EnerHarv 2024

PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

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EnerHarv 2024 Workshop:

Thermal Energy Harvesting:

From Low to High ΔT

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Thursday, June 27, 2024

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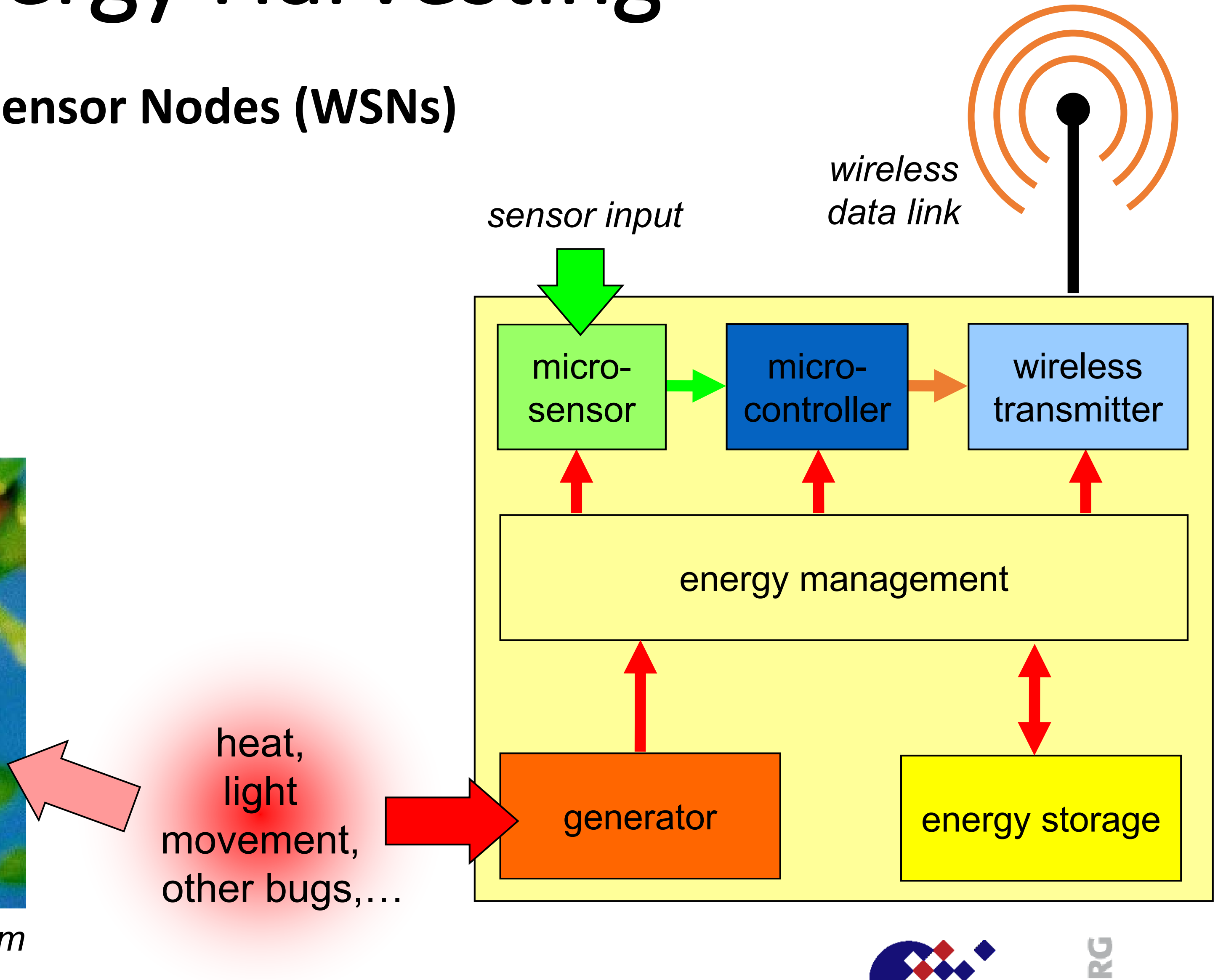
The Vision: Micro Energy Harvesting

… for Energy-Autonomous Wireless Sensor Nodes (WSNs)

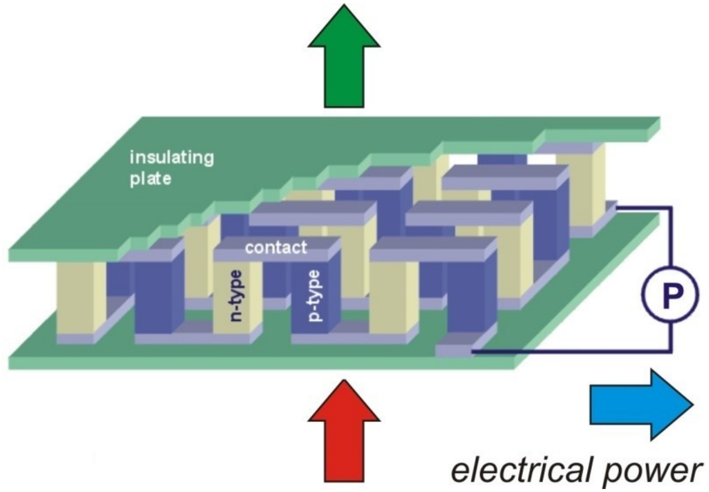
- „always on“
- no battery recharging or exchange
- no power cords
- easy to install …
- … in numerous applications

Graphosoma lineatum



Thermoelectric generators (TEGs)

heat sink: Temperature T_1



heat source: Temperature T_2

Seebeck voltage ΔU

$$\Delta U = n \cdot \alpha \cdot \Delta T$$

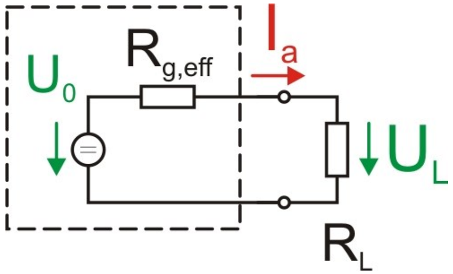
n: *number of thermocouples*

α: *Seebeck-coefficient of thermocouples*

ΔT: *temperature difference at the TEG*

electric output power

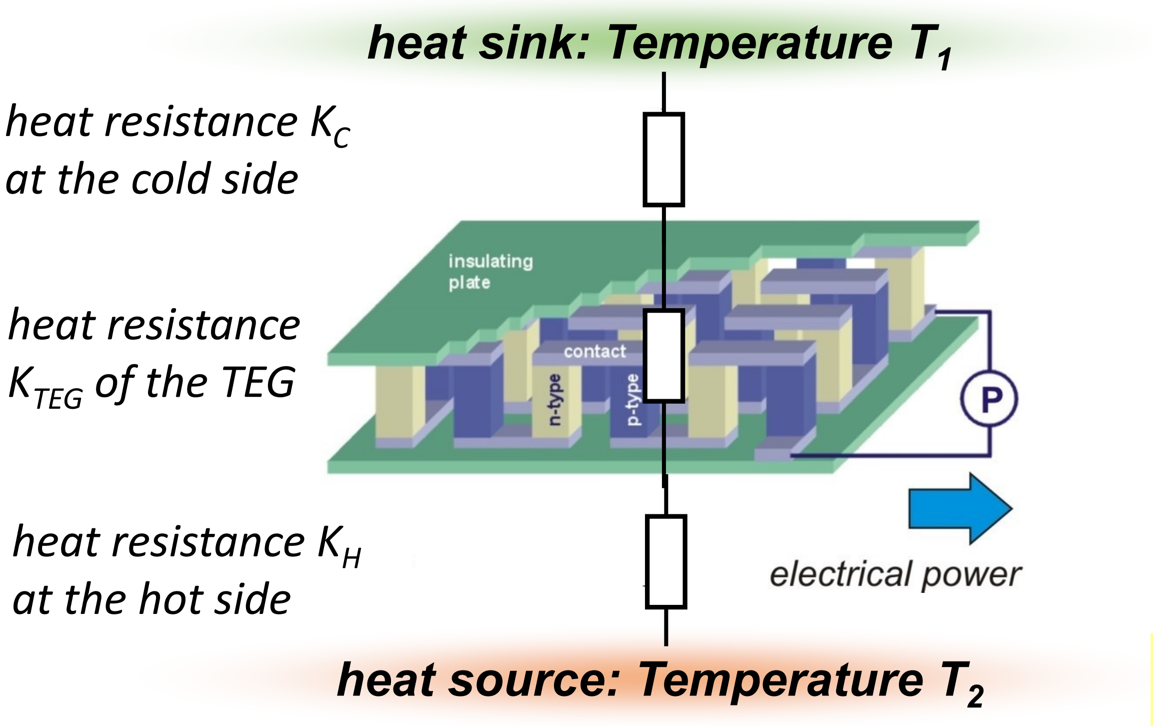
$$P_{el} = \frac{n^2 \cdot \alpha^2 \cdot R_L}{\left(R_{g,eff} + R_L\right)^2} \cdot \Delta T^2$$



Properties

- no moving parts
- DC-like currents, however…
- **voltage polarity changes** with the direction of the temperature field
- very low to fair output voltages (10 mV … V)

TEGs: influence of thermal resistances



real temperature difference at the TEG

$$\Delta T_{TEG} = \underbrace{\frac{K_{TEG}}{K_H + K_{TEG} + K_C}}_{d:\ thermal\ feed\ factor} \cdot (T_2 - T_1) = d \cdot \Delta T$$

realistic electric output power

$$P_{el} = \underbrace{\left(\frac{K_{TEG}}{K_{TEG} + K_H + K_C}\right)^2}_{d^2} \cdot (n \cdot \alpha)^2 \cdot \Delta T^2 \frac{R_L}{(R_{g,eff} + R_L)^2}$$

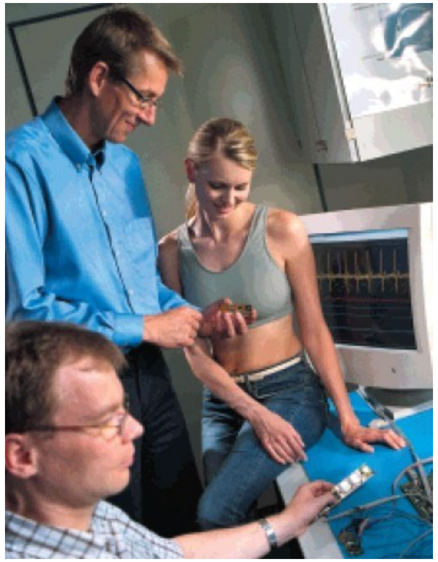
Resumee

- Thermal heat resistances - and the heat flux - play a crucial role for the electric output power.
- The electric output power scales with ΔT^2.

Small ΔT applications

Boundary conditions

- small ΔT: **one to a few Kelvin**
- small heat flux
- highly dynamic fluctuations of both can happen



human, biomedical, …

home automation

Infrastructure monitoring

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Small ΔT: example infrastructure monitoring in tunnels

What for ?

- traffic monitoring
- environmental monitoring
- detection of accidents, explosions, earthquakes,…
- structural health monitoring

Available energies in a tunnel ?

	railway tunnel	car tunnel
thermal	✘	✘ ✓
sound	✘ ✓	✘ ✓
vibration	✓	✘
airflow	✓	✓

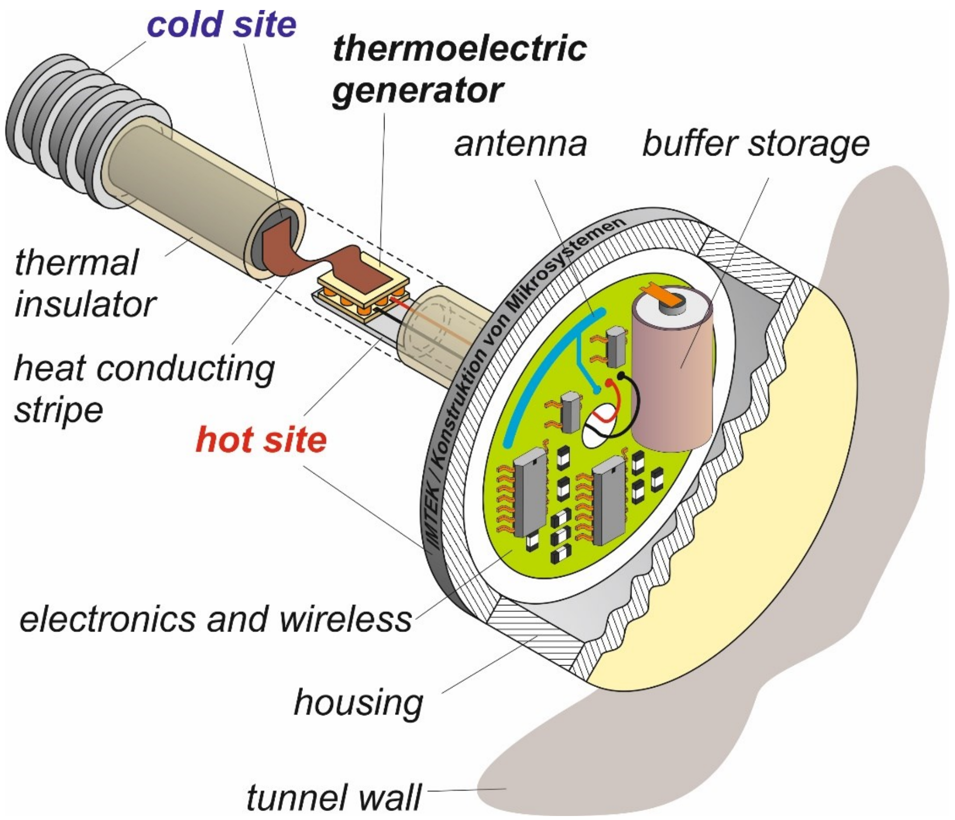
Geothermal energy harvesting in tunnels?

Concept

- thermal probe embedded in the tunnel wall
- thermoelectric energy harvesting between the (cold ?) tunnel bed and the (warmer ?) wall surface

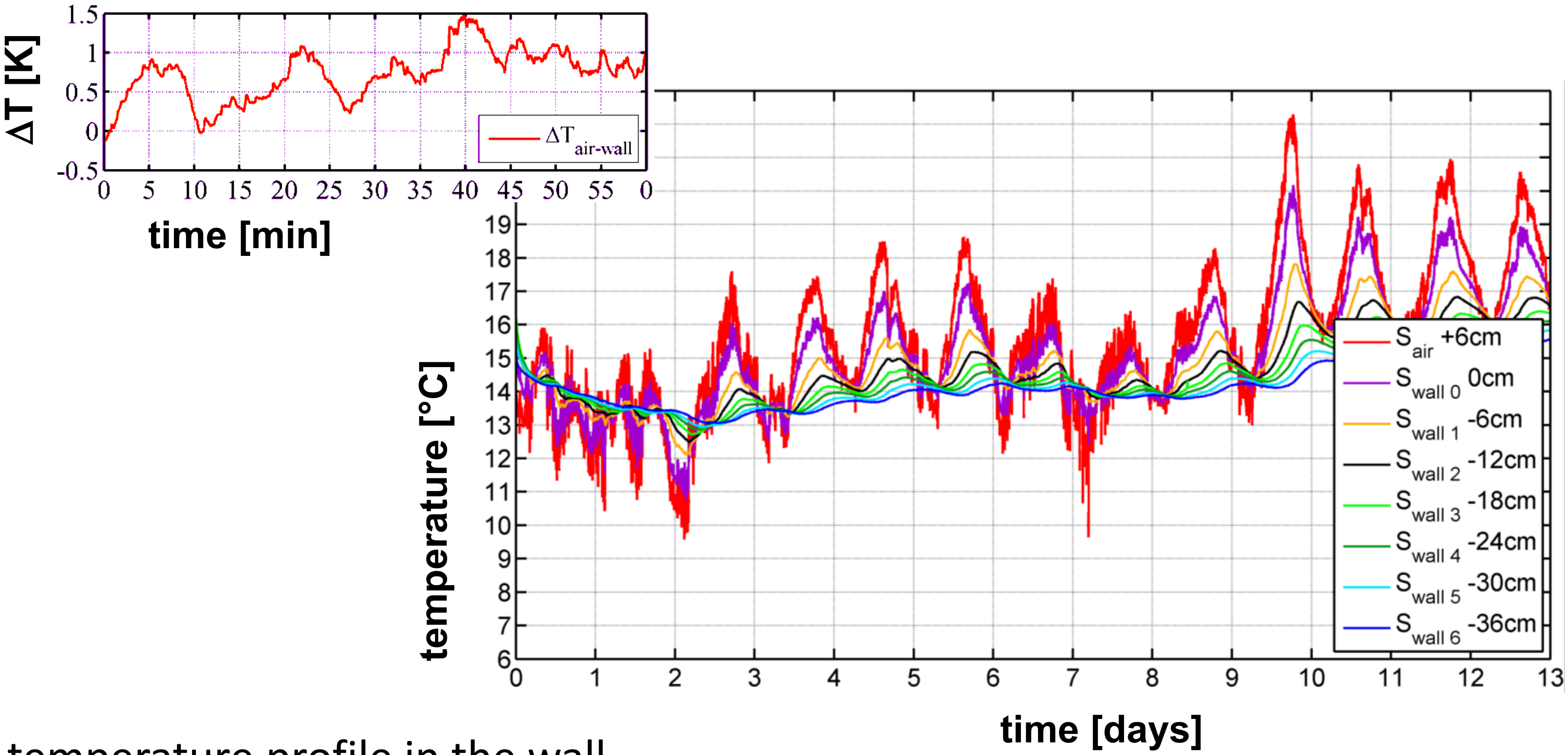
But first: measurement of the available ΔT

- temperature profile in the wall
- surface and air temperature
- wind speed



geothermal probe with integrated thermoelectric generator (conceptual drawing)

Temperature budgets in a road tunnel: measurements



Hugenwald tunnel,
Freiburg, Gemany

Results

- predictible temperature profile in the wall
- highy dynamic air temperature
- influence of weather and traffic density
- **small temperature gradients (1…2 K) between tunnel wall and air**

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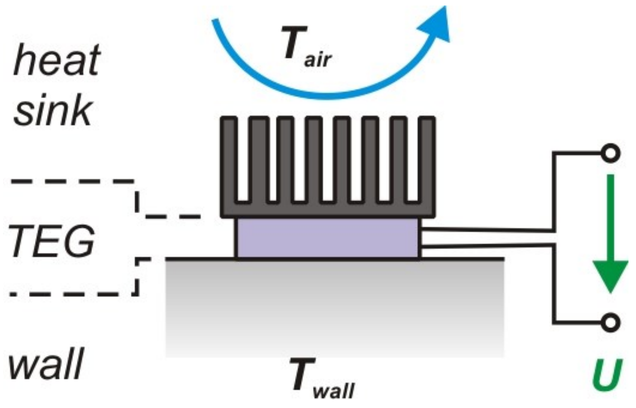
TEG at a wall-air interface with static and low ΔT



thermal | TEG and ΔT | electrical

$$P_{el} = \underbrace{\left(\frac{K_{TEG}}{K_{TEG} + K_H + K_C}\right)^2}_{d^2} \cdot (n \cdot \alpha)^2 \cdot \Delta T^2 \cdot \frac{R_L}{\left(R_{g,eff} + R_L\right)^2} \cdot \eta_{DC-DC} = E \cdot \Delta T^2$$

DC-DC-converter efficiency, as only small output voltages are expected

Design considerations under static conditions

- make the thermal resistances small ➡ larger **d** through a **large heat sink** with a **small K_C**
- use highly efficient TEGs ➡ larger Seebeck coefficient **n·α**
- use a highly efficient DC-DC converter ➡ high power conversion efficiency **η_{DC-DC}**, low start voltage

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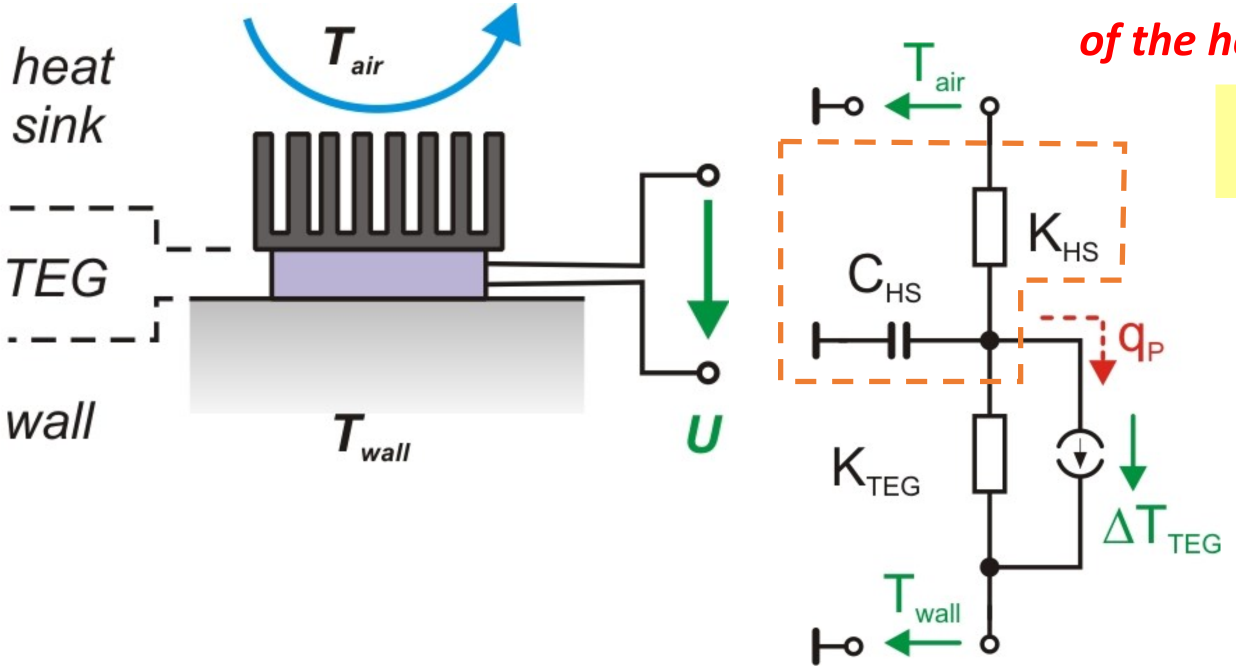
TEG at a wall-air interface with dynamic and low ΔT



thermal time constant* τ *of the heat sink:

$$\tau = K_{HS} \cdot C_{HS}$$

simplified transfer function (for optimal thermal wall coupling)

$$\Delta T_{TEG} = T_{wall} - T_{air} \cdot \frac{1}{1 + s \cdot \tau}$$

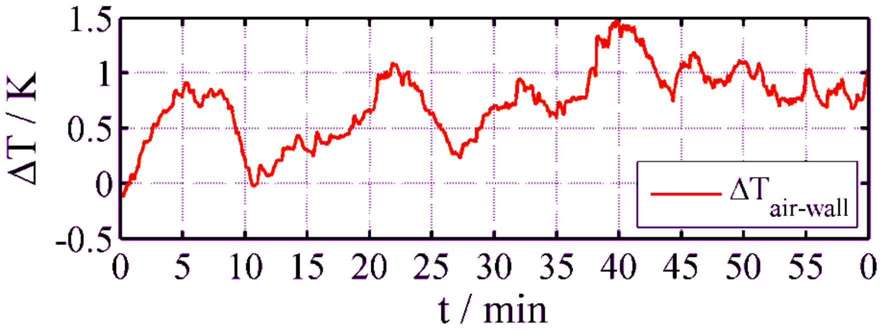
$$P_{el} = P_{el}(t) = E \cdot [\Delta T(t)]^2$$

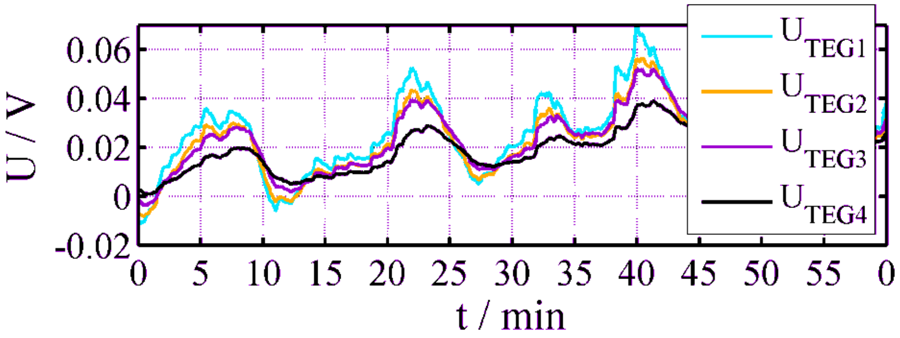
***temporal behaviour** of ΔT^2 defines the output power*

Design considerations under dynamic conditions

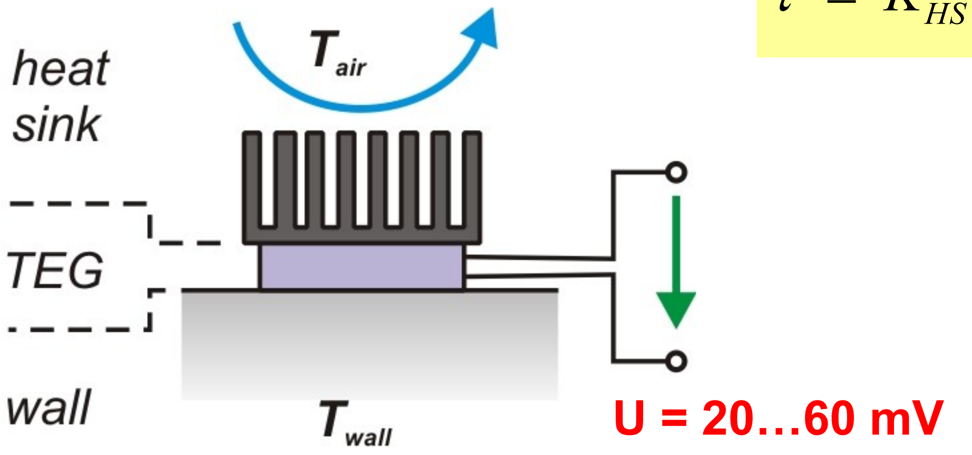
- The heatsink‘s heat storage capacity C_{HS} dampens out fast - and desired - **fluctuations of T_{air}**
- Therefore: reduce the heatsink‘s **thermal time constant τ** and not primarily K_{HS}

Energy harvesting from dynamic low ΔT in a tunnel





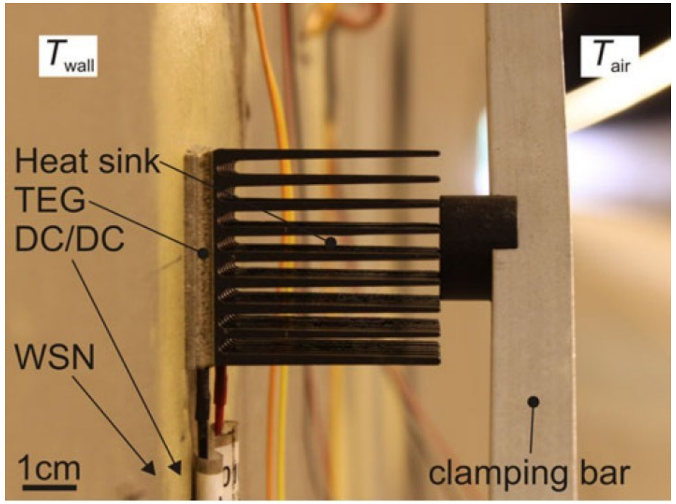
$$\tau = K_{HS} \cdot C_{HS}$$

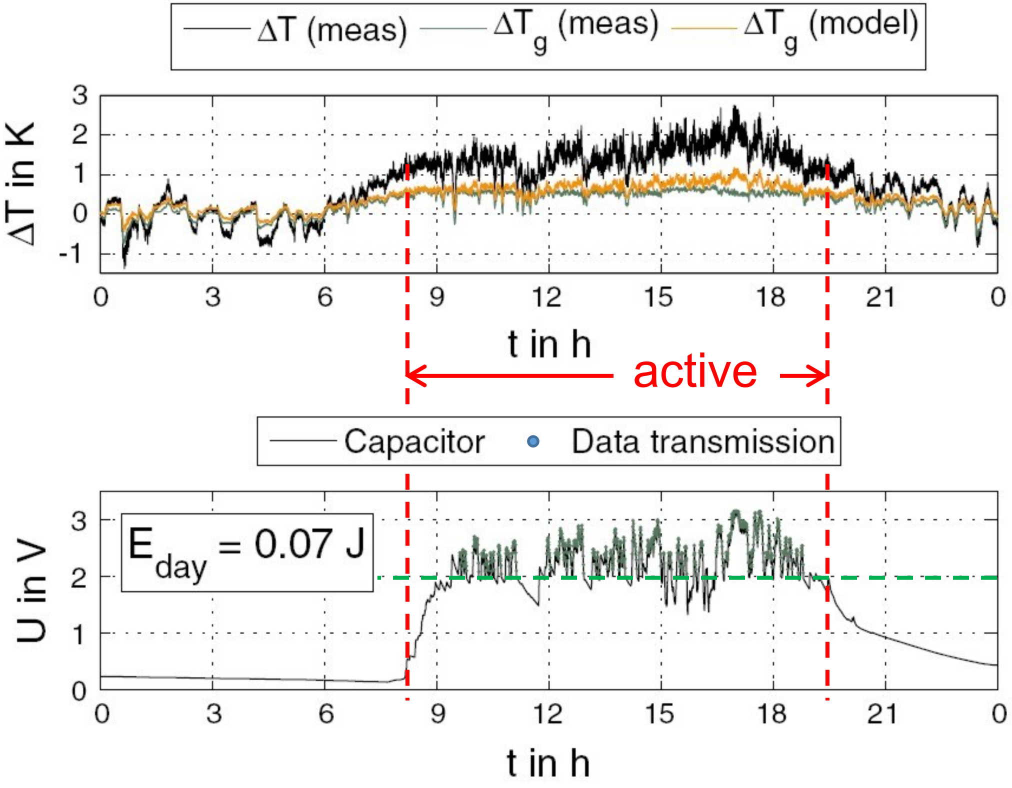


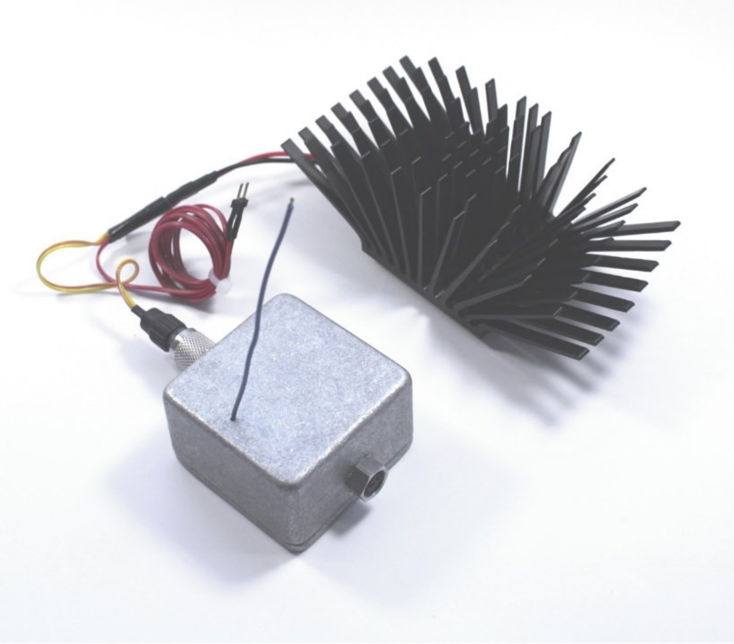
TEG	K_{HS} [K/W]	τ [s]	E [J/day]
1	8.3	239	1.74
2	8.5	374	1.32
3	2.8	402	0.87
4	4.9	416	0.68

A. Moser et al., *Proc. PowerMEMS **2010***, Leuven, Belgium, 431-434.

Energy harvesting from dynamic low ΔT in a tunnel







Results

- harvesting of 0.07 J/day,
  from **ΔT ≥1.2 K** at the TEG over appr. 20 hrs
- 415 energy-autonomous radio telegrams per day
  (200 µJ per telegram, average interval: 3.5 min)
- wireless system and DC-DC converter: Enocean

A. Moser et al., *Journal of Electronic Materials* 41 (6), **2012**, 1653-1661.

Small ΔT: example pet tracking and wildlife tracking

Today

- **battery-operated** wireless and GPS module in/at the collar
- wearable wireless receiver or …
- satellite link or …
- GSM link into your mobile phone

Disadvantages

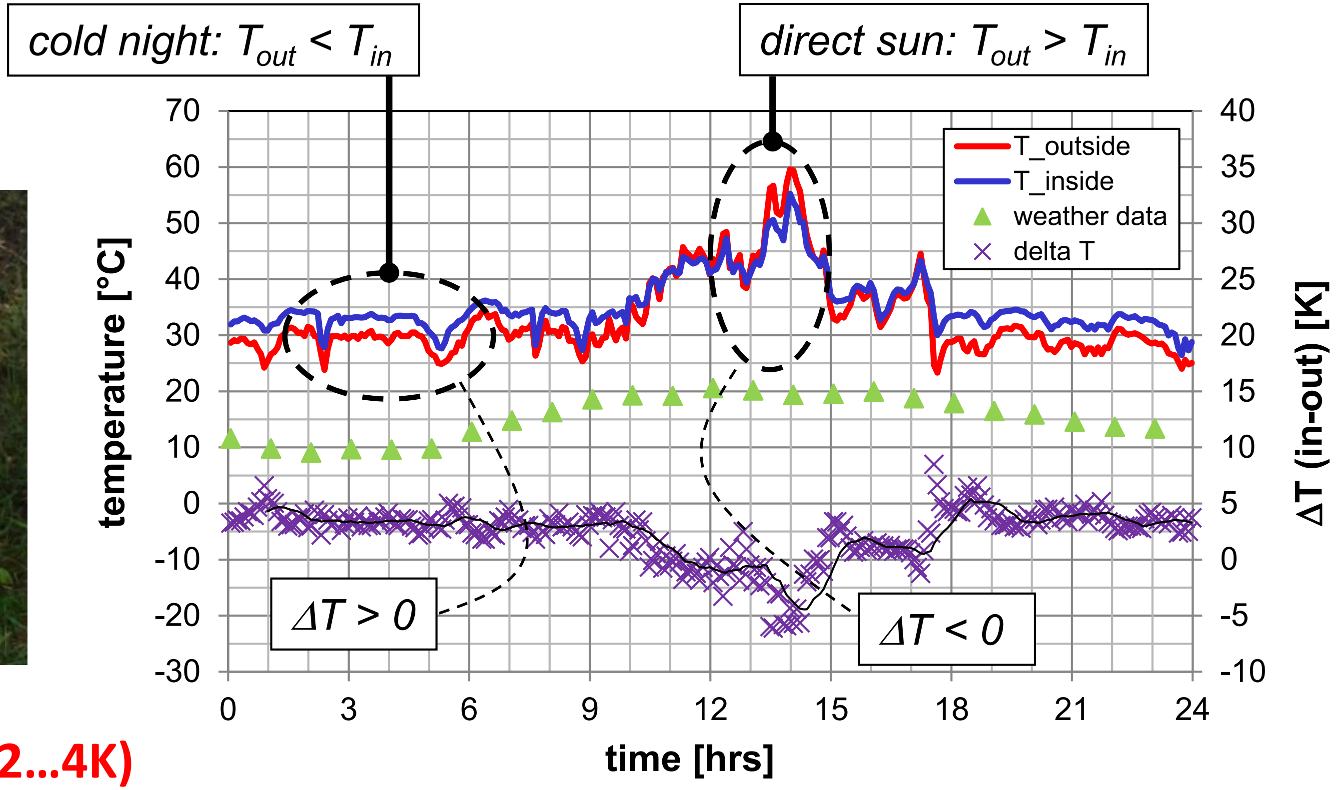
- limited battery lifetime
- limited space and weight allowed
- expensive collar exchange for wild animals

➡ a **promising application** for energy-autonomous systems

Temperature budget at wildlife: measurements

collar with two temperature data loggers …

… at a freely grazing German sheep („Heidschnucke“)



- only **small temperature gradients** available **(2…4K)**
- **voltage polarity changes** with the direction of the temperature field
- very low output voltages for small temperature gradients **(10s of mV)**

➡ high heat flux required ➡ thermal heat connector (THC) as „fur penetrator“

➡ voltage boost required ➡ low-voltage DC-DC converter

P. Woias *et al., IOP Conference Series* 557, **2014**, 012084

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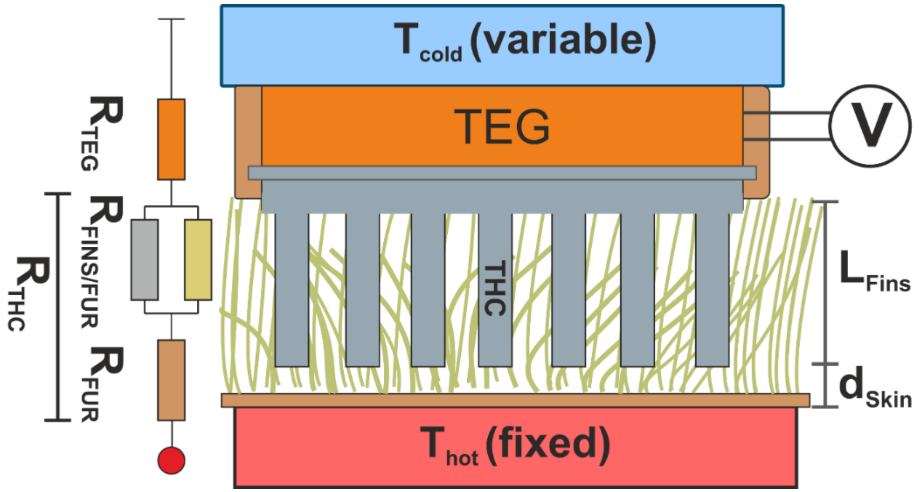
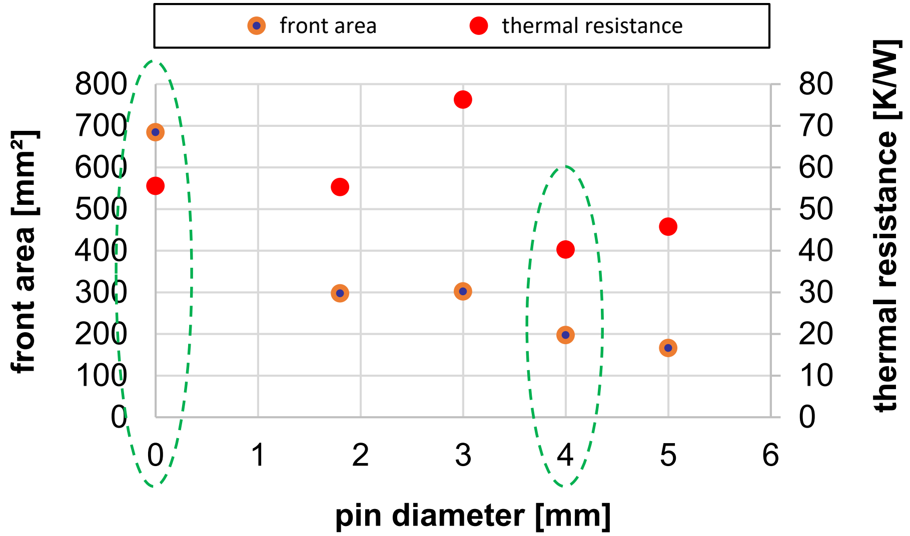
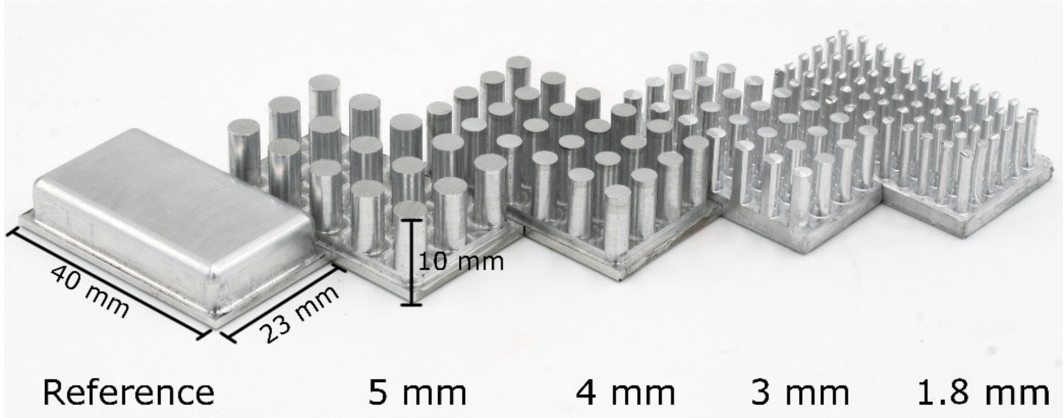
Thermal heat connectors (THCs) for fur

Design concept and results

- fin-type fur penetrator, bypassing "most of the fur"
- rounded fin tips (no harm to animal)
- fur-adapted fin length and fin spacing
- significant reduction of front area: 684 mm² ➡ 200 mm²
- significant reduction of thermal resistance: 55 K/W ➡ 40 K/W
- significant reduction of weight: 17.6 g ➡ 12 g



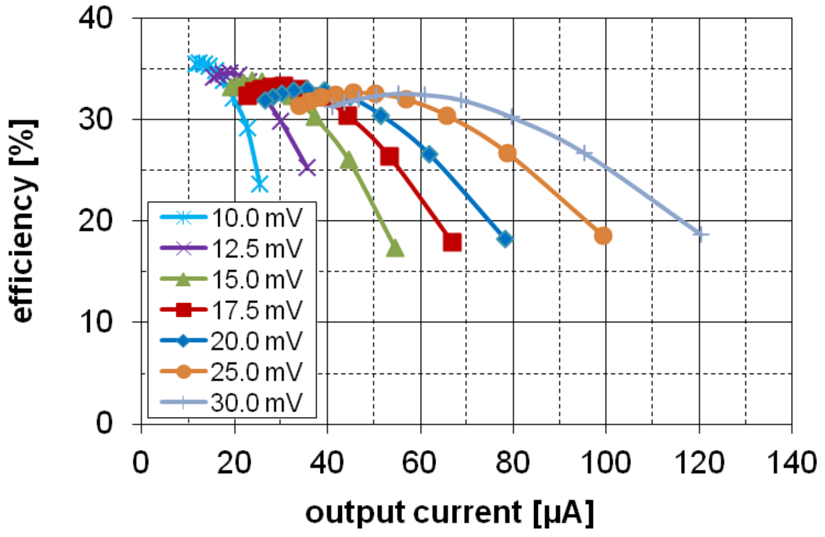




E. Bäumker *et al.*, *Energies* 13, 2769, **2020**

Low-voltage step-up converters

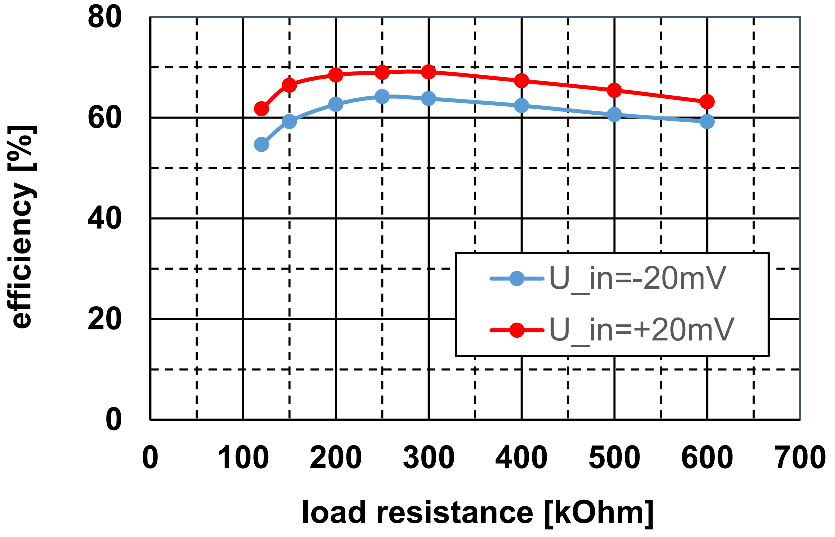
Generation 1 (2012)



P. Woias *et al.*, IOP Conference Series 476, **2013**, 012081

P. Woias, Patent *DE102011122197B4*, **2011**

Generation 3 (2019)



- start-up voltage: **10 mV**
- power-down voltage: **6 mV**
- best efficiency: > 35 % at 10 mV
- step-up ratio: 60 ...140
- no influence of input voltage onto power conversion efficiency

- start-up voltage: **+/- 20 mV**
- power-down voltage: **appr. +/- 8 mV**
- best efficiency: **55 ... 70 %**
- voltage step-up ratio: 150 ... 250
- no significant efficiency loss with input voltage and load resistance

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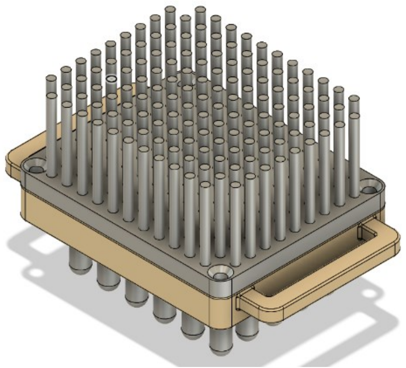
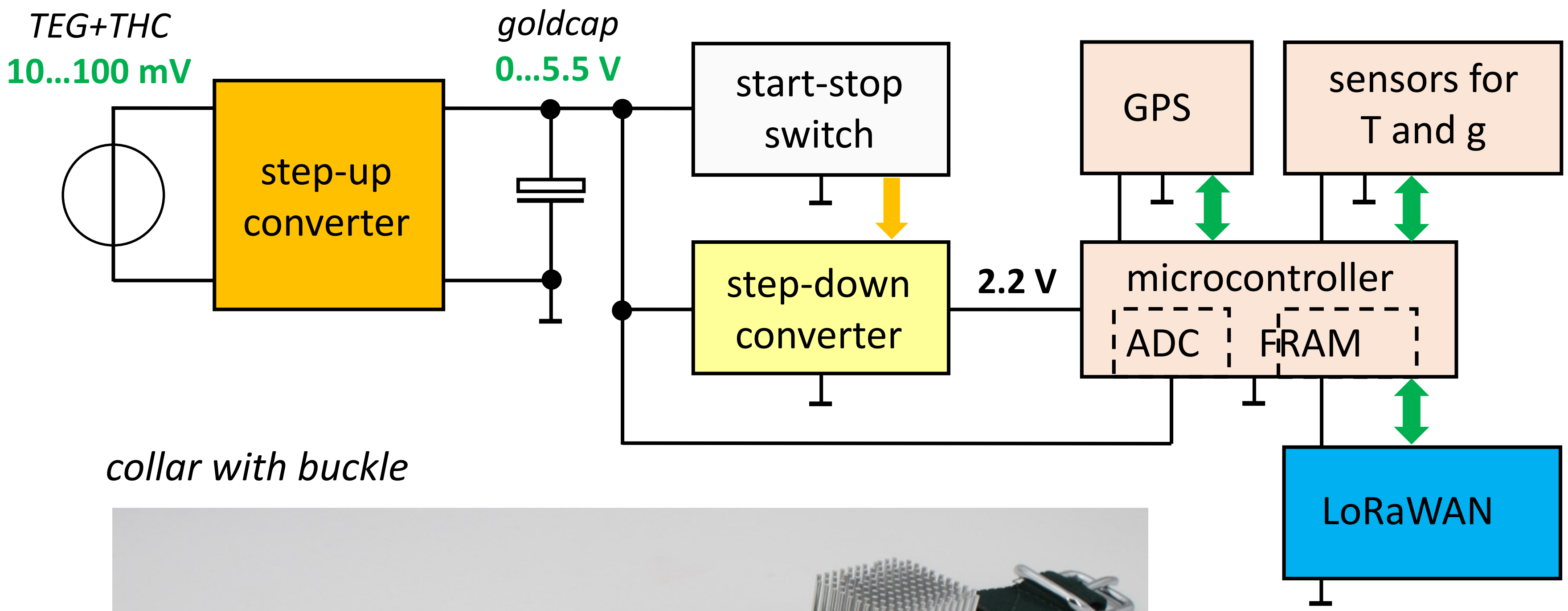
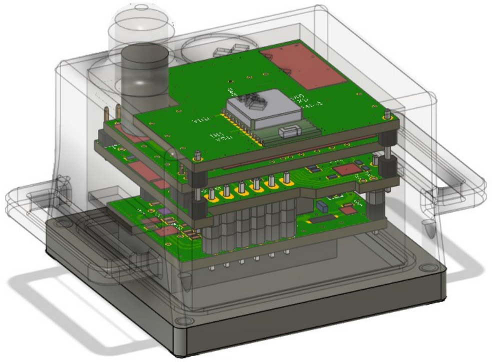
Thermally powered wildlife tracker: system design



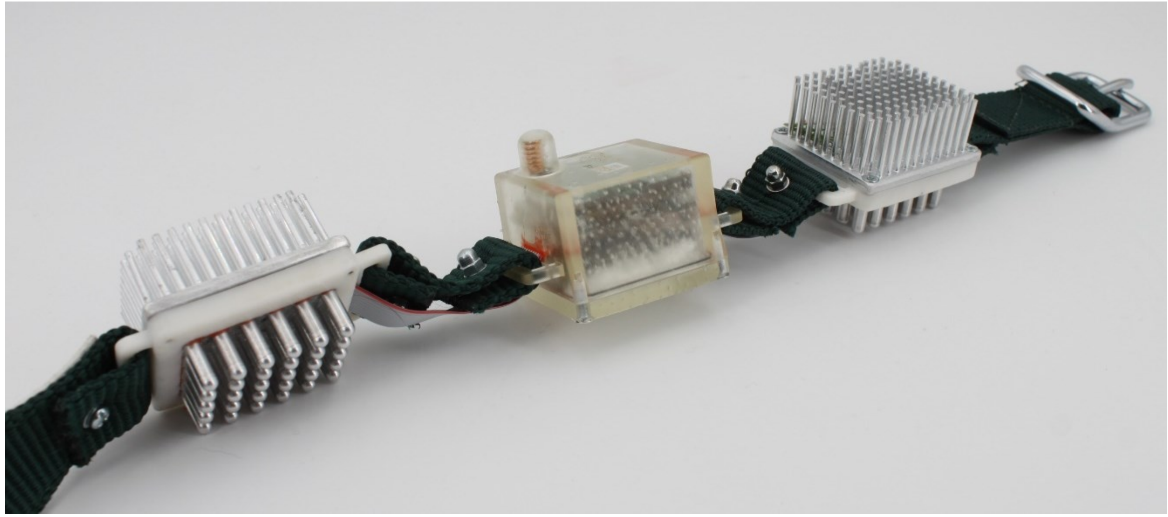
TEG with THC and integrated temperature sensors





electronic module

collar with buckle



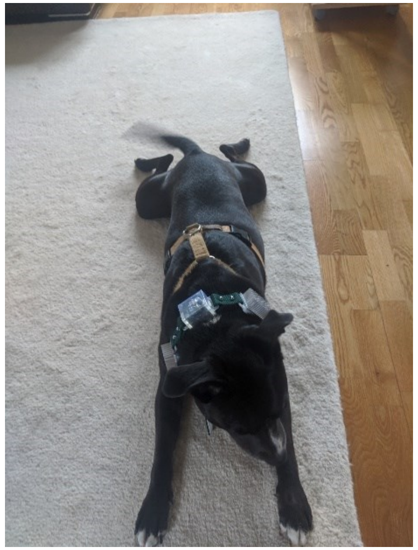
Thermally powered wildlife tracker: system test

Promising results from a dog (2019) …

- ΔT at the TEGs: 5 K @ 19 °C ambient
- goldcap charging power: 360 µW @ 4.5 V
- appr. 1 GPS-fix within less than 30 minutes
- not annoying or harming for the animal !

… and from a field test with sheep (2020)

- average ΔT at the TEGs: 2…3 K
- peak ΔT value at night: 4.5 K
- night: **more than 400 µW** (P_{max} = 800 µW)
- day: **below 100 µW**



E. Bäumker *et al.*, *Energies* 14 (19), 6363, **2021**

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Medium ΔT applications

Boundary conditions

- acceptable ΔT: **at least 10s of Kelvin**
- reasonable heat flux
- moderate dynamics of both

Process control

Fabrication

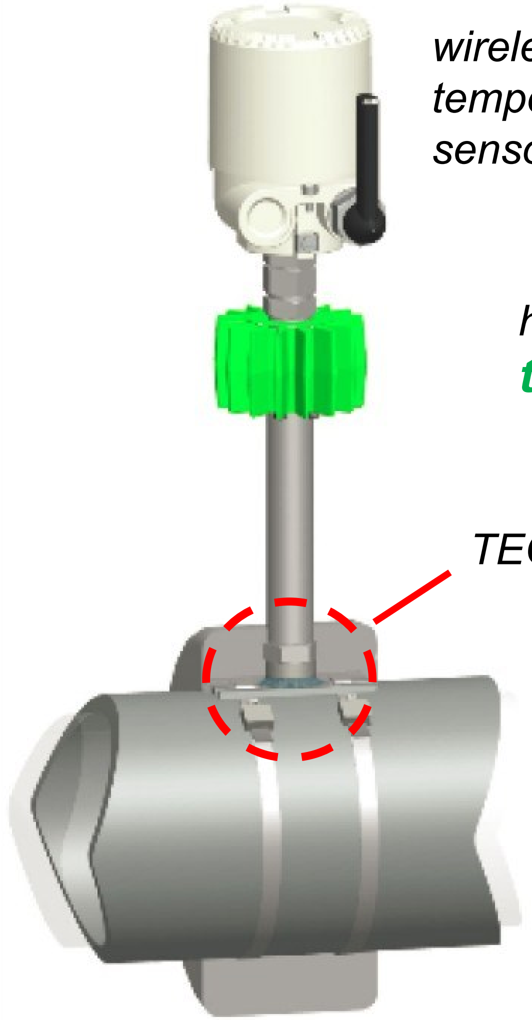
Automotive

© Citroen

Medium ΔT: example process automation

Energy-autonomous wireless temperature sensor

- thermal energy harvesting from a „large enough" ΔT **(ΔT > 30 K)**
- non-rechargeable battery for auxiliary power supply
- WirelessHART interface **400 µA @ 3 V = 1.2 mW**
- **in the product portfolio of ABB since appr. 2012**



all pictures: © ABB

Medium ΔT: example automotive

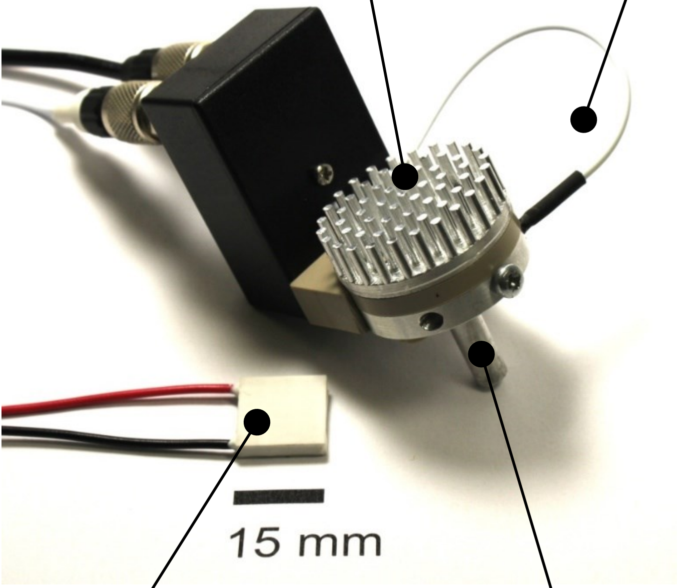
What for ?

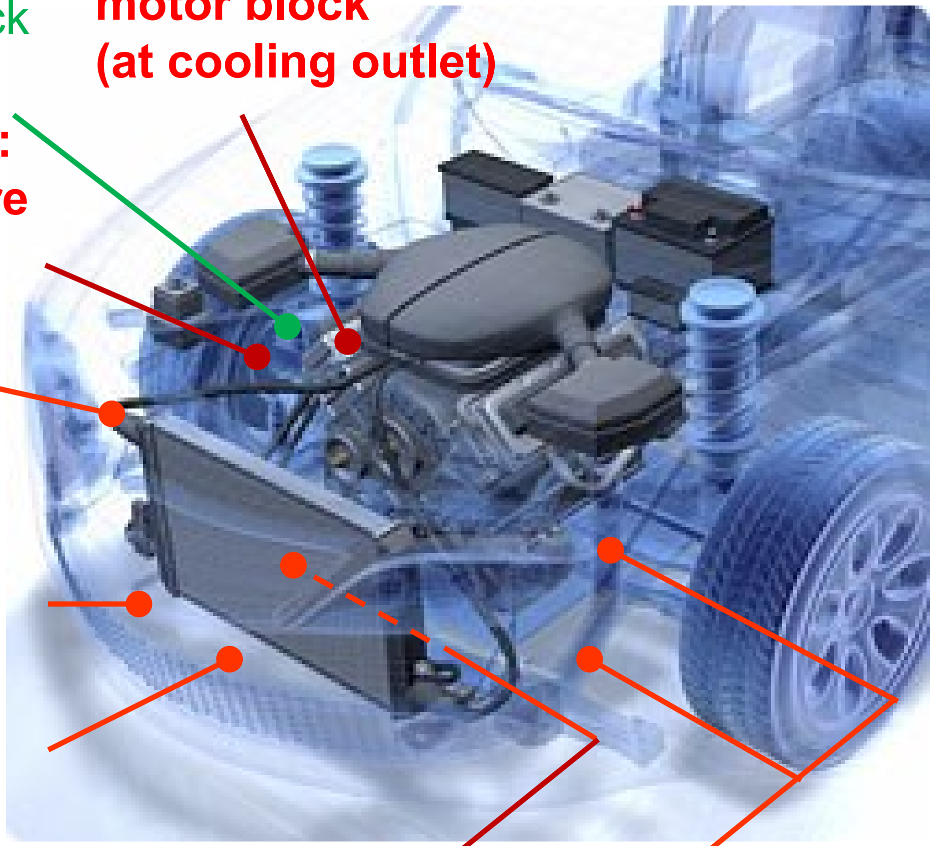
- tire pressure monitoring
- **engine monitoring and control** (oil and water cycle, knocking…)
- tire rotation sensors
- comfort function …

Available energies at/in a car or truck ?

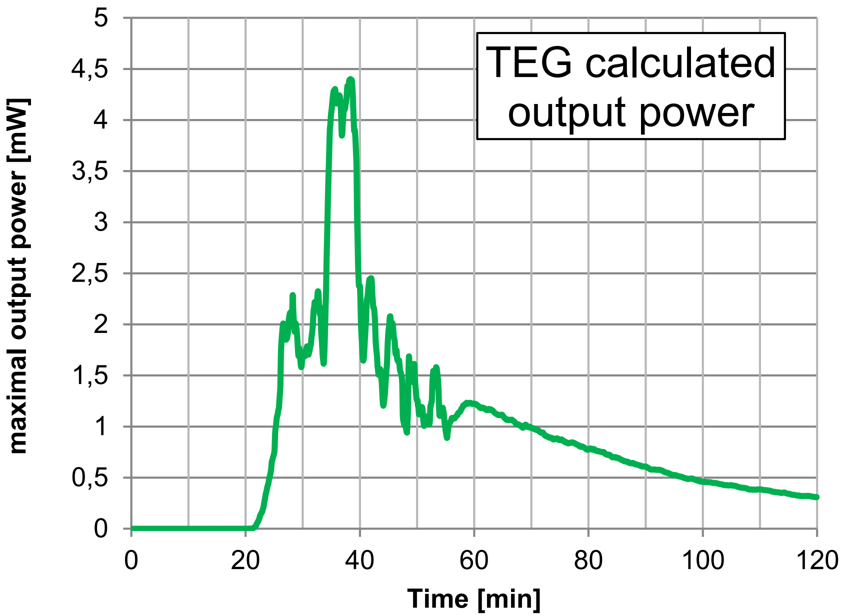
- light
- movement
- acceleration
- **heat and cold**
- sound
- vibration
- gas and liquid flow

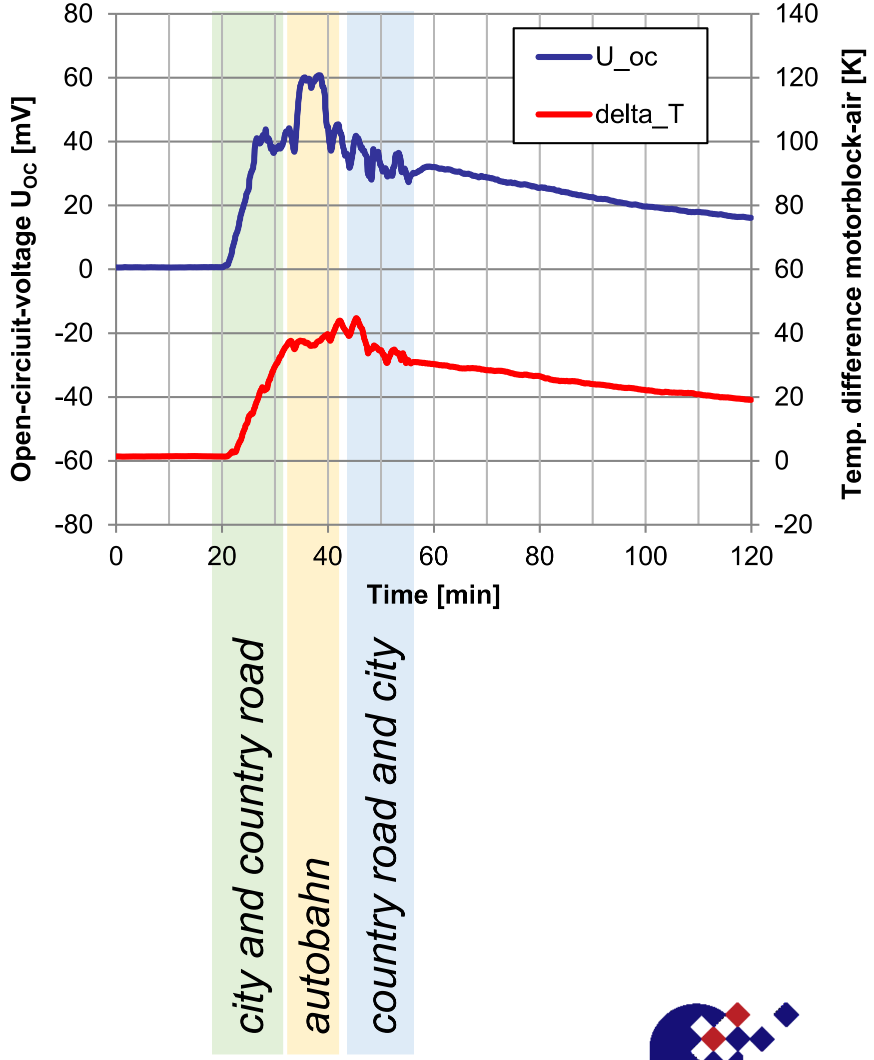
Thermal budgets in/around a car engine ?





Thermoelectric EH in cars: Exemplary test results

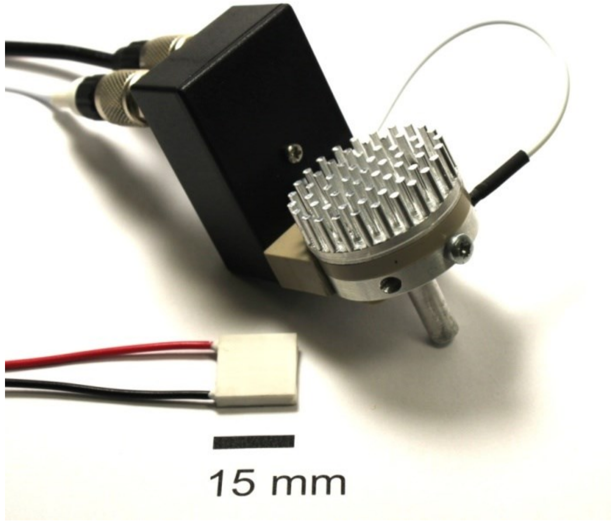


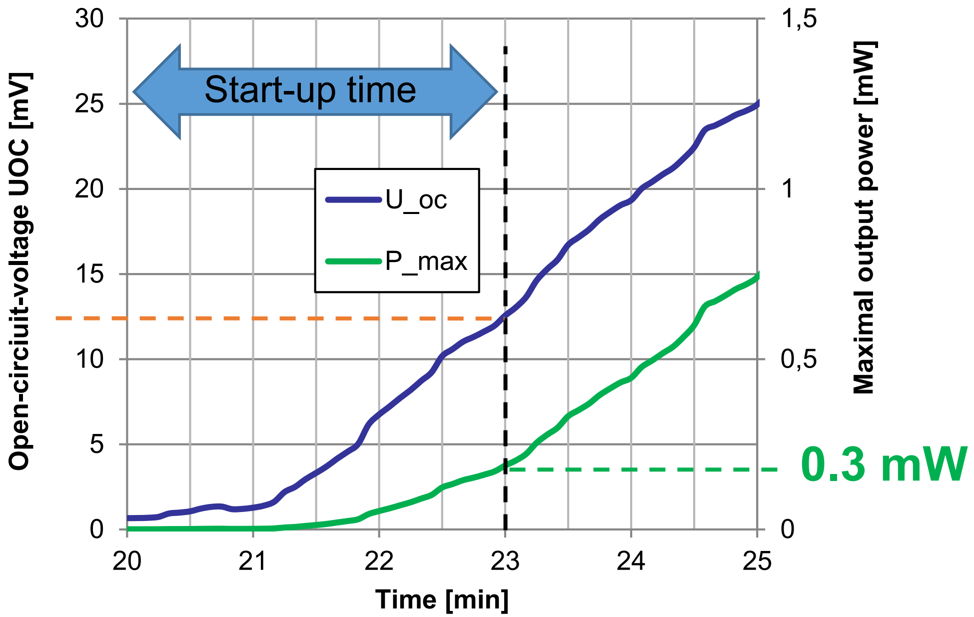


Resumee

- high output power (up to a few mW)
- low output voltages (a few 10 mV)
- obvious influence of car speed
- significant energy harvesting **after** the end of a journey

Thermoelectric EH in cars: Coldstart conditions ?





Resumee (for a small commercial TEG)

- 100 µWs of output power available after a few minutes
  a small TEG = sufficient for low-power wireless sensors ***only***
- efficient low-voltage DC-DC converter required
  "starting from as low ΔT as possible and as soon as possible"
- higher output power required for realistic application scenarios (e.g. through larger TEGs…)

High-temperature and ΔT applications

Boundary conditions

- high temperatures: **100s of Kelvin**
- high ΔT: **100 to 100s of Kelvin**
- reasonable to high heat flux
- low dynamics of both (usually huge thermal masses involved)

Highly energetic combustion processes

Gas and aircraft turbines

High-power geothermy

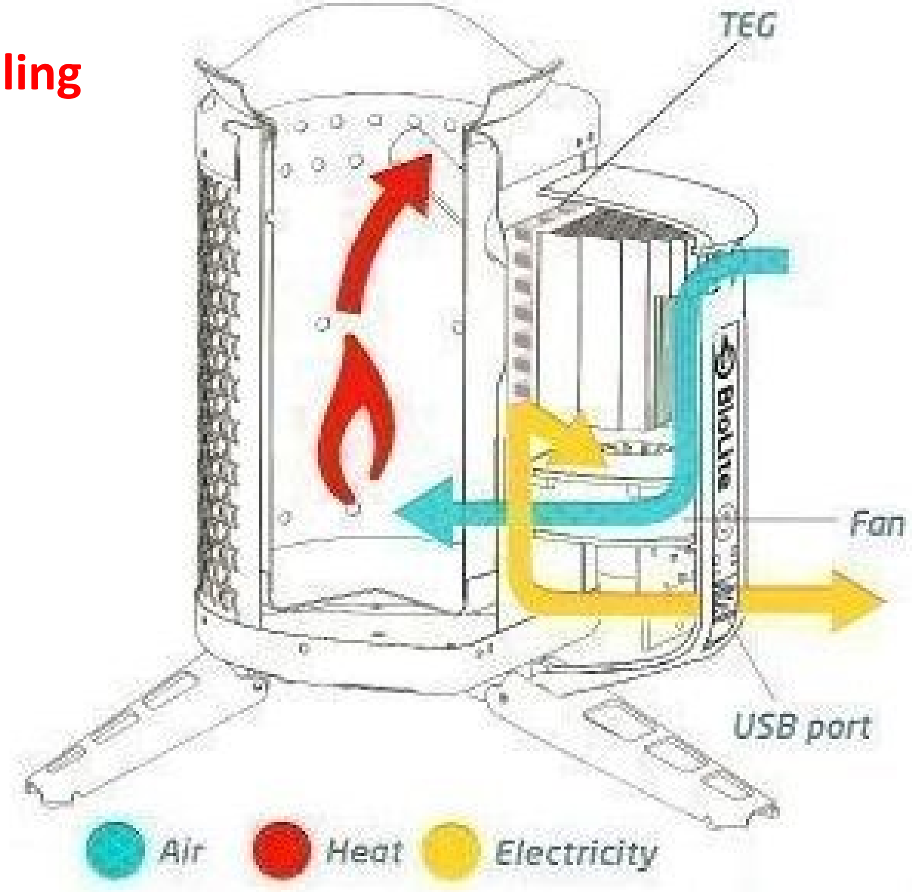
High-temperature applications: a gadget example ?

Properties, to be learned from

- cold temperature at the TEG enhanced via **active convective cooling**
- **with that: active cooling of the TEG, to prevent its destruction**
- with that: an average electric power of 3 W
- integrated and also air-cooled battery (2.600 mAh)

BioLite 2® thermoelectric energy harvesting stove

150 € (2024)



High-temperature applications: What TEGs are needed?

Resumee

- T at the hot side is high ➡ high-temperature thermoelectric materials required
  ➡ a „bad“ thermoelectric material may be „good enough“
  ➡ reduced requirements on system design (step-up converter)

$$P_{el} = \frac{n^2 \cdot \alpha^2 \cdot R_L}{\left(R_{g,eff} + R_L\right)^2} \cdot \left(T_2 - T_1\right)^2$$

➡ **Output power ~ (Seebeck · ΔT)²**

… but also: at least T_2 is high

Choice of termoelectric materials

- high-temperature semiconducting thermoelectrica: *PbTe, SiGe, MgSi,…*
- **Why not metals ?**

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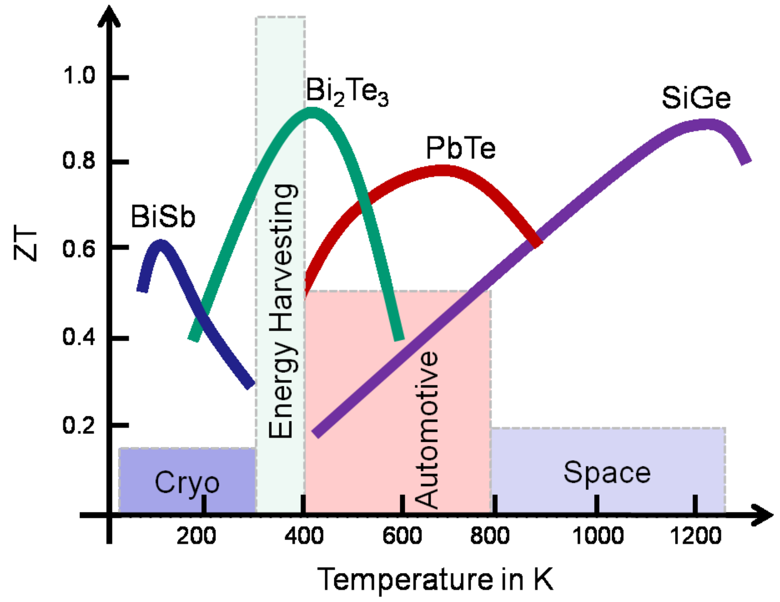
High-temperature thermoelectric materials

Why metal TEGs ?

- very small Seebeck coefficient ✘
- high operational temperature ✓
- very robust systems ✓
- raw materials readily available ✓

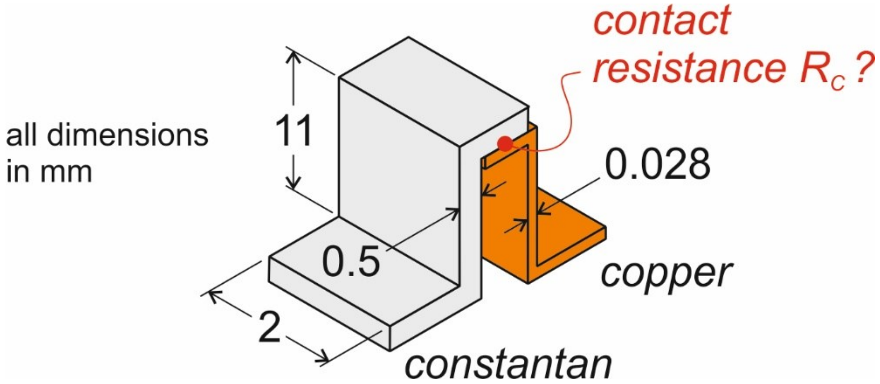


	Typical Seebeck coefficient	Melting point
Copper	6.5 µV/K	1085 °C
Constantan ($Cu_{55}Ni_{45}$)	-35 µV/K	1280 °C
Bi_2Te_3	~ 200 µV/K	573 °C
PbTe	~ -100 µV/K	905 °C

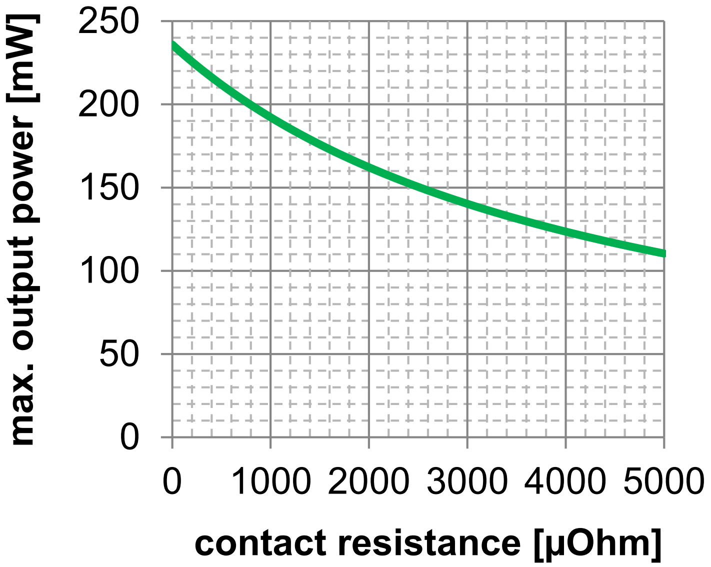
Copper-Constantan TEG: Theoretical case study

Device specification

- temperature difference at the TEG: 100K
- min. output power: ~100 mW
- thermal heat flux: ~100 Watt



Number of thermocouples	241
Seebeck coefficient (generator)	10 mV/K
no load output voltage	1.0 V
loaded output voltage	0.5 V
max. output power	
too optimistic: R_C = 0 mOhm	236 mW
realistic: R_C = 1 mOhm	192 mW
thermal heat flux through TEG	100.78 W



Summary and conclusions

Thermoelectric energy harvesting is feasible in a number of conceivable application scenarios, ranging from low to high temperature differences and temperatures.

In any case, **a thorough system design** is required, by tailoring ….

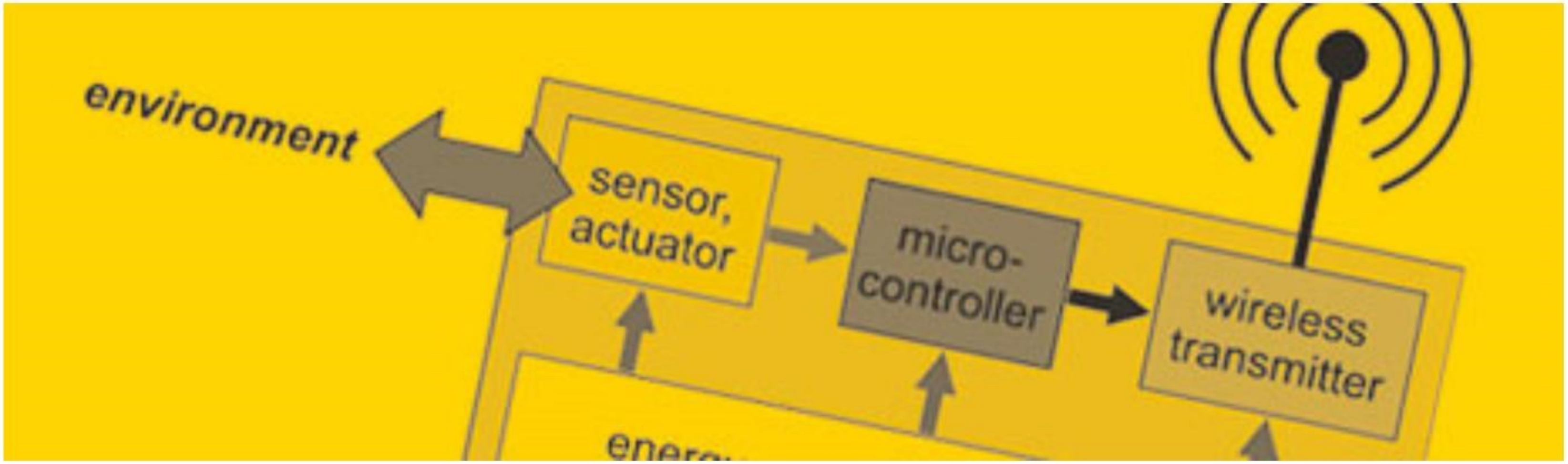
- the TEG itself, and its thermal interfaces,
- all power management electronics,
- the connected wireless sensor node.

Primary requirements and needs for further R&D are …

- a realistic determination of energy densities available for harvesting,
- improved power management electronics,
- power-optimized wireless data transmission,
- a solution for the “low-ΔT-start-up”.

Thank you very much for your attention

… and if you are interested in more on energy harvesting:



Energy Harvesting

This course provides an overview on the wide field of energy harvesting and a selected in-deep knowledge on various areas as the design of microgenerators and power management. It gives some insight into energy-autonomous embedded systems in some application fields e.g. building infrastructure and automotive.

- in-depth course at EMPA, Duebendorf, Switzerland
- October 28, 2024, 9:00-17:00
- more info at **https://fsrm.ch/doc/c419.php?lang=e**