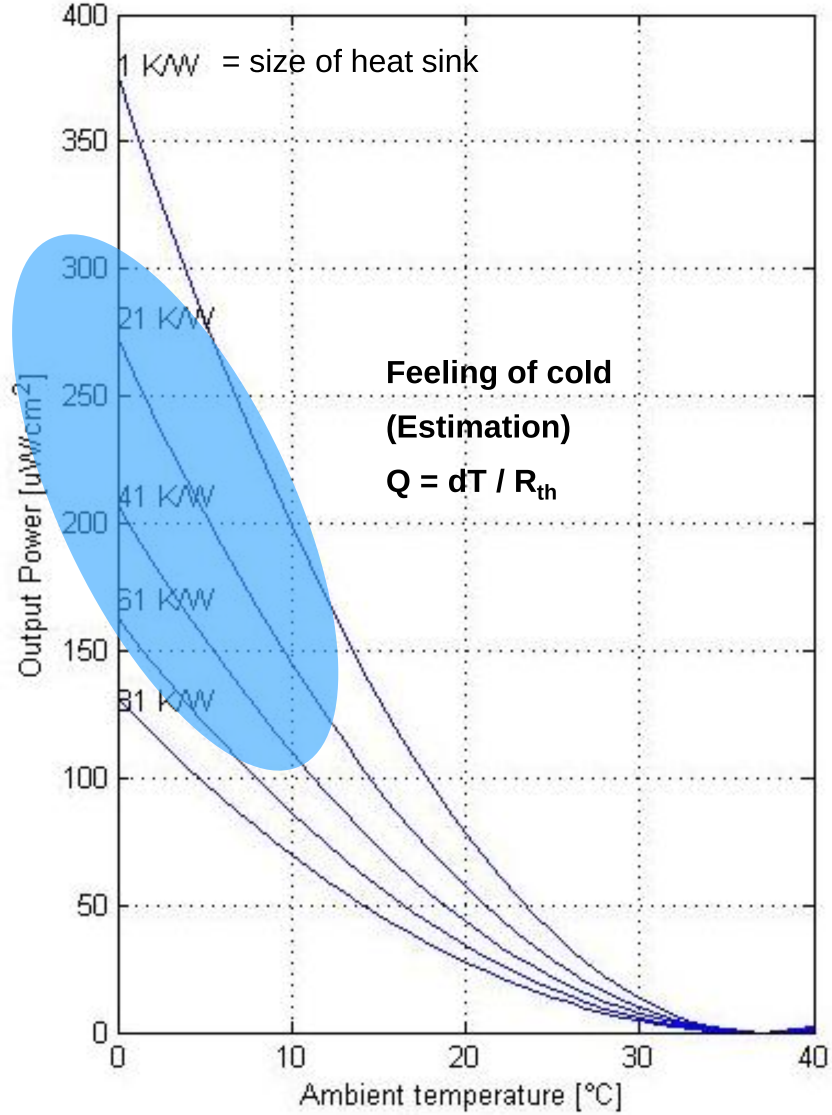
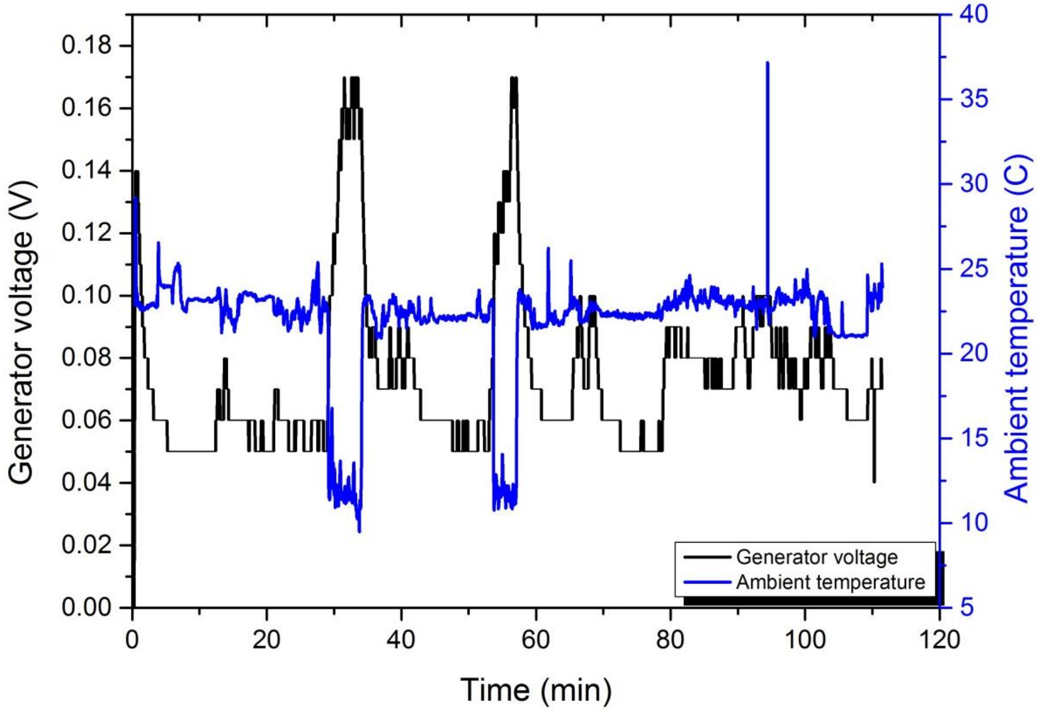
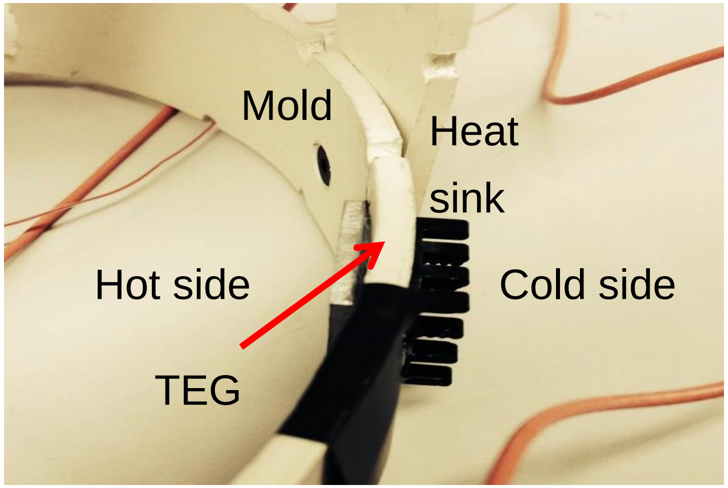


Promising for compact power supply.

Engineering vs human centered design!

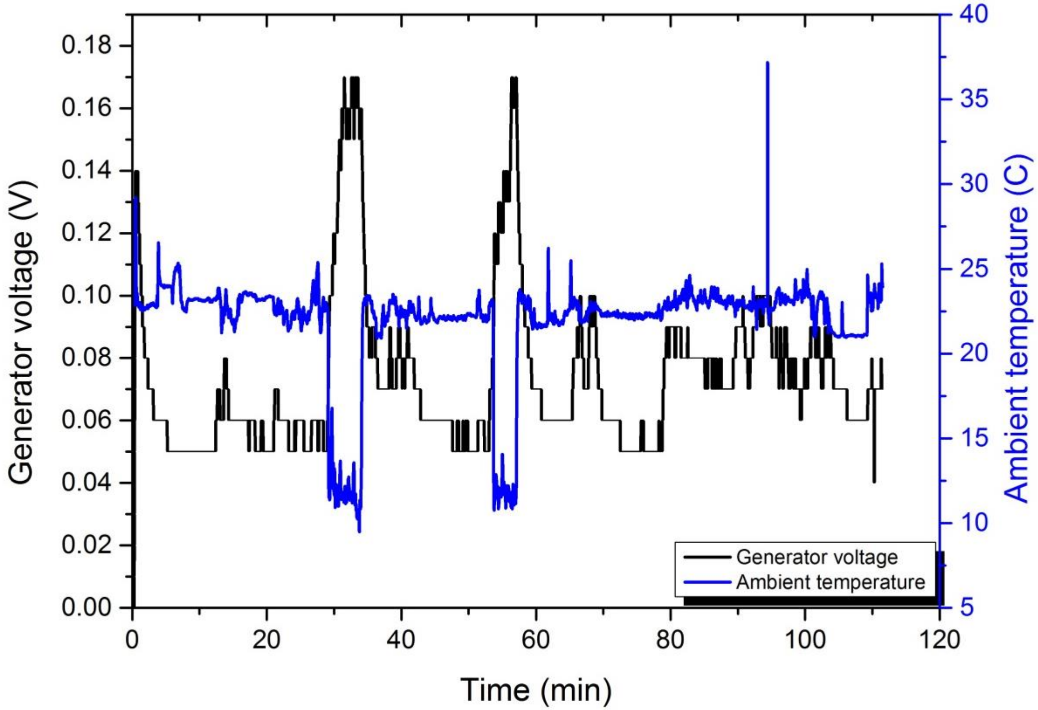
Prototype for generator headset





Measurement time:	2	h
Average Voltage	74	mV
Max. Voltage	170	mV
Min. Voltage	40	mV
Average Power	0.55	mW
Max. Power	2.62	mW
Min. Power	0.14	mW

Prototype for generator headset



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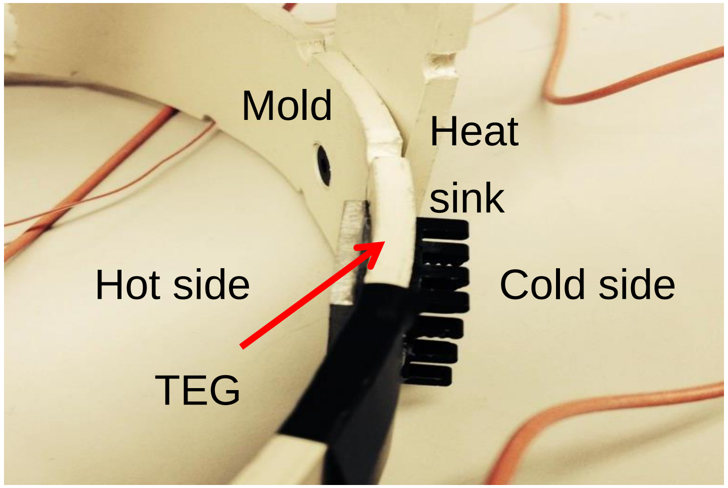
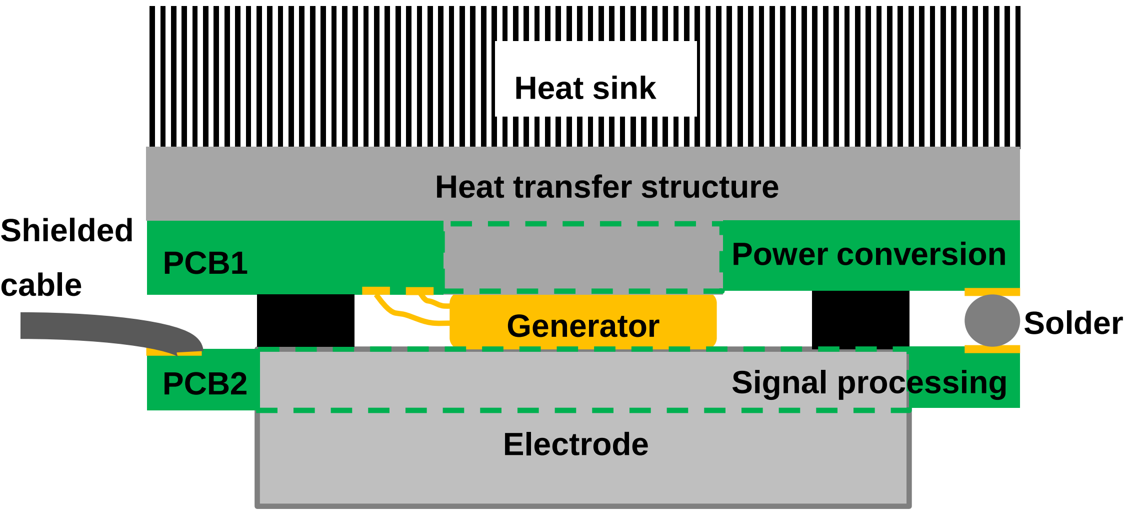
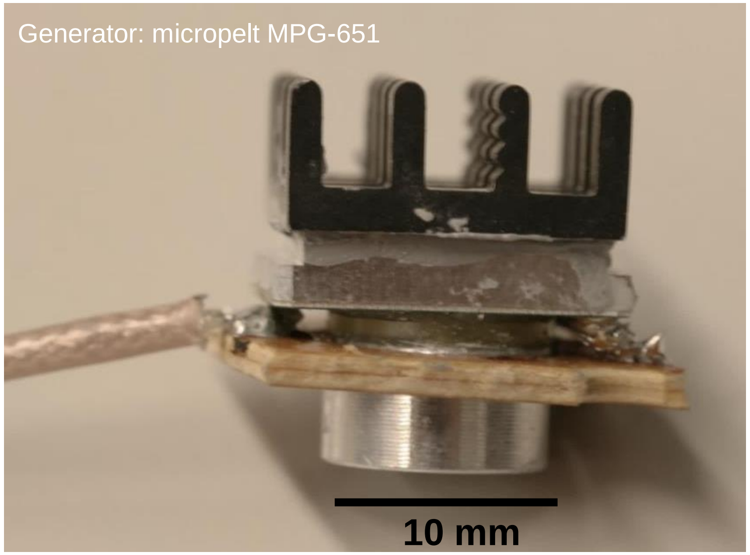


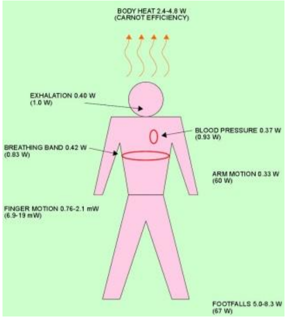
Current research: Energy autonomous active EEG electrode



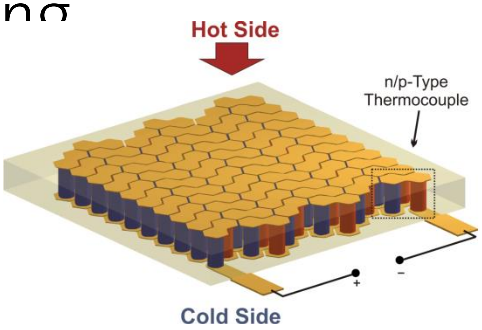


Conclusions

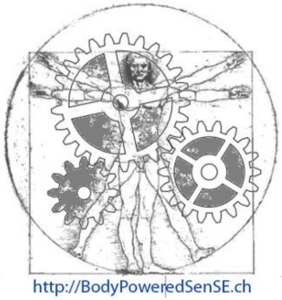
- The human body provides a variety of energy resources
  - Movement
  - Biochemical
  - Heat



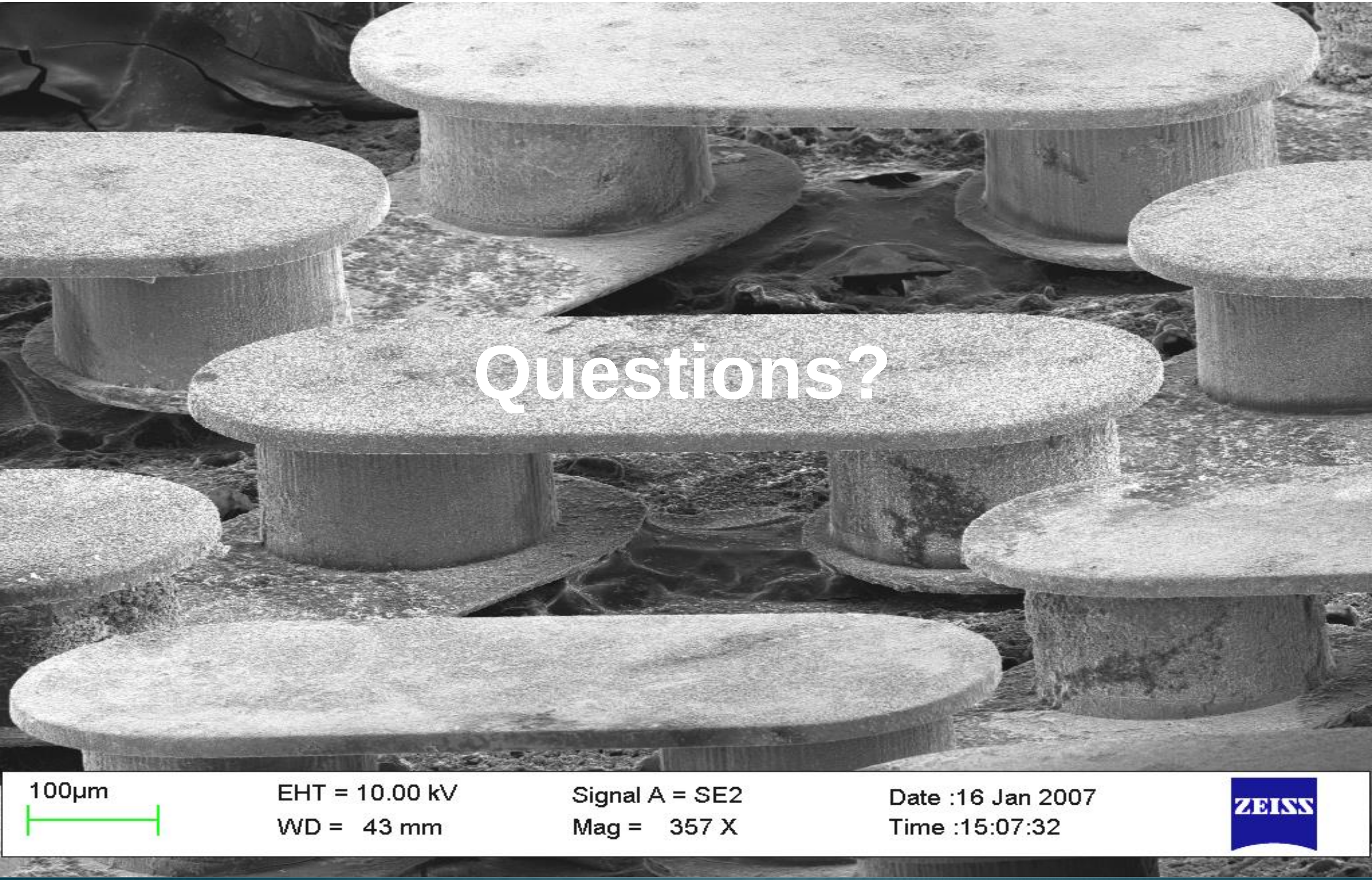
- We can tap into these resources with matching harvesters
  - Electromagnetic
  - Piezoelectric
  - Electrochemical
  - Thermoelectric



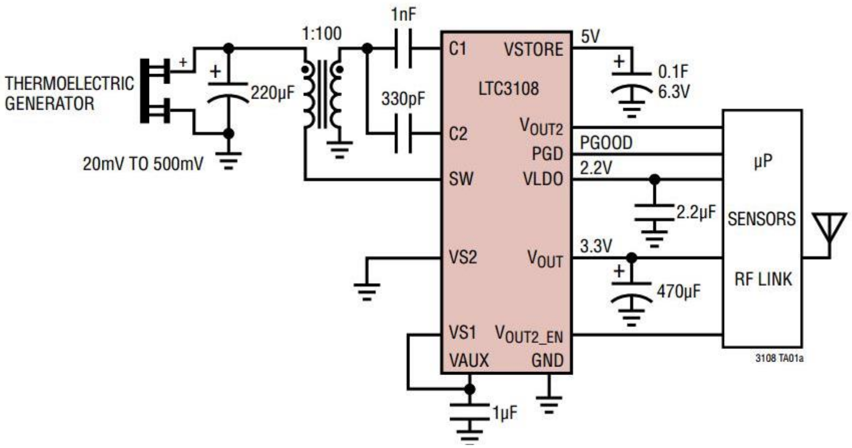
- TEG based energy harvesters can be used to power body sensor networks

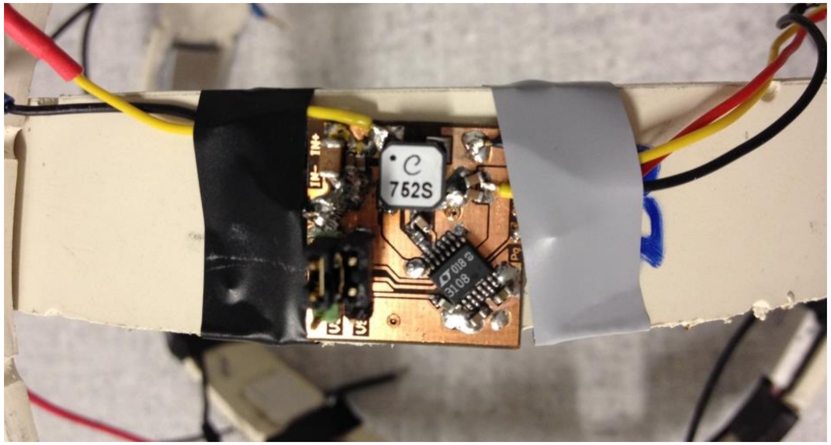


Thanks for your attention!



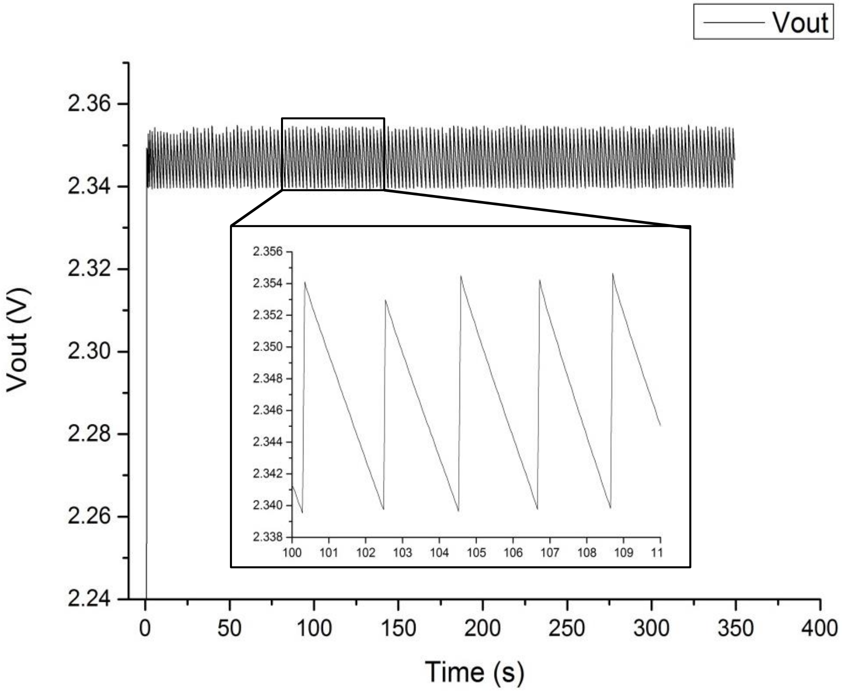
Headset + LTC3108 DCDC converter





- Uin = 20 mV – 500 mV
- Rin = 2 – 10 Ohm
- Efficiency = 40% (1:100,V_{in}=60mV,V_{out}=4.5V)

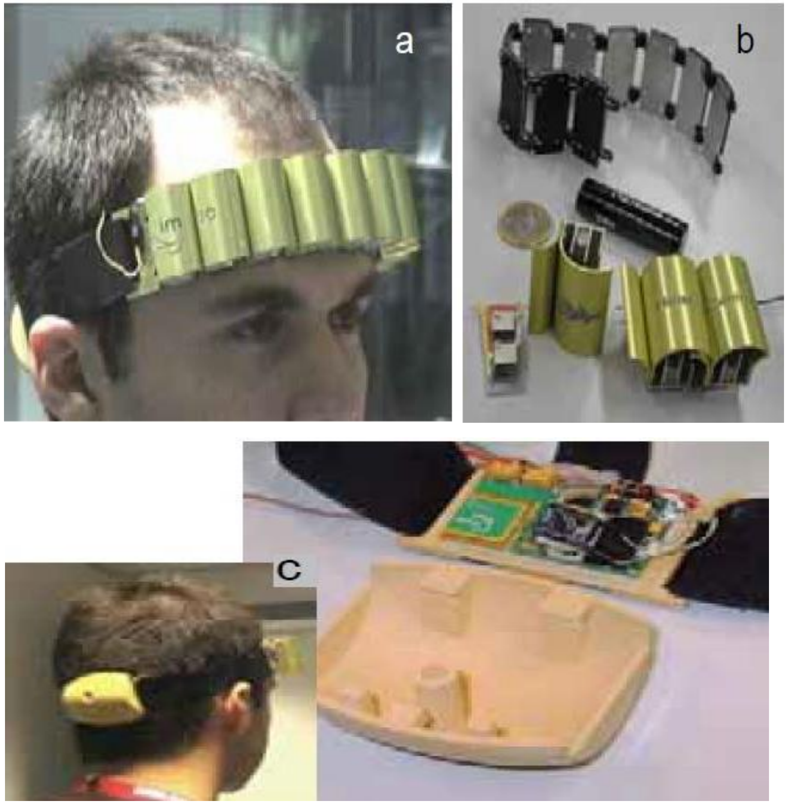
- Stable output of 2.3 V produced with headset
- Can trickle charge capacitor
- Blinking of LED



Wearable battery-free wireless 2-channel EEG system

Van Bavel et al. Sens. Trans. J. 94(7). 2008

Sensor type:	Electroencephalogram (EEG)
Power consumption:	0.8 mW
Body location:	Forehead
Notes:	Channels: 2 2.4 GHz radio transceiver CMOS based EEG frontend 40 s to startup Temperature range: 21-26 ° C



Implanted

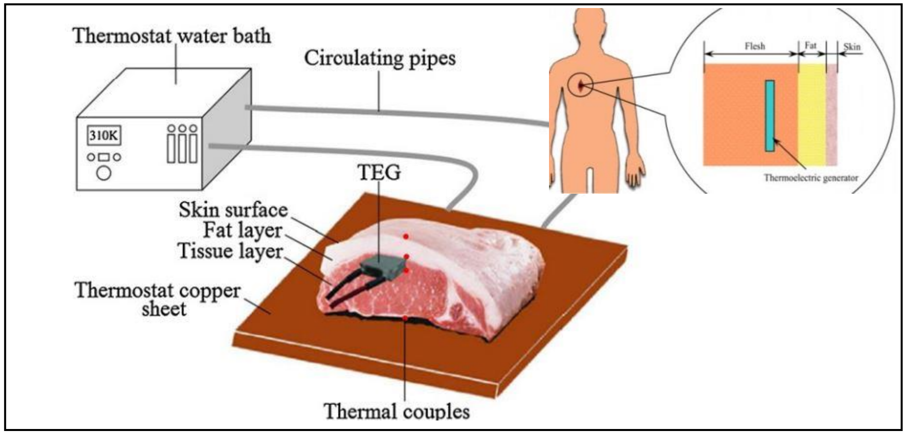
Characteristics:

- Good thermal coupling (fluid, forced convection)
- Small size (typically < 1cm^2)

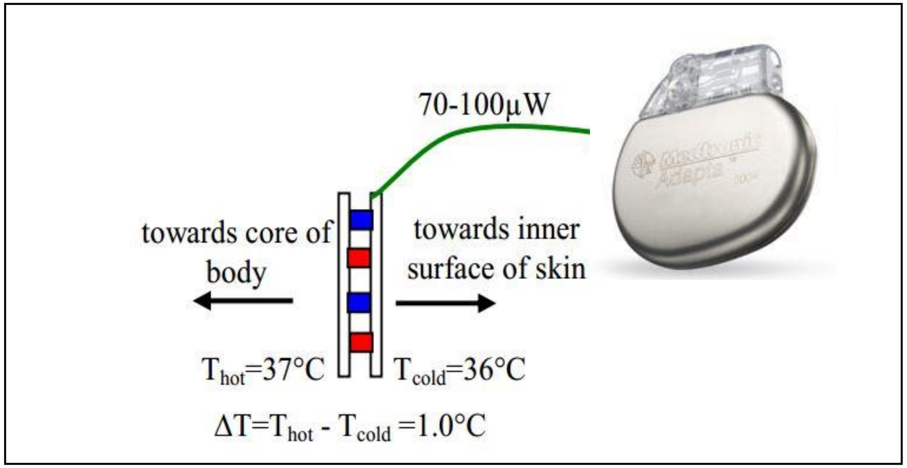
Challenges:

- Biocompatibility of materials
- Packaging
- Corrosive environment

Current stage: In-vivo testing (animals)



Yang et al. J. Phys. D: Appl. Phys. 40. 2007



Based on: Venkatasubramanian et al. 6th Int. Workshop on Micro and Nanotechnology for Power Gen. and Energy Conversion Appl. 2006

Spin-off Company

- 2009 Foundation of greenTEG
- Products:

Heat Flux Sensing

gSKIN®

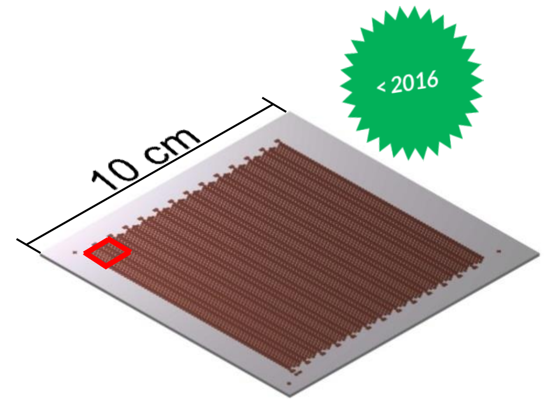
- Applications:
  - Heat flux in buildings
  - Fluid flow measurements
  - Solar, infra-red and laser power sensing

Energy Harvesting

gTEG ®

- Applications:
  - Wireless sensor nodes
  - Consumer electronics

Waste Heat Recovery



- Applications:
  - Automotive industry
  - Power plants
  - Ships

Flexible Bi_2Te_3 µTEGs

- Fabrication process requirements:
  - Scalable and low-cost fabrication method
  - Flexibility in design parameters
  - High thermocouple length (~100-300 µm)
- Fabrication approach used at MNS:
  - Electrochemical deposition (ECD)

  → low temperature, high deposition rate,

  large scale batch fabrication
  - Substrate: polymer mold

  → cheap, flexible, light