Energy-autonomous systems based on thermoelectric energy harvesting:

- application-oriented system design and integration -

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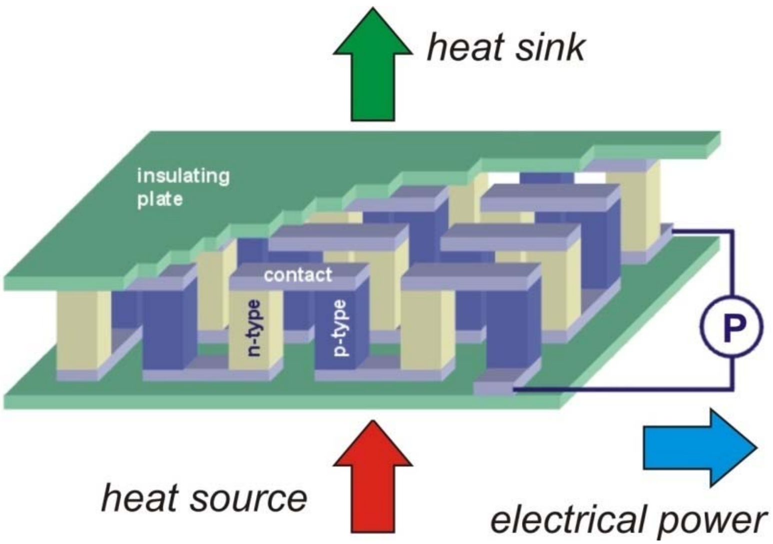
Thermoelectric generators



Seebeck voltage

$$\Delta U = S \cdot \Delta T$$

output voltage

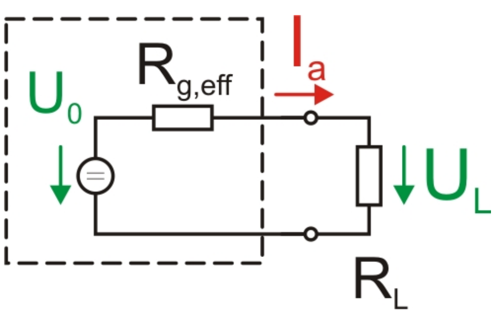
$$U_{out} = S \cdot \Delta T \cdot \frac{R_L}{R_{g,eff} + R_L}$$

output power

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

Properties

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



Maximum electrical output power

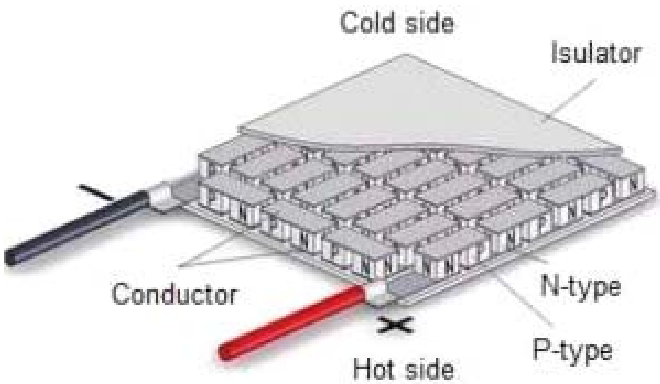
Example calculation for a mesoscale TEG

TEG: thermalforce™ TEG 049-150-30

- *material system:* Bi_2Te_3
- *internal resistance:* $R_{g,eff} = 0.57$ Ohm
- *Seebeck coefficient:* $S = 16$ mV/K
- *dimensions:* 25 x 25 x 3.7 mm³

Assumptions

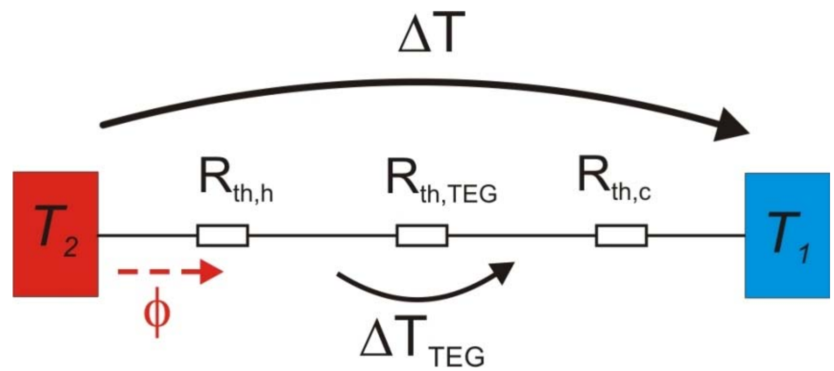
- *temperature difference* ***$\Delta T = 10K$***
- *ideal - and nonrealistic - thermal interface*
- *electrical load matching, i.e. = $R_L = R_{g,eff}$*



$$P_{out,ideal} = \frac{1}{4} \cdot \frac{S^2}{R_{g,eff}} \cdot \Delta T^2 = 11.2\, mW$$

Thermal and electrical interfaces

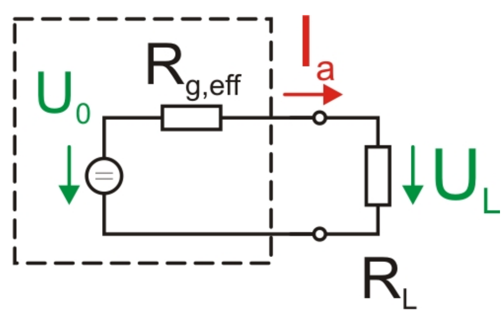
Influence on output voltage and output power



$$U_{load} = \frac{R_{th,TEG}}{R_{th,TEG} + R_{th,h} + R_{th,c}} \cdot S \cdot \frac{R_L}{R_{g,eff} + R_L} \cdot \Delta T$$

thermal interfaces *TEG* *electrical interface*

$$P_{el} = \left(\frac{R_{th,TEG}}{R_{th,TEG} + R_{th,h} + R_{th,c}} \right)^2 \cdot \frac{S^2}{R_L} \cdot \left(\frac{R_L}{R_{g,eff} + R_L} \right)^2 \cdot \Delta T^2$$



Thermal and electrical interfaces

Thermal „feed factor“ f

- parameter for the thermal temperature divider at the TEG and its interfaces
- $0 < f < 1$: The higher f the better

$$f = \frac{R_{th,TEG}}{R_{th,TEG} + R_{th,h} + R_{th,c}}$$

Electrical „delivery factor“ d

- parameter for the electrical voltage divider at the TEG output
- $0 < d < 1$: For maximal power output $d_{opt} = 0.5$

$$d = \frac{R_L}{R_{g,eff} + R_L}$$

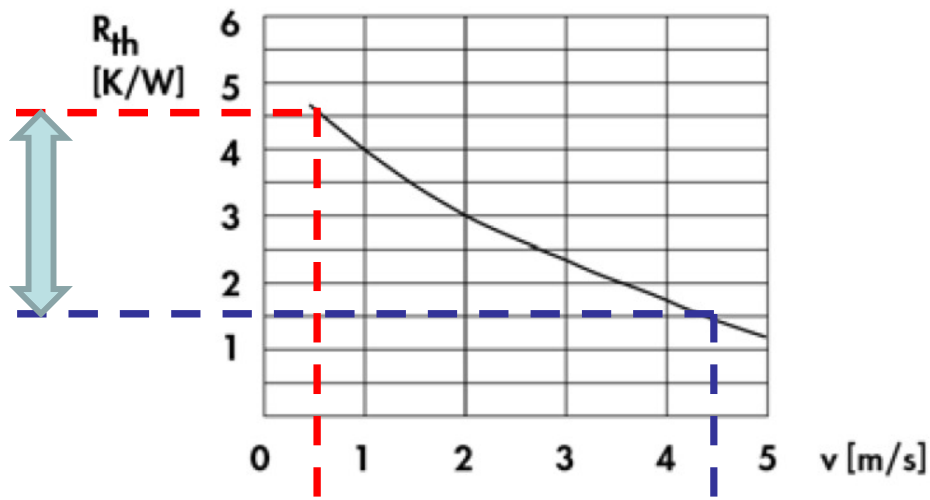
$$U_{out} = f \cdot d \cdot S \cdot \Delta T \quad and \quad P_{out} = f^2 \cdot d^2 \cdot \frac{S^2}{R_L} \cdot \Delta T^2$$

$U_{out} \sim f \cdot d$ $\qquad$ $P_{out} \sim f^2 \cdot d^2$

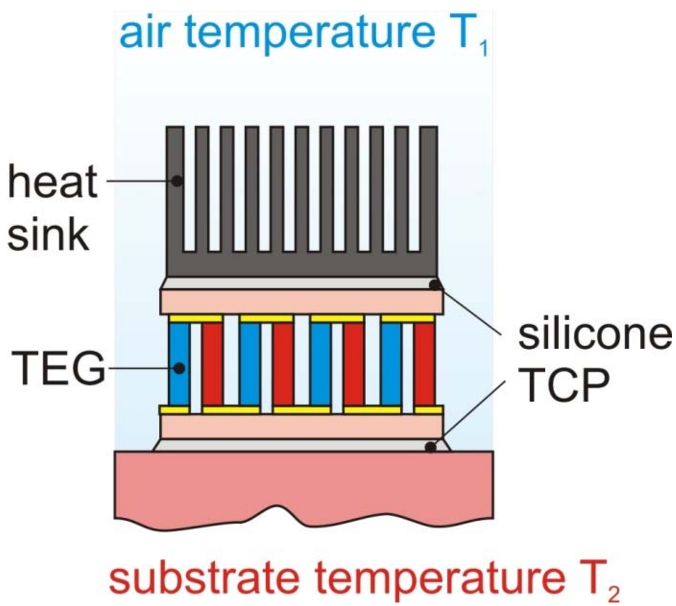
Influence of the thermal interfaces

Practical example: TEG in a solid-air interface

Heat sink: Fischer ICK S
1.5 K/W … 4.5 K/W
depending on air convection



TEG 049-150-30
5.263 K/W



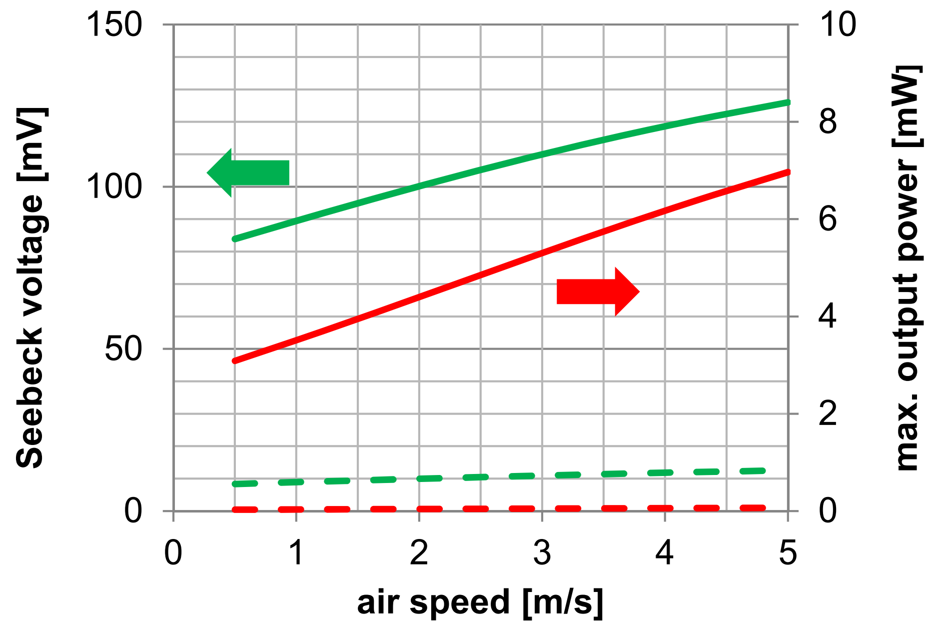
Wacker P12 (50 µm thick)
2 x 0.1 K/W

Influence of the thermal interfaces

Example calculations

$$U_{Seebeck} = f \cdot S \cdot \Delta T$$

$$P_{max} = f^2 \cdot \frac{1}{4} \cdot \frac{S^2}{R_{g,eff}} \cdot \Delta T^2$$



	acceptabe ΔT = 10K		very low ΔT = 1K	
	$U_{seebeck}$ [mV]	P_{max} [mW]	$U_{Seebeck}$ [mV]	P_{max} [mW]
low convection (0.5 m/s)	83.9	3.1	8.39	0.031
forced convection (4.5 m/s)	121.8	6.5	12.18	0.065

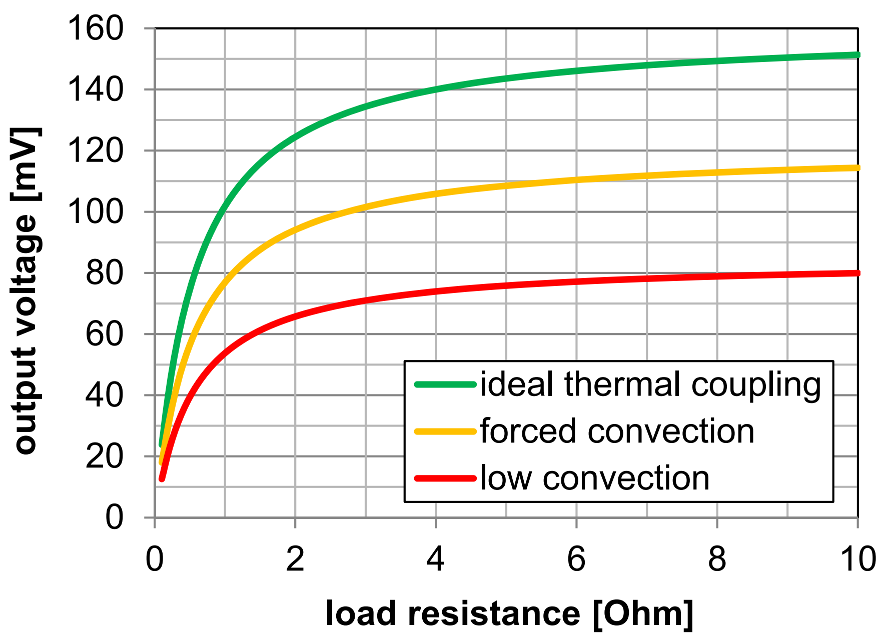
Influence of the electrical interface

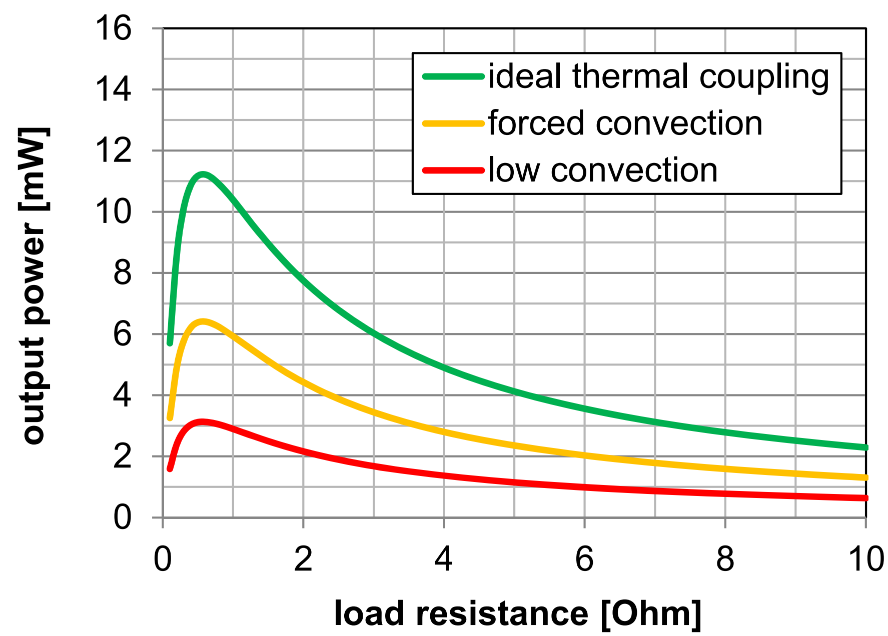
Output voltage and power for various load resistances and ΔT = 10K

- low output voltage (10…100 mV)
- low-voltage step-up conversion **is mandatory**
- reasonable output power (mW…10 mW)

$$U_{out} = f \cdot d \cdot S \cdot \Delta T$$

$$P_{out} = f^2 \cdot d^2 \cdot \frac{S^2}{R_L} \cdot \Delta T^2$$





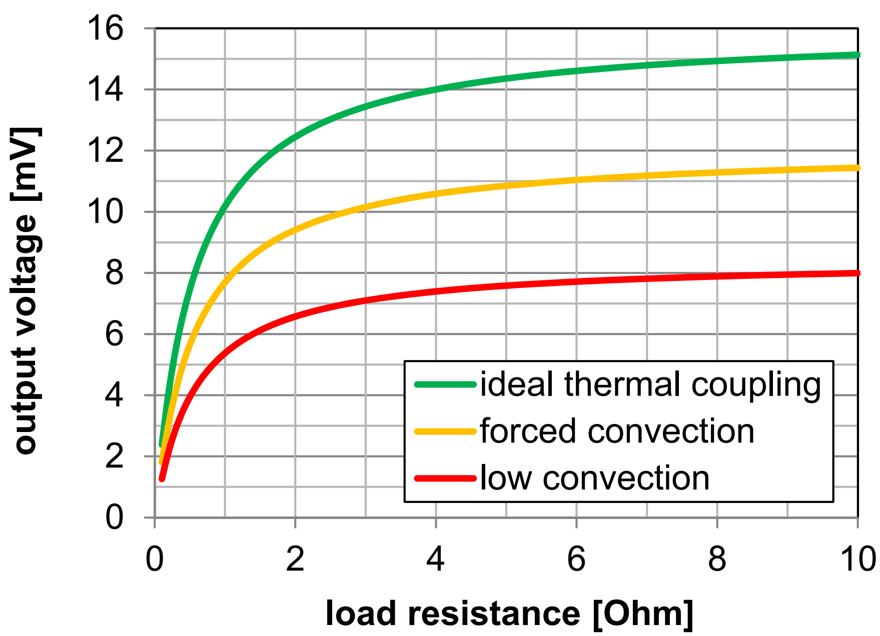
Influence of the electrical interface

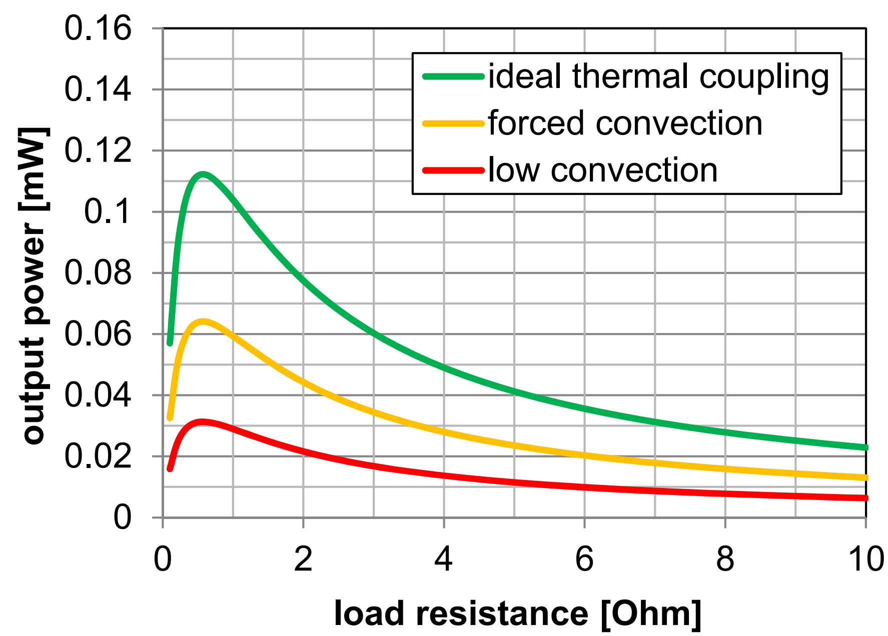
Output voltage and power for various load resistances and ΔT = 1K

- **very** low output voltage (mV...10mV)
- **very** low-voltage step-up conversion **is mandatory**
- **very** low output power (10 µW…100 µW)

$$U_{out} = f \cdot d \cdot S \cdot \Delta T$$

$$P_{out} = f^2 \cdot d^2 \cdot \frac{S^2}{R_L} \cdot \Delta T^2$$





Total system power output

$$P_{el} = \underbrace{\left(\frac{R_{th,TEG}}{R_{th,TEG} + R_{th,h} + R_{th,c}} \right)^2}_{f^2} \cdot \underbrace{\left(\frac{R_L}{R_{g,eff} + R_L} \right)^2}_{d^2} \cdot \frac{S^2}{R_L} \cdot \Delta T^2 \cdot \eta_{DC-DC}$$

Low output voltages (e.g. 100 mV) are not sufficient to power up an electronic system. A low-voltage step-up converter is required to boost the TEG output voltage up to an acceptable level (e.g. 2 V)

efficiency of an electronic step-up converter

Power losses in the step-up converter

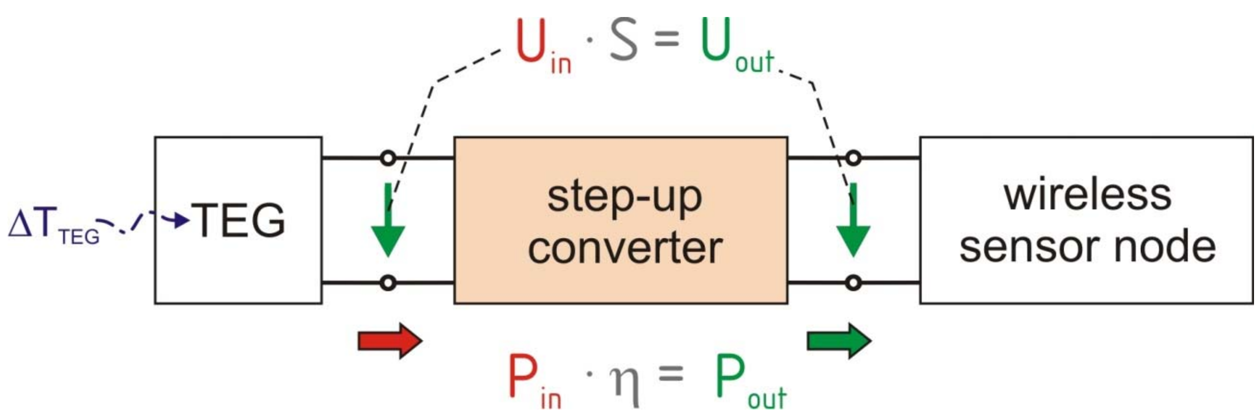
- low efficiency at low input voltages (in many cases 25 % or less)
- minimum start-up voltage required (best commercial device: 20 mV in 2011)

➡ *consequence:* No harvesting at „really low temperature gradients"

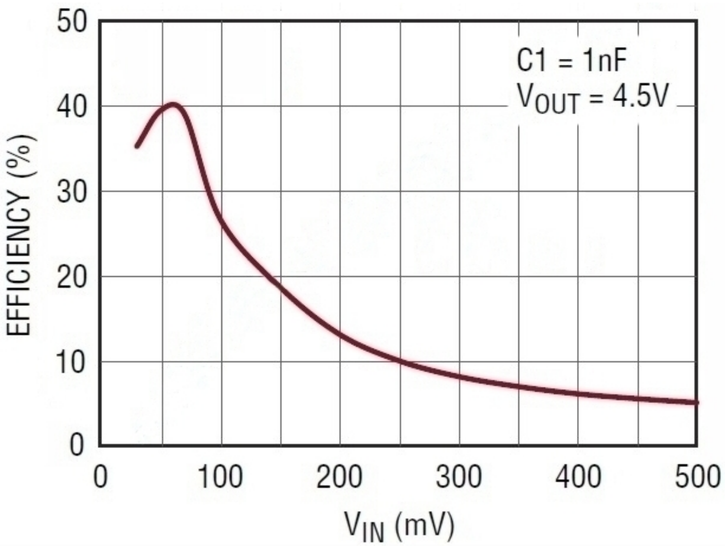
Low voltage (LV) step-up converters

Design issues

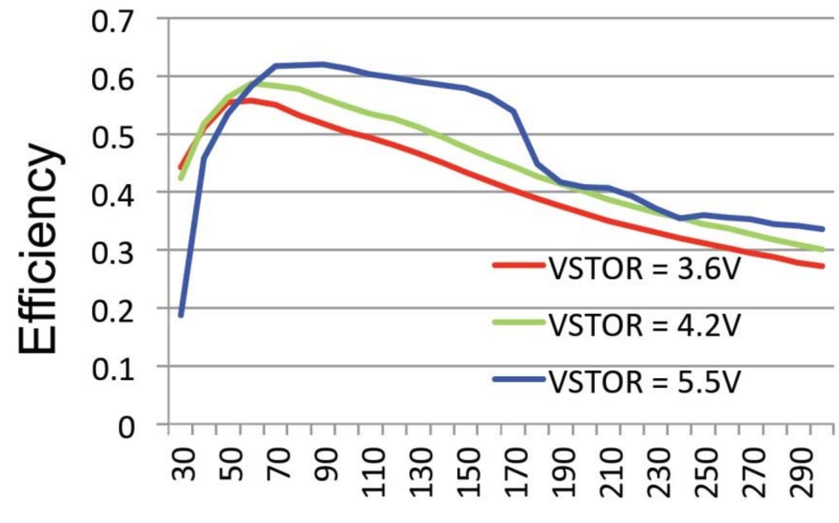
- high step-up ratio S
- high power conversion efficiency η
- **cold-start from low voltages** $U_{in,\ min}$
- self-supply from low input voltages
- matched electrical impedances of TEG and converter input, for d ~ 0.5



Power conversion efficiency of „usual“ low-voltage step-up converters



datasheet Linear Technology LTC 3108



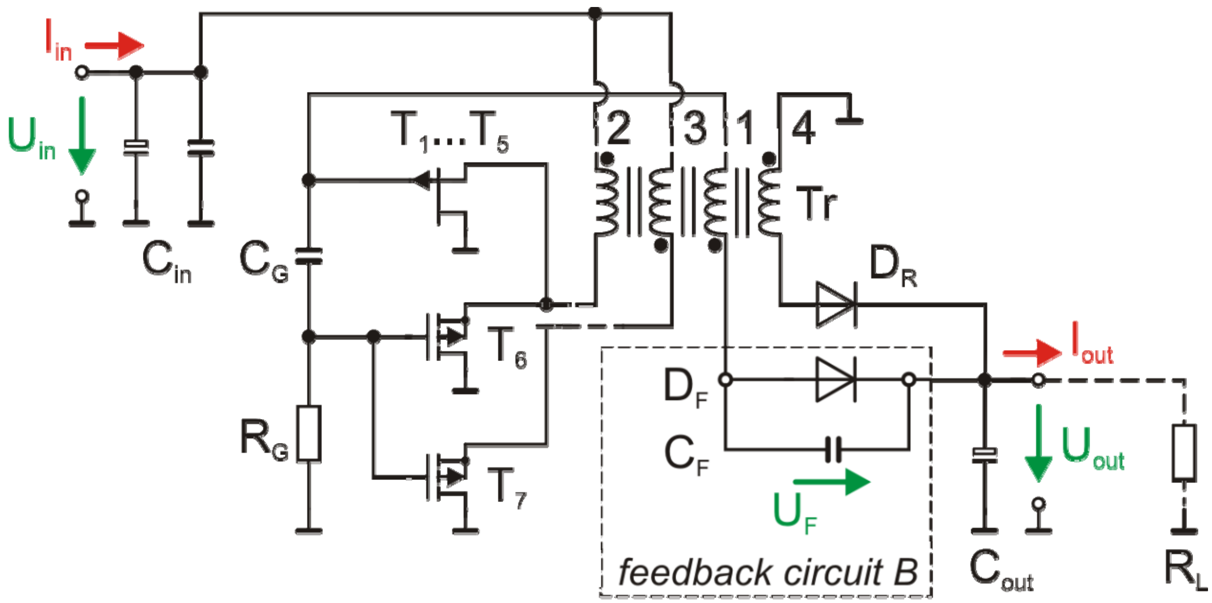
(a) V_{sup} (mV) > 0

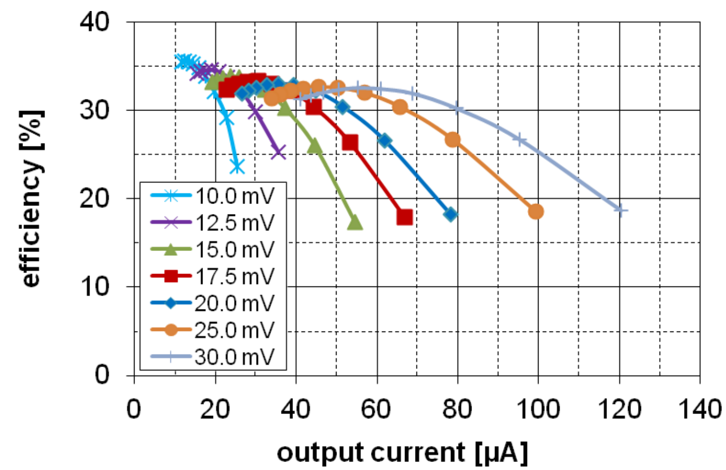
N. V. Desai et al., Proc. ISLPED 2014, 221-226

Resumee

- optimal power conversion only for a fixed input voltage V_{in}.
- not ideally suited for variable input voltage.
- minimal start-up voltage limited to 20 mV (today, with reasonable effort).

Our own LV step-up converter (patented)





P. Woias et al., *J. Phys. Conf. Ser.* 476, **2013**, 012081.

Properties

- combination of a Meissner oscillator and forward converter
- start-up voltage of 10 mV is possible (reasonable: 20 mV)
- power conversion efficiency **above 50 % at 20 mV U_{in}** (most recent results)
- no influence of input voltage on conversion efficiency

Temperature regimes and design considerations

$$U_{out} = f \cdot d \cdot S \cdot \Delta T$$

Output power ~ (Seebeck · ΔT)²

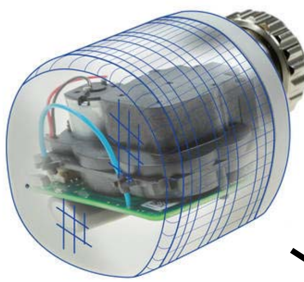
$$P_{out} = f^2 \cdot d^2 \cdot \frac{S^2}{R_L} \cdot \Delta T^2$$

Resumee

- **In general:** make output voltage U_{out} and output power P_{out} high enough, save on power in the electronic system
  - ➨ *high S = high-efficiency TEG*
  - ➨ *high f = thermal interfaces with good heat conductance*
  - ➨ *d = 0.5 (load-matched electrical interface) for max. power*
- **For a small ΔT:** use high-efficiency thermoelectric materials !
  establish a ΔT as large as possible !
- **For a large ΔT:** even a „bad“ thermoelectric material may be sufficient !

Small ΔT applications

Human, biomedical, …



© PMDM

Home automation

Boundary conditions

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

Infrastructure monitoring

Small ΔT: Energy-autonomous sensors in railway and road 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	✓	✓

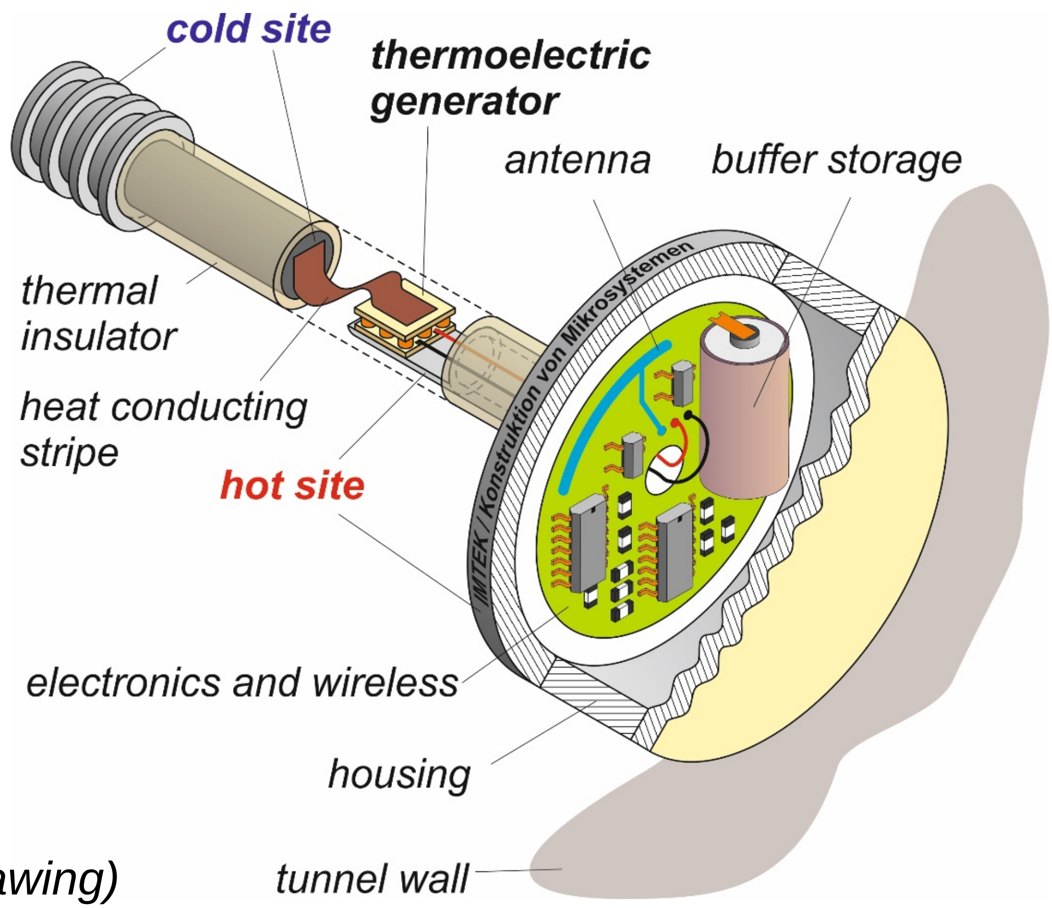
Geothermal energy harvesting in tunnels?

Concept

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

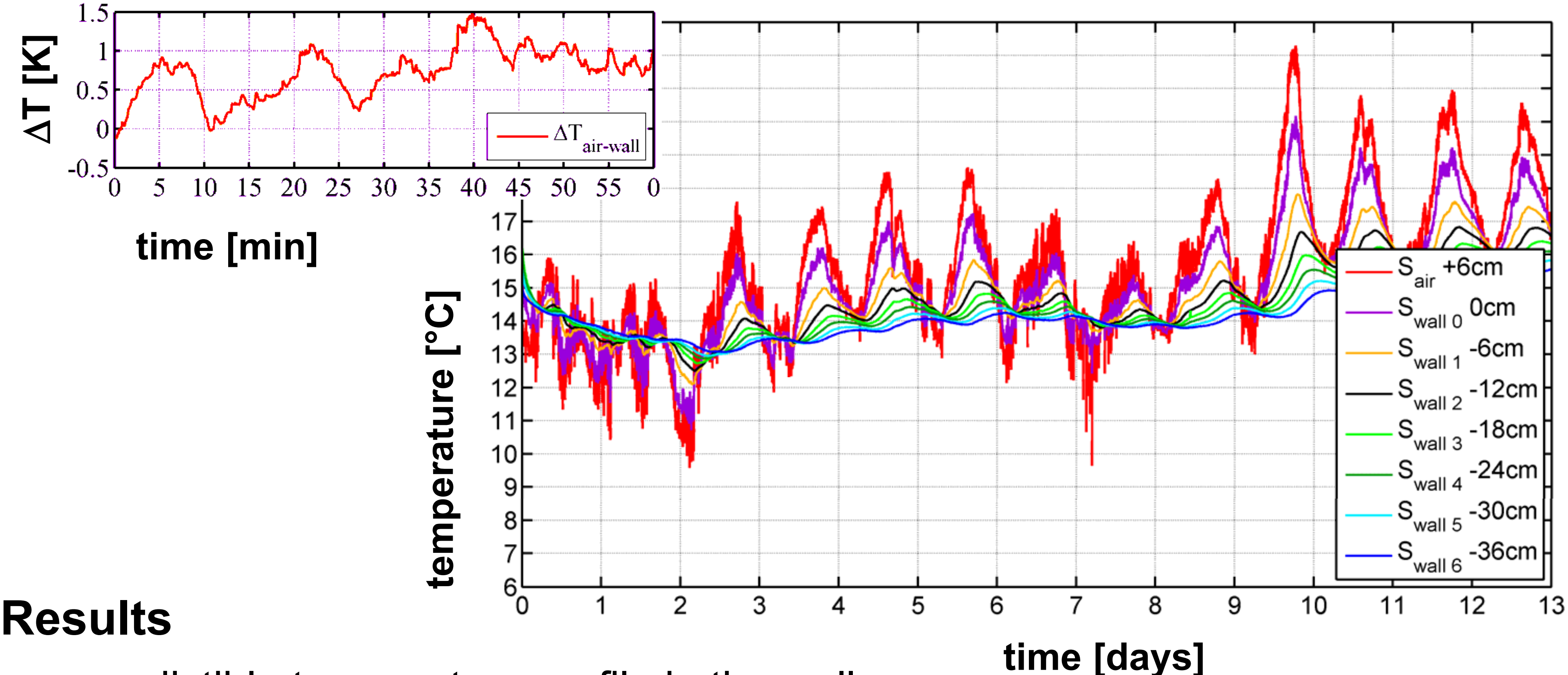
But first: measurement of the available ΔT

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



thermal probe with integrated thermogenerator (conceptual drawing)

Road tunnel: field measurements

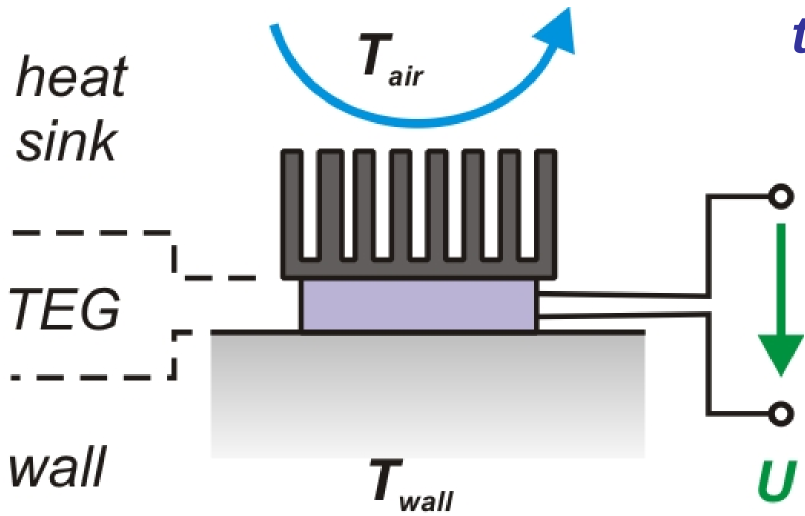


Results

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

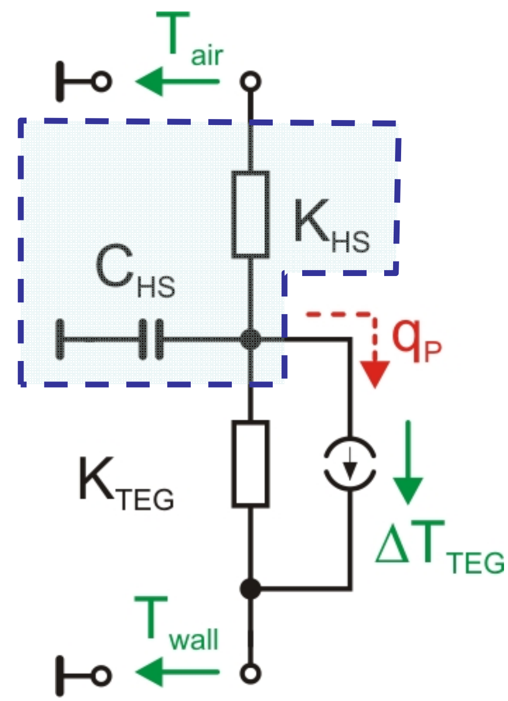
Hugenwald tunnel, Freiburg, Gemany

Thermal time constants



thermal time constant τ:

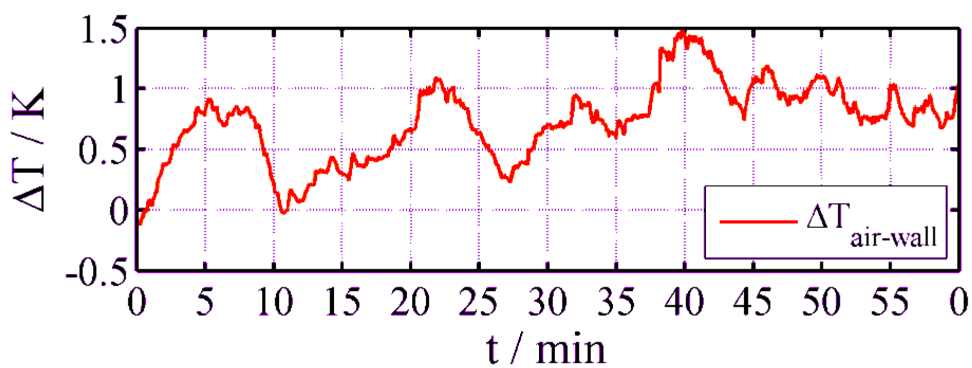
$$\tau = K_{HS} \cdot C_{HS}$$

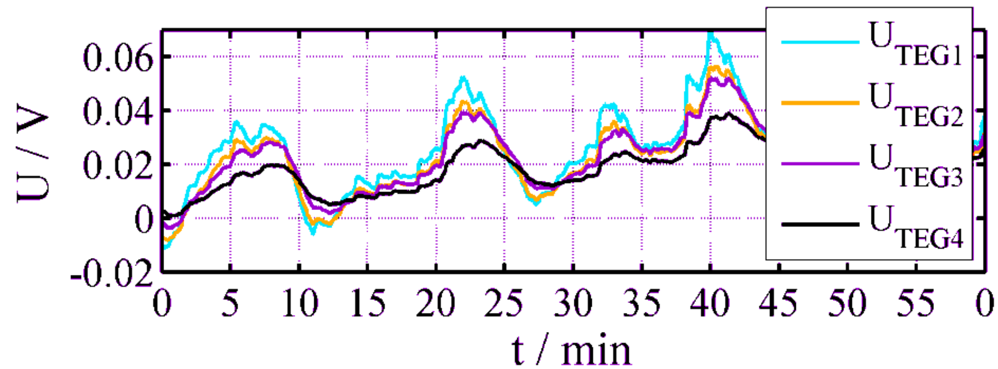


$$P_{out} = P_{out}(t) \sim \underbrace{[\Delta T(t)]}^{2}$$

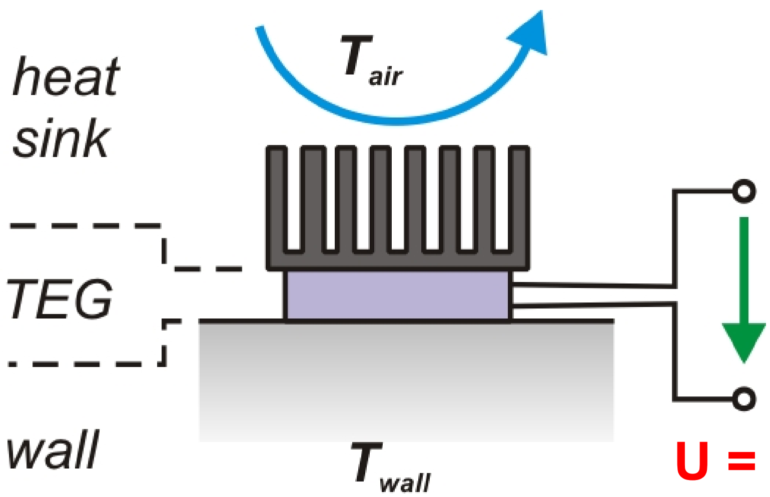
***temporal behaviour** of ΔT² does **also** define the output power*

Energy harvesting from low ΔT in a tunnel





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

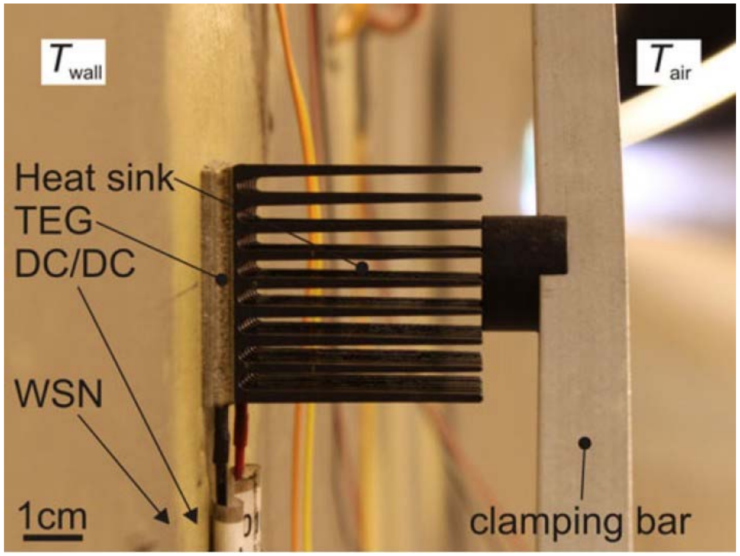


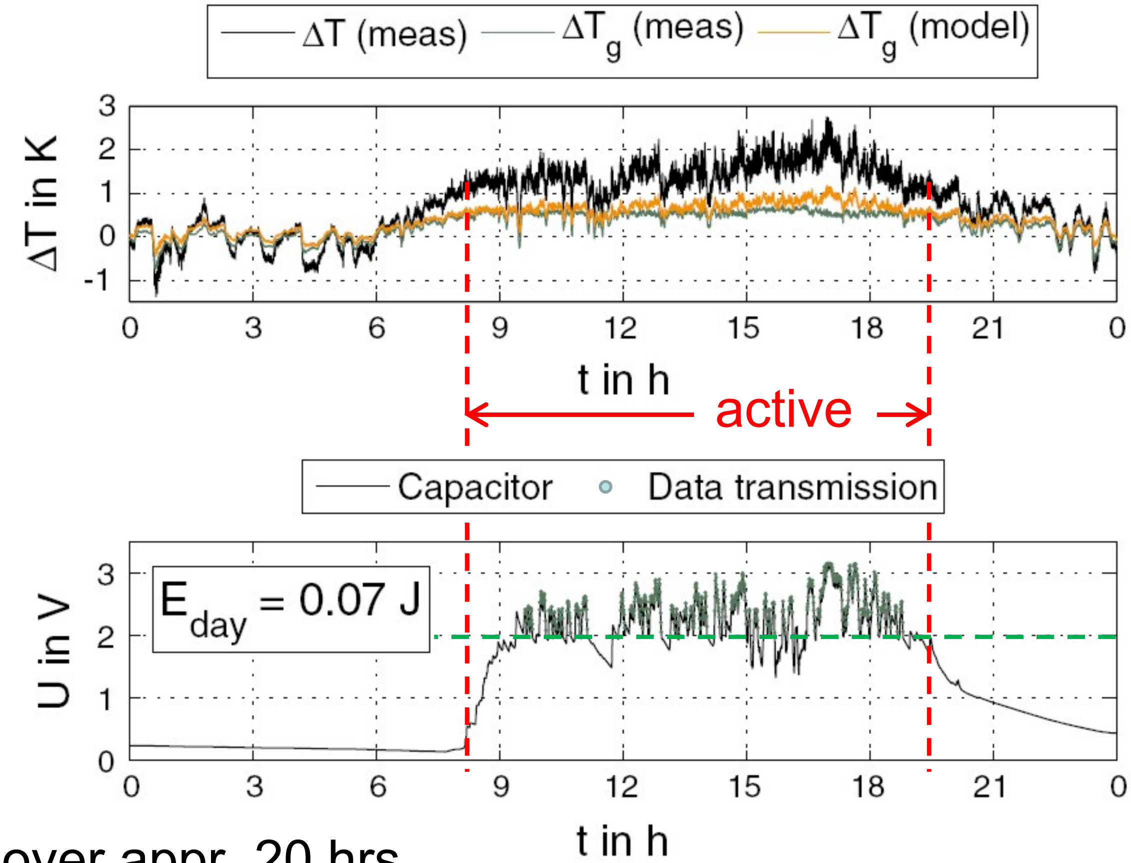
U = 20…60 mV

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 low ΔT in a tunnel



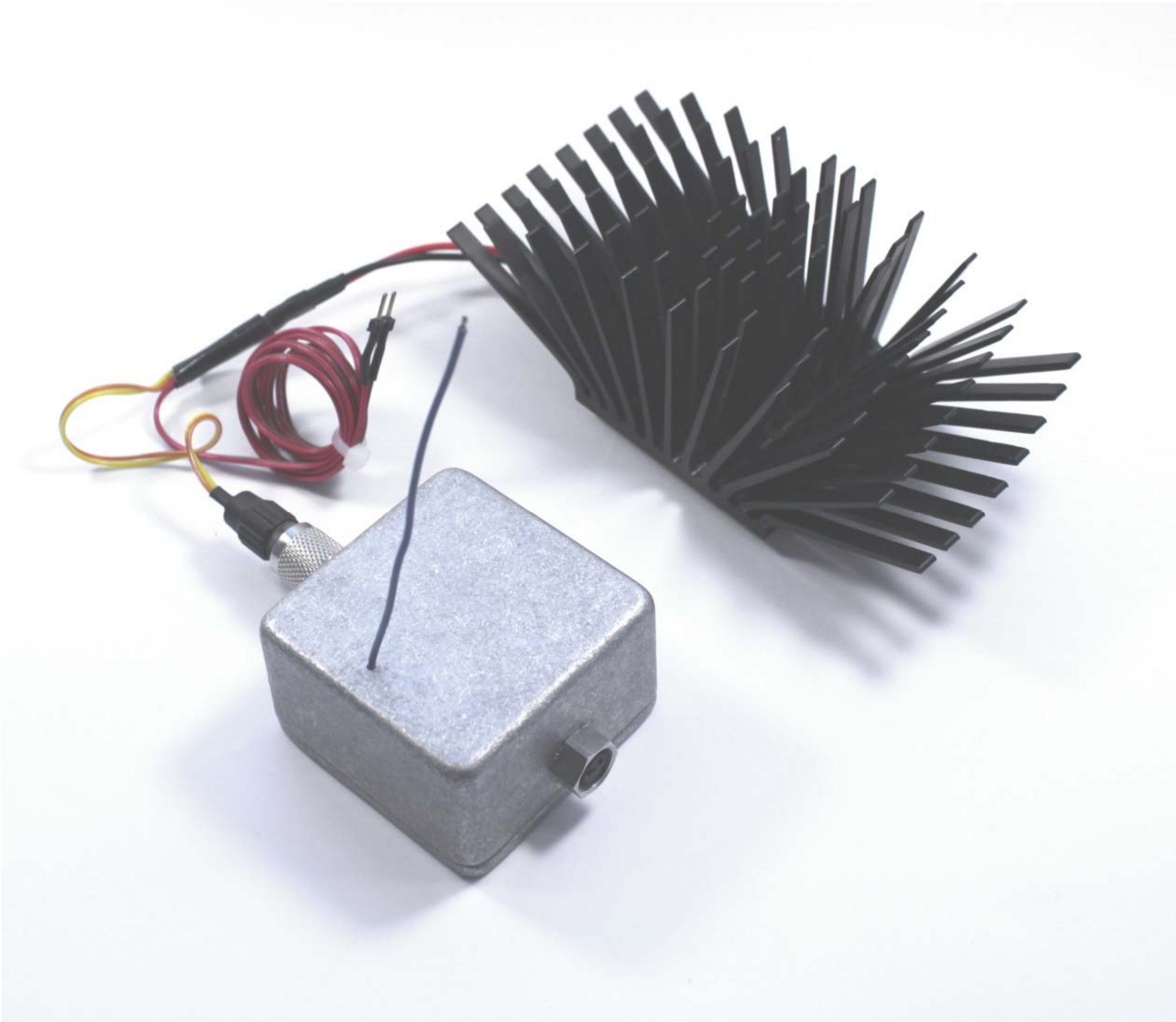


Results

- 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: Enocean transmitter

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

Wall-mountable modular sensor system



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

Medium ΔT applications

Fabrication

Boundary conditions

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

Process control

© Citroen

Automotive

© ABB

Energy-autonomous sensors in automotive applications

What for ?

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

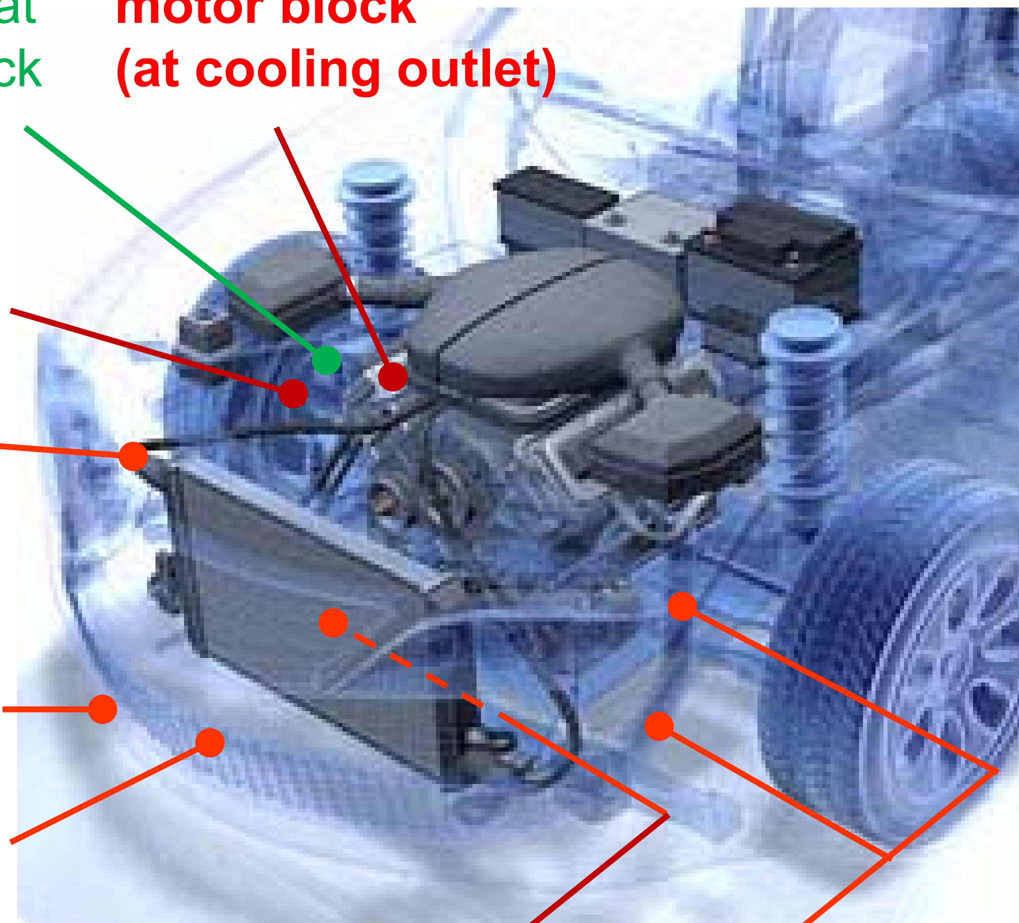
Available energies at/in a car or truck ?

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

First measurement campaign: Thermal budgets in/around a car engine

Peugeot 306 ***(2000)****,*
90 PS, gasoline

PT 1000
temperature sensor

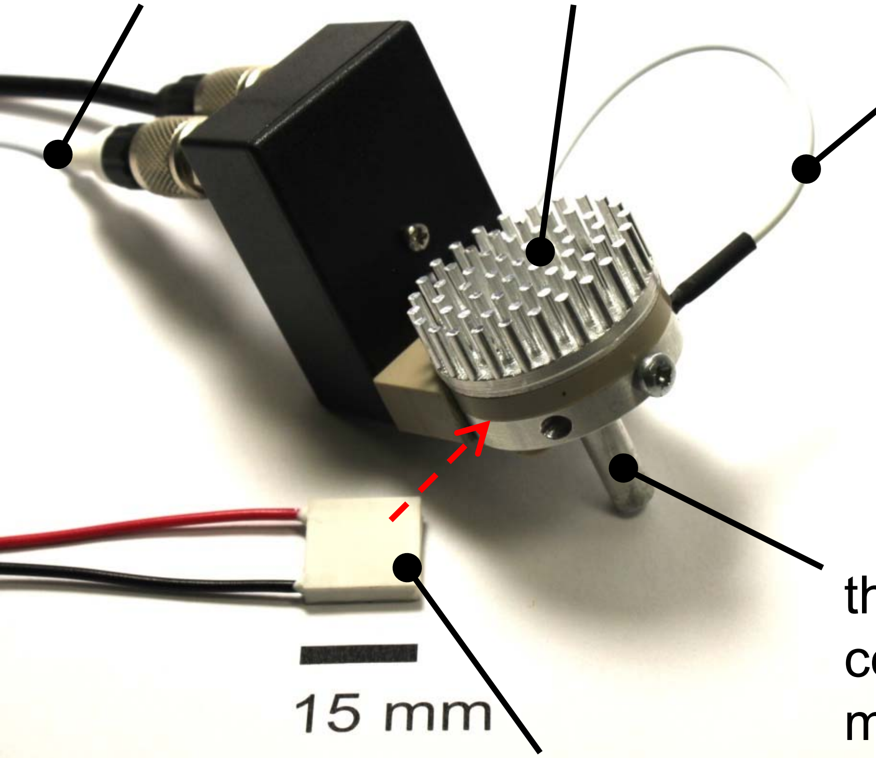


Miniaturized TEG module

electric connector

heat exchanger

Pt 1000 (hot side temperature)

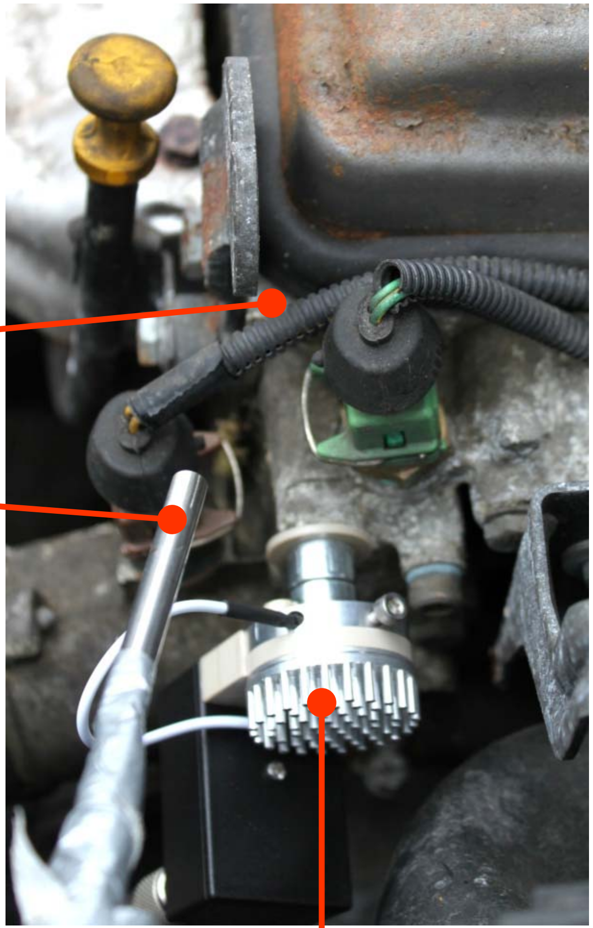


thermal connector to motor block

TEG:
$n \cdot \alpha = 4\ mV/K$
$R_g = 0{,}21\ Ohm$

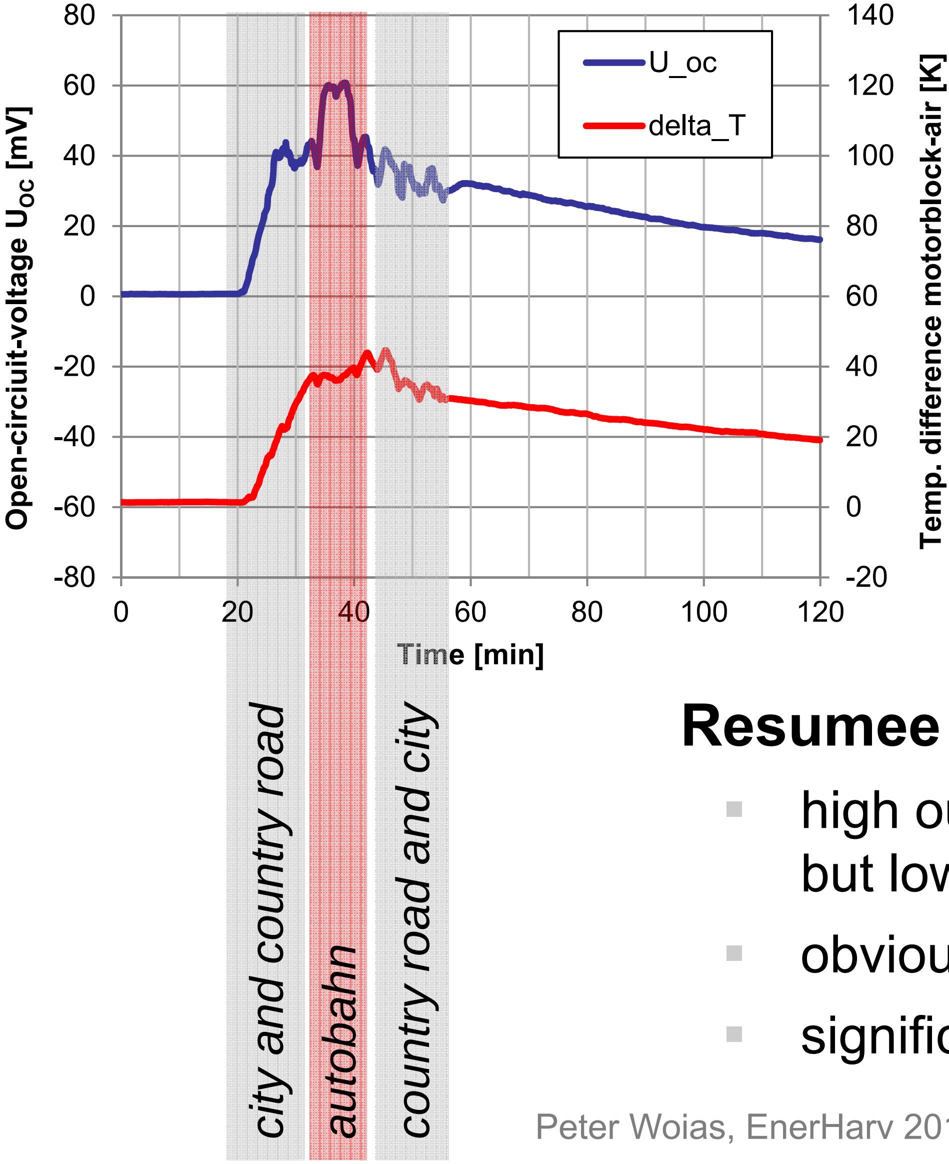
motor block

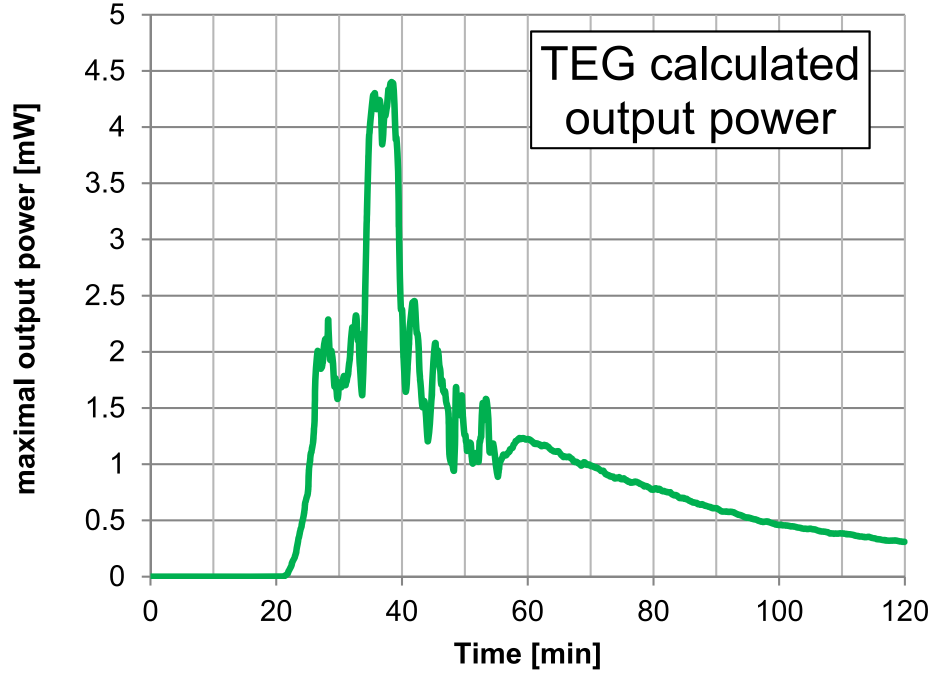
Pt 1000 (air temperature)



TEG module

Exemplary measurement results

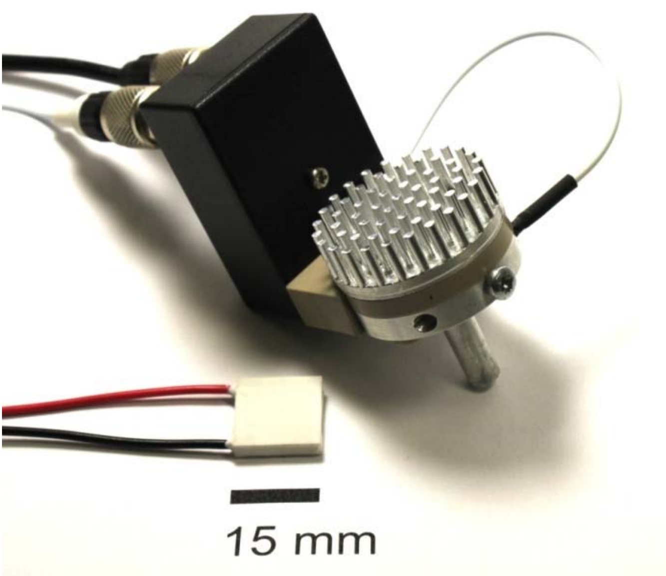


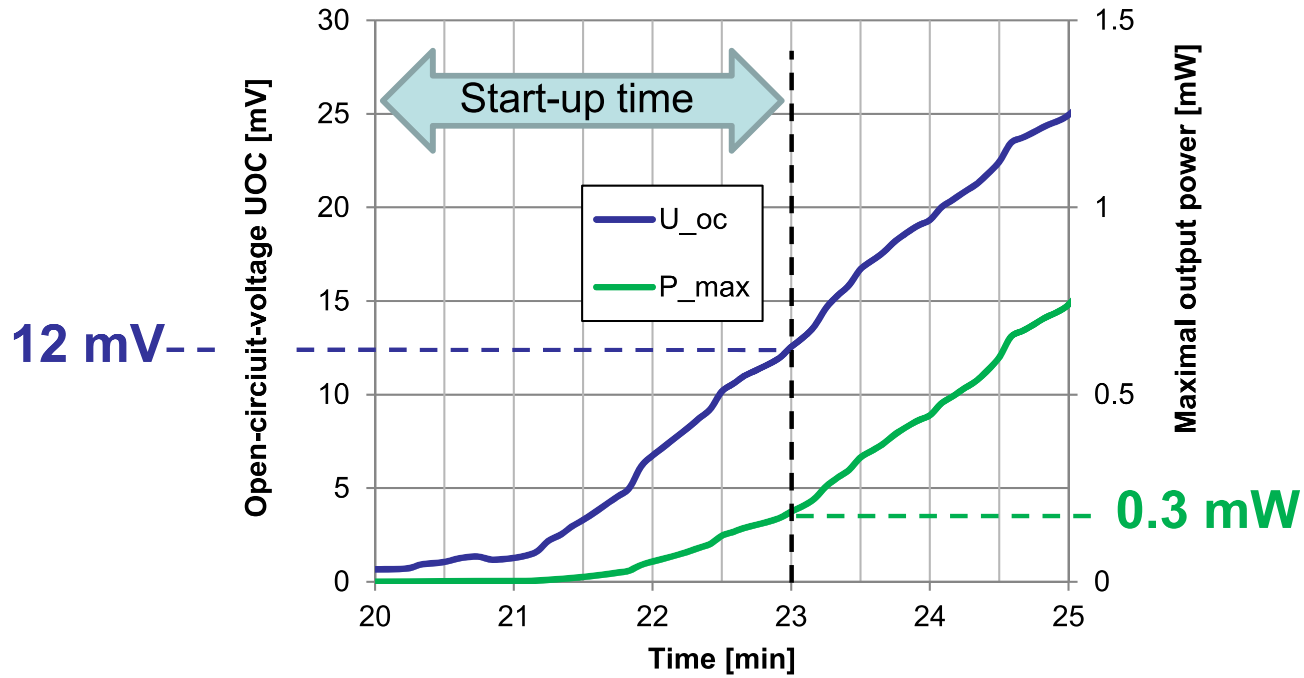


Resumee

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

Cold-start delay and conditions ?



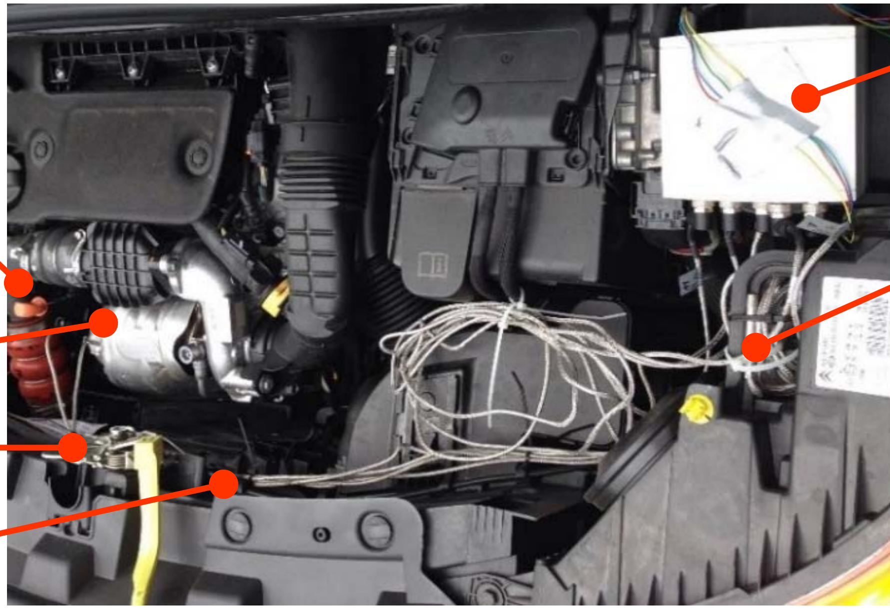


Resumee (for a small commercial TEG)

- 100 µWs of output power available after a few minutes

  a small TEG = sufficient for low-power wireless sensors ***only***
- low-voltage step-up required *"starting from as low as possible"*
- higher output power required for realistic application scenarios

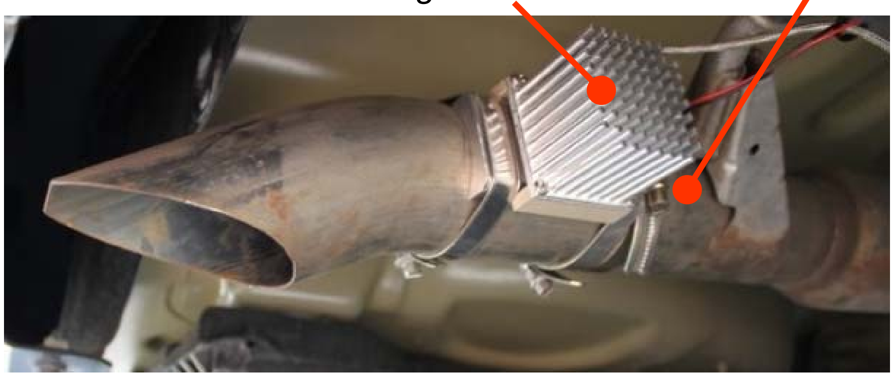
Second measurement campaign: A larger TEG in a modern car



Citroen C3 Picasso blueHDI 100 ***(2016)****, 100 PS, diesel engine*

TEG + heat sink

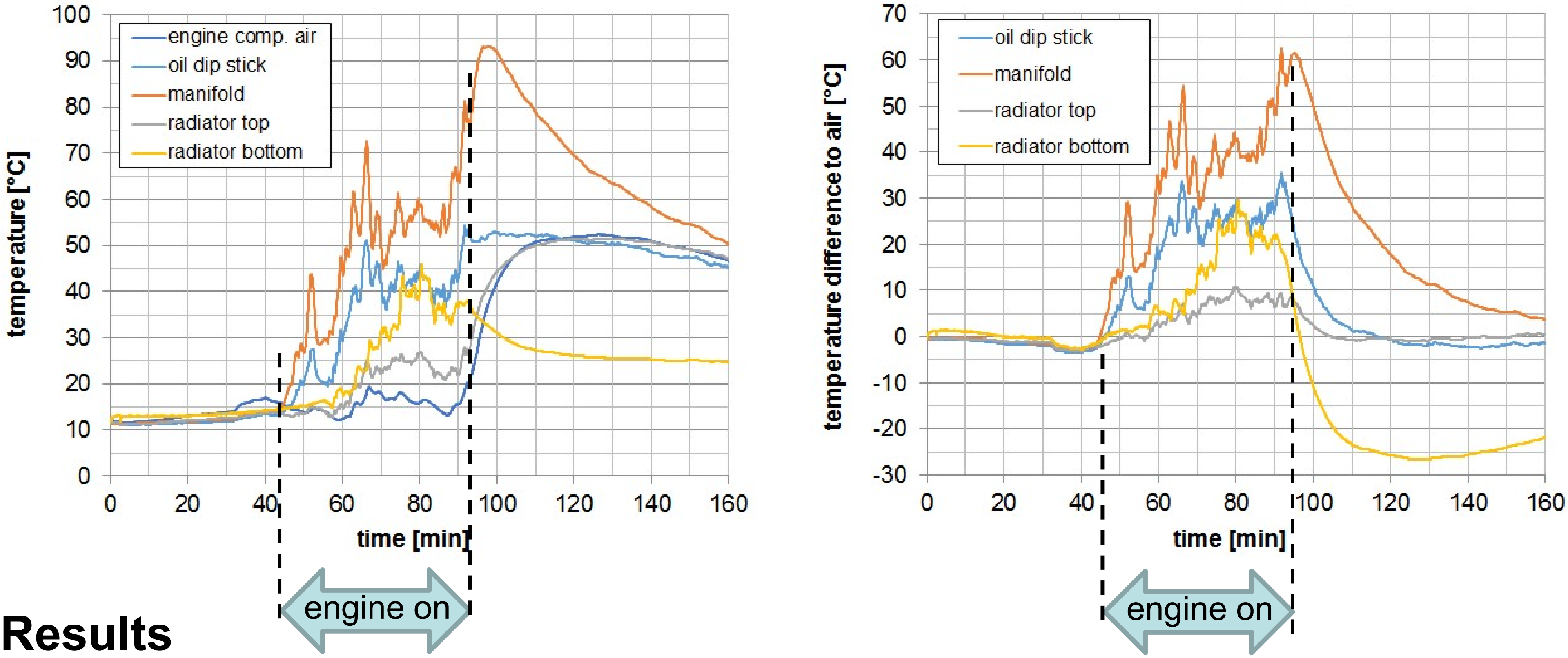
$n \cdot \alpha = 30\ mV/K\ R_g = 0{,}89\ Ohm$



A: tip of oil level dip stick
B: cooling manifold
C: radiator support (top)
D: radiator support (bottom)
E: motor compartment air
G: exhaust surface temperature
H: chassis bottom (ambient air)

P. Mehne et al., *J. Phys. Conf. Ser.* 773, **2016**, 012041.

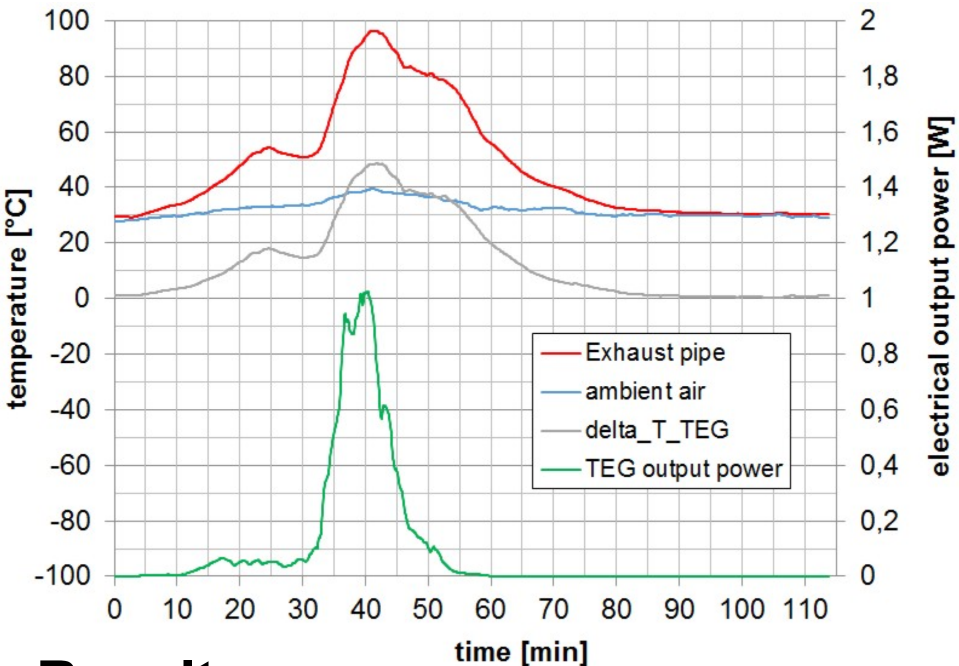
Typical measurement results: Engine compartment

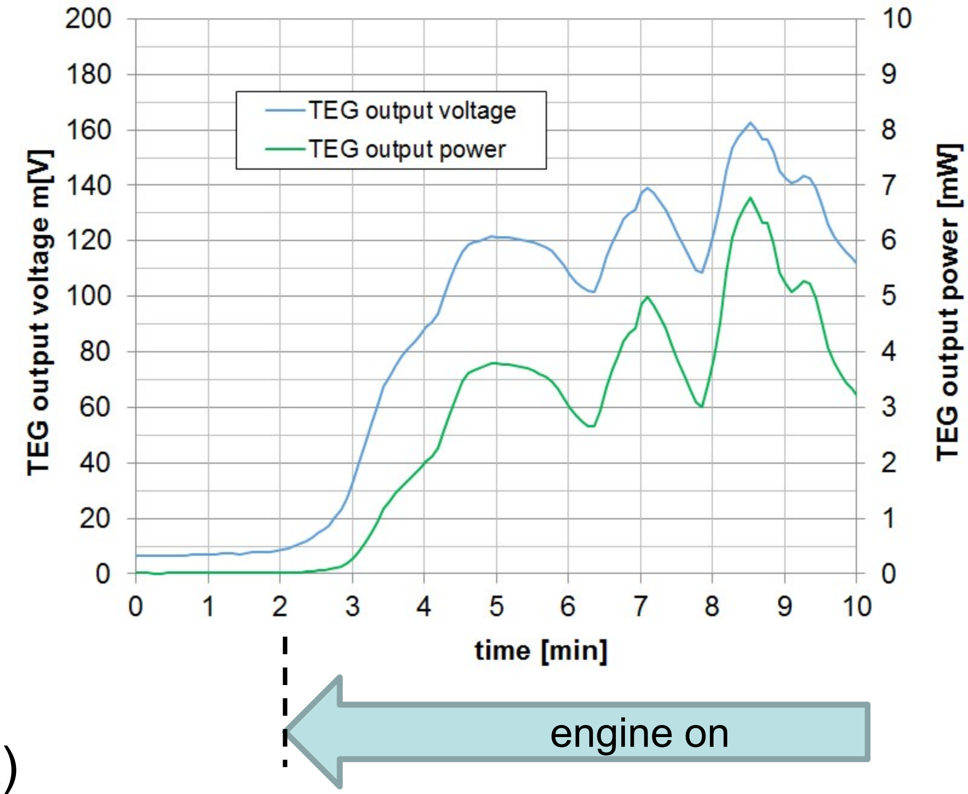


Results

- much lower temperatures in modern cars (2016) vs. elder cars (2000)
- substantial heat-up of the engine compartment at the end of a ride ➡ lower ΔT
- nevertheless potential for energy harvesting

Typical measurement results: TEG at the exhaust pipe





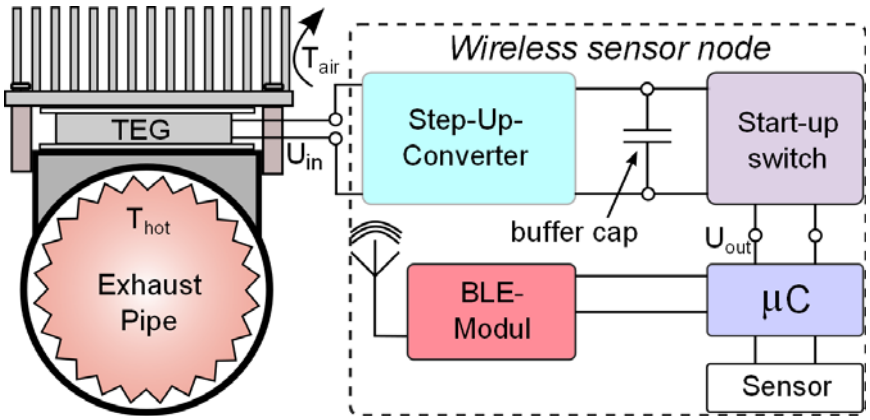
Results

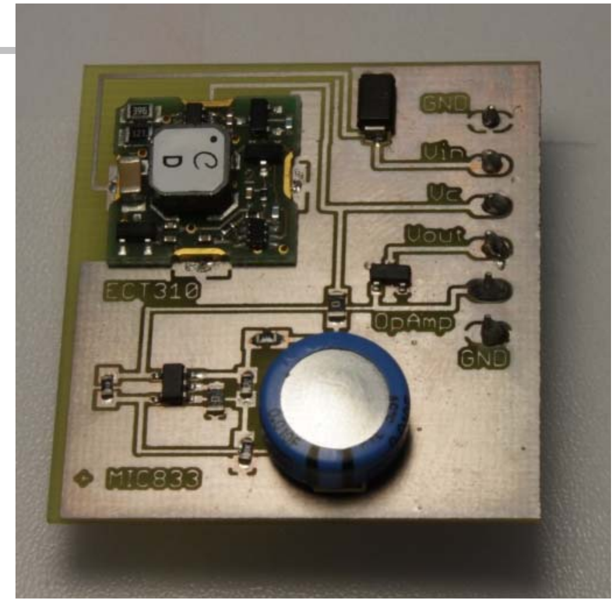
- very high output power (up to 1 watt)
- significant start-up time (several minutes)
- requirements:
  - *step-up converter with vey low start-up voltage*
  - *system electronics with low power draw (especially the wireless interface)*

load resistance at TEG:
R_L = 3.89 Ohm

Energy-autonomous temperature sensor at the exhaust pipe

System design and power consumption





part	type	current	energy	power
start-up switch	MIC833	1 µA		~ 4 µW
microcontroller	MSP430F5529	a few µA		~ 10 µW
bluetooth module	BLE112		4.5 mJ/telegram	4.5 mW

Resumee

- start-up at 20 mV input voltage (with an Enocean ECT 310 step-up converter)
- stable operation already with the car in idle mode
- however: further optimization required

P. Mehne et al., *J. Phys. Conf. Ser.* 773, **2016**, 012041.

UNI FREIBURG

High-temperature and ΔT applications

Highly energetic combustion processes

Gas and aircraft turbines

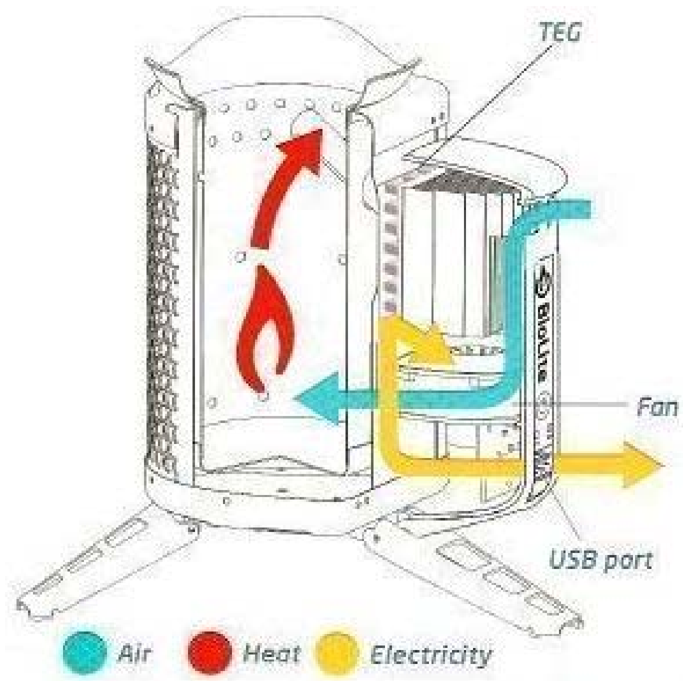
Boundary conditions

- 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)

High-power geothermy

High-temperature applications: a gadget example ?

BioLite 2® thermoelectric energy harvesting stove



Properties

- cold temperature level decreased via **active convective cooling**
- average electric power: 3 W
- integrated battery (2.600 mAh)

High-temperature applications: What TEGs are needed to power WSNs ?

$$P_{out} = f \cdot d \cdot \frac{S^2}{R_L} \cdot (T_2 - T_1)^2$$

➡ **Output power ~ (Seebeck · ΔT)²**

… but also: at least T_2 is high

Resumee

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

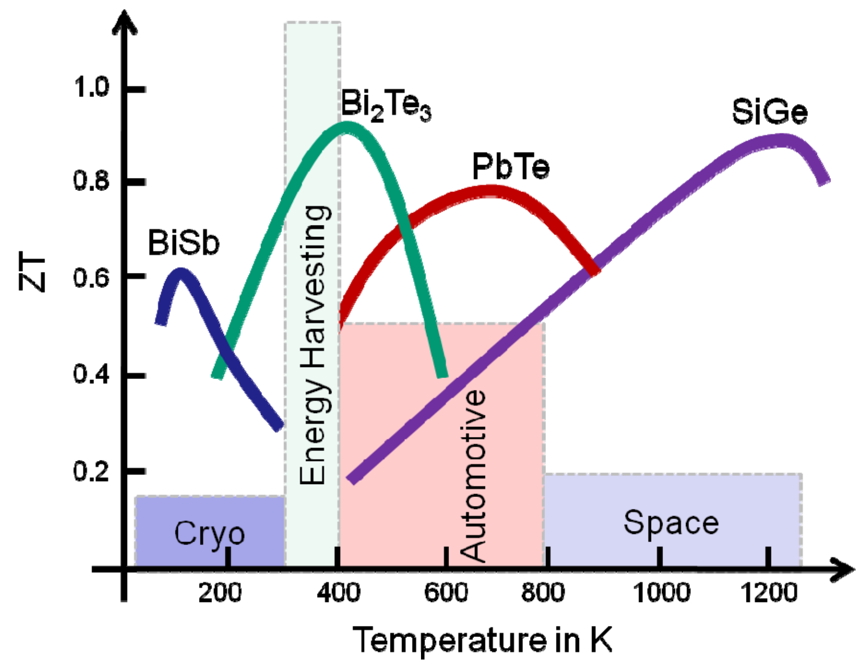
Choice of termoelectric materials

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

High-temperature thermoelectric Materials

Why metal TEGs ?

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

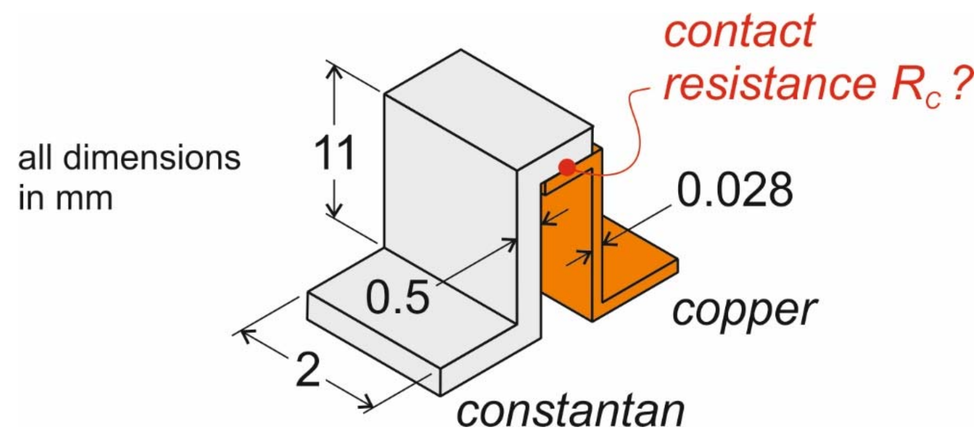


	Typical Seebeck coefficient	Melting point
Copper	6.5 µV/K	1085 °C
Constantan ($Cu_{55}Ni_{45}$)	-35 µV/K	1280 °C
Bi_2Te_3	~ 200 µV/K	573 °C
PbTe	~ -100 µV/K	905 °C

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 promising – and feasible – for harvesting from thermal reservoirs with high and/or low heat fluxes and temperature differences.

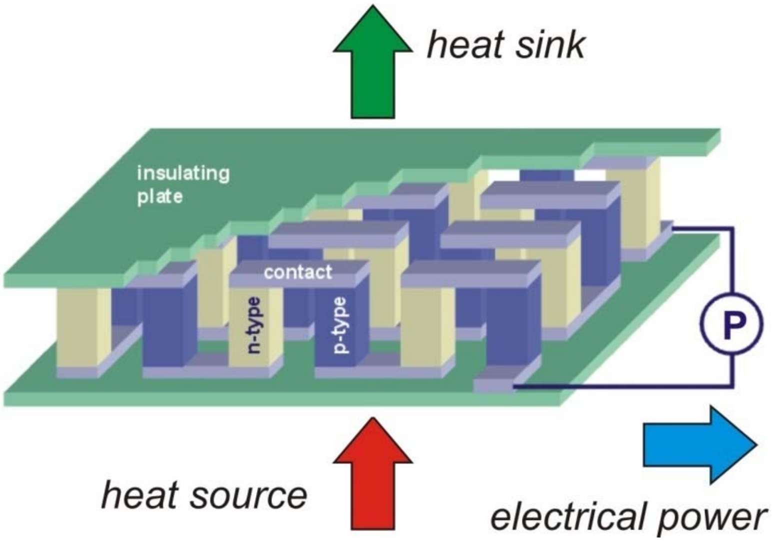
In any case, a thorough system design is required, by tailoring ….

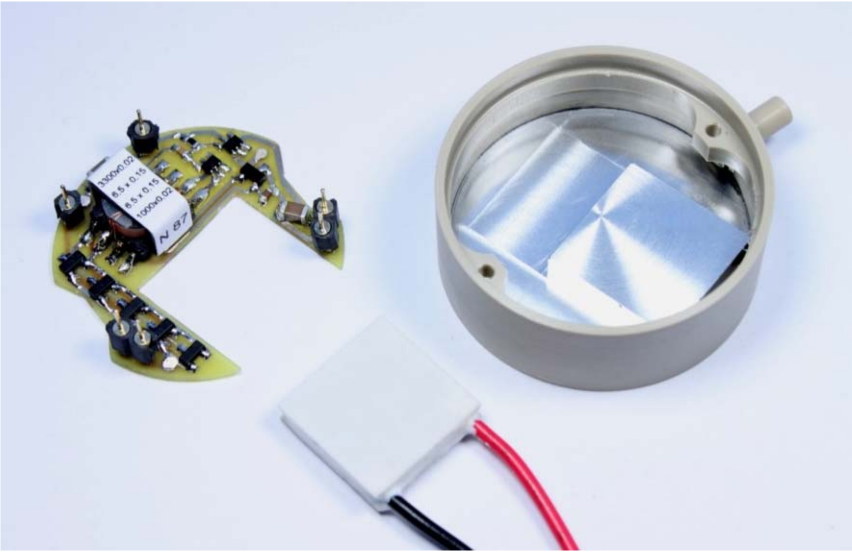
- the TEG itself, and its thermal interfaces,
- all power management electronics,
- the connected wireless sensor node.

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





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