Thermoelectric waste heat recovery on the way to mass production and into applications

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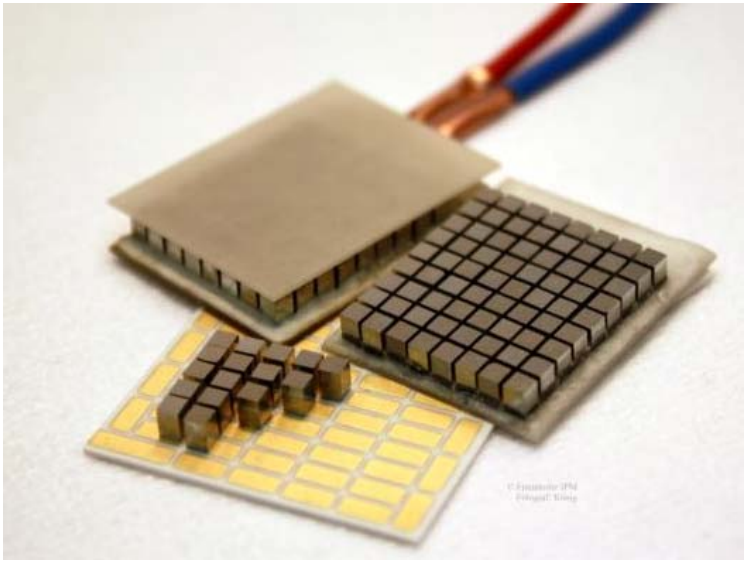


Fraunhofer IPM

Thermoelectric waste heat recovery on the way to mass production and into applications

Content

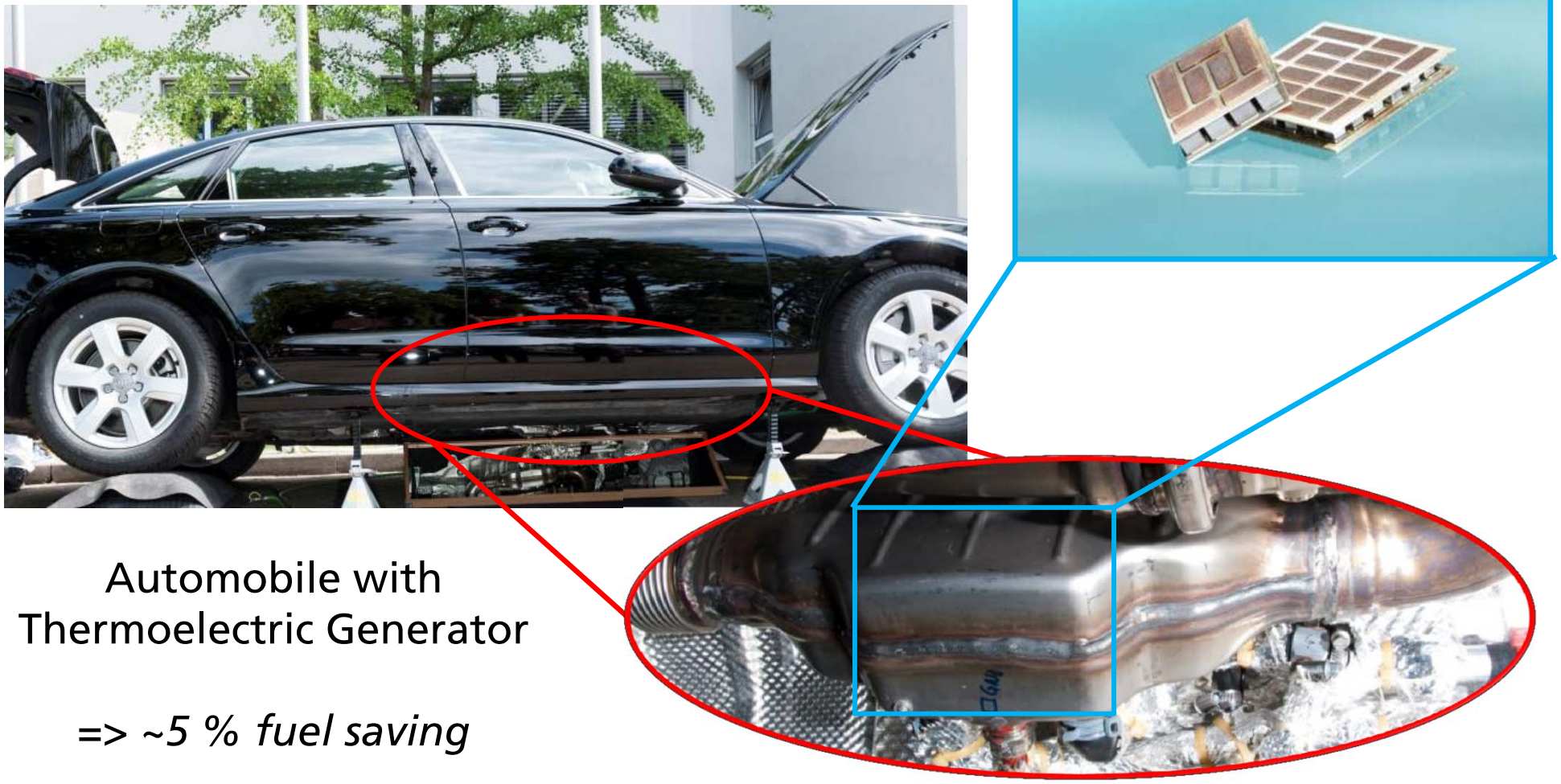
- On the way to applications
- Module Fabrication
- New Half-Heusler Modules and Arrays
- Cost Considerations
- Summary

Application

Bundesministerium für Wirtschaft und Energie

TÜVRheinland® Genau. Richtig.

Project: ThermoHeusler 2

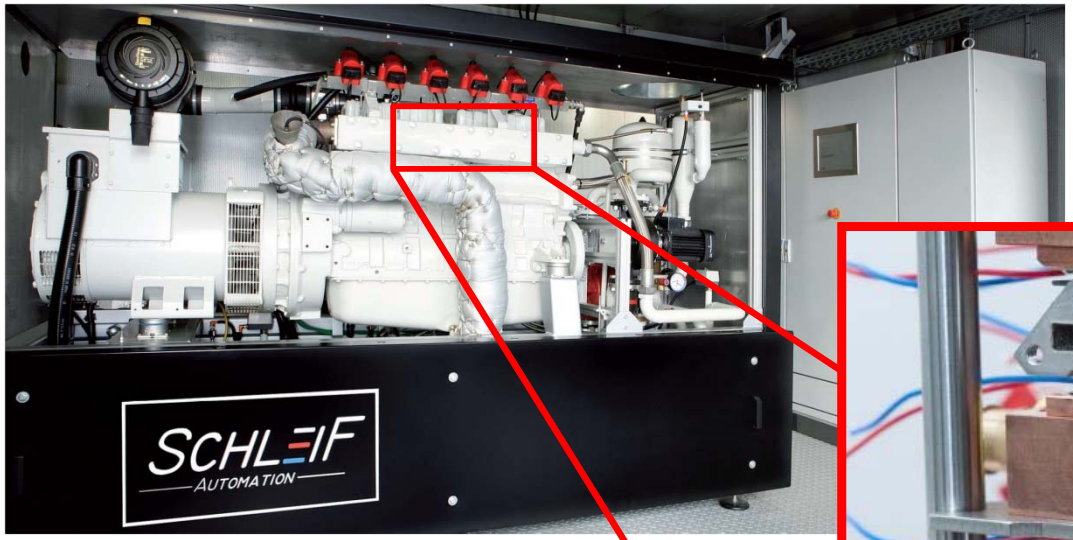


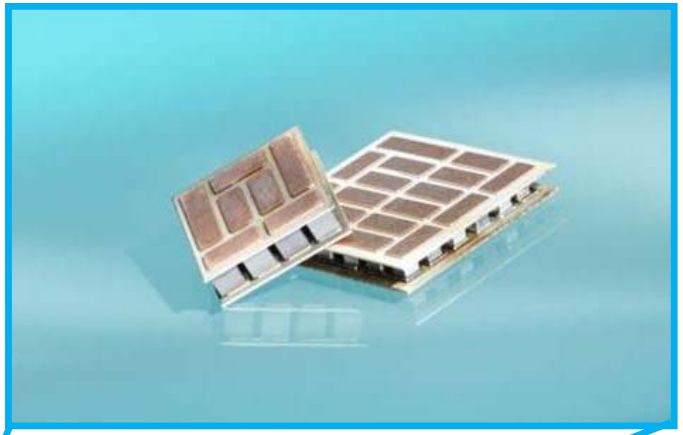
Automobile with Thermoelectric Generator

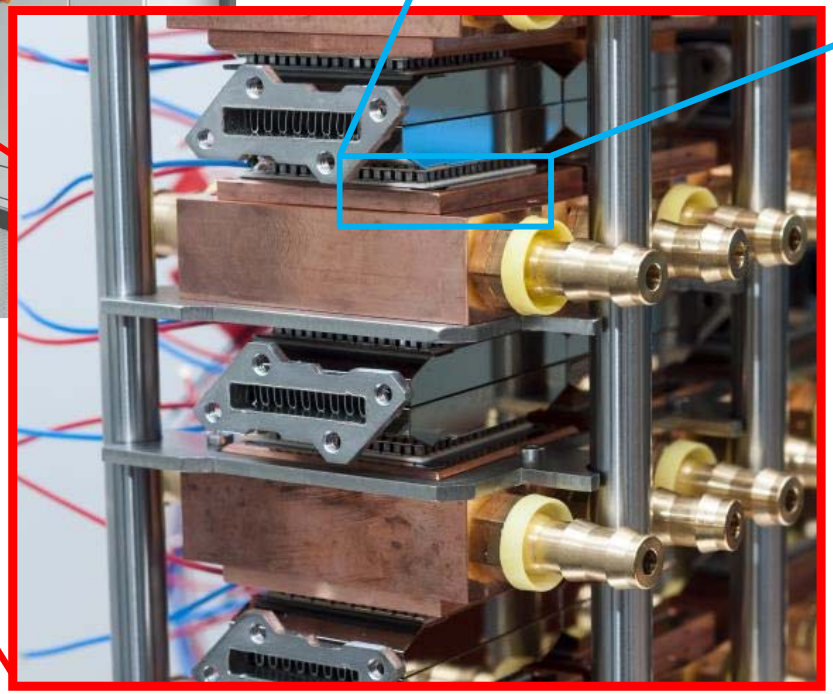
=> ~5 % fuel saving

Application

Project: Thermoelectric CHPs







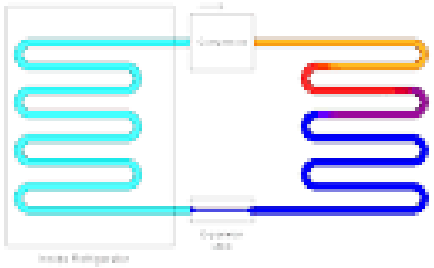
CHP with
Thermoelectric Generator

=> ~3 % improvement in electrical efficiency

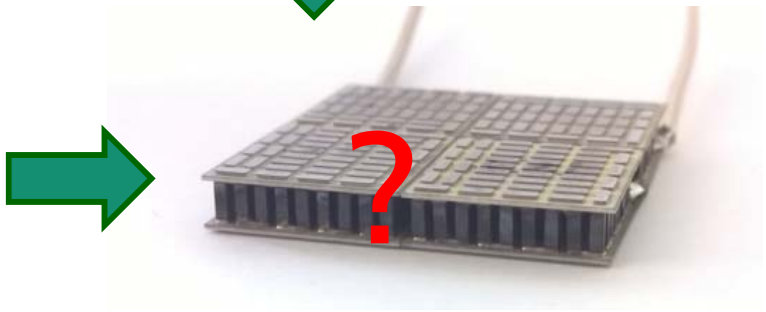
System Design Aspects
TE-Module Design and Integration

mass-flow,
temperature,
back-pressure

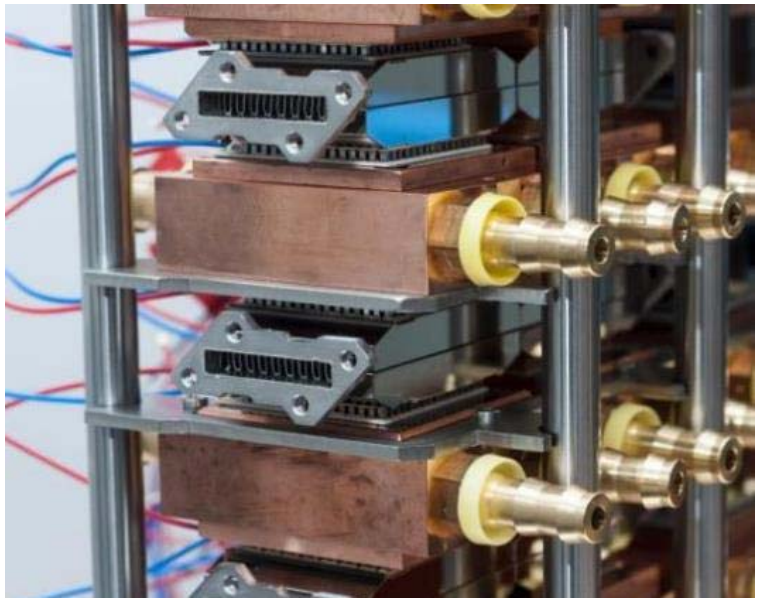
Application

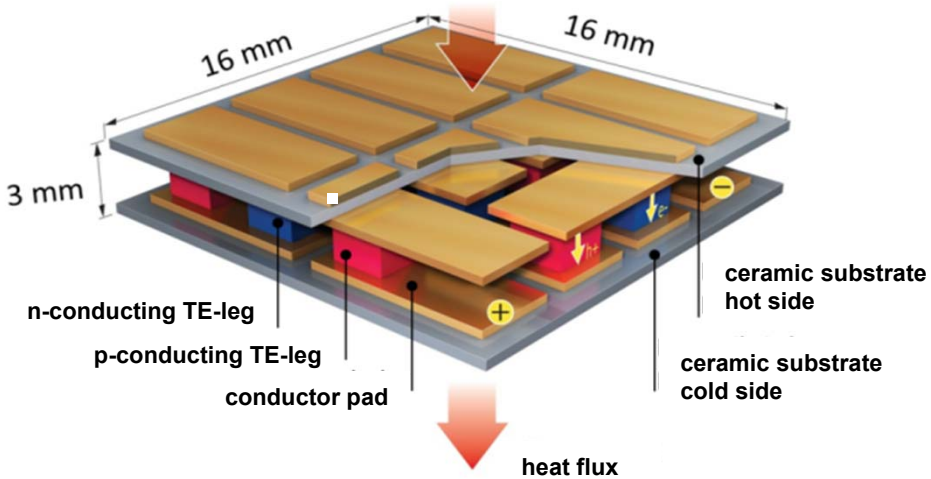


Coolant flow,
temperature,
(back-pressure)



System Design Aspects
TE-Module Design and Integration





System design essentials

- Thermal matching with heat exchangers $R_{th,TE} = \left(R_{th,H} + R_{th,C}\right) \cdot \sqrt{ZT + 1}$
- Electrical matching with load circuit $R_{el,TE} = R_{el,L}$
- Power management, Voltage conversion $U_0 = f(T_H, T_C)$

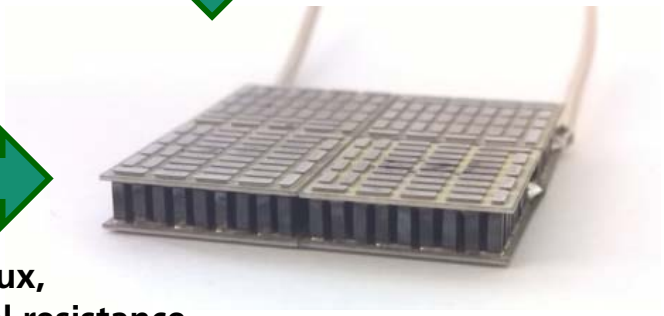
System Design Aspects
TE-Module Design and Integration

mass-flow,
temperature,
back-pressure

Voltage / current (@ ΔT, T)

⇔

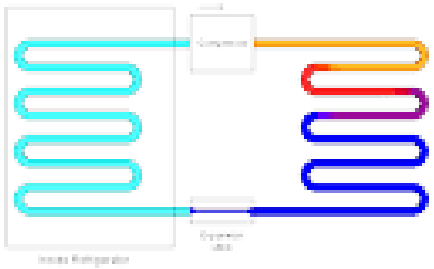
Number of legs



Heat flux,
thermal resistance

⇔

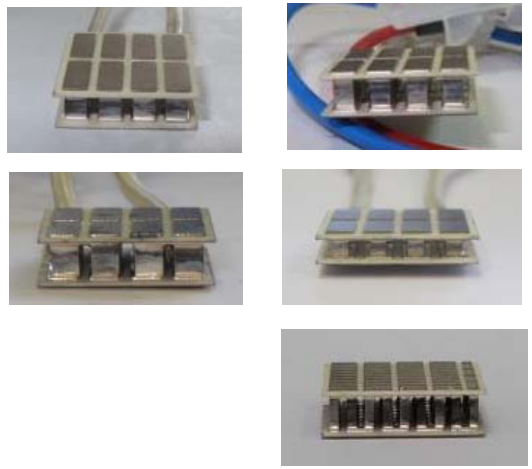
Height of legs;
legs diameter;
filling factor



Coolant flow,
temperature,
(back-pressure)

High Temperature Module Manufacturing

Customized Half-Heusler Module designs

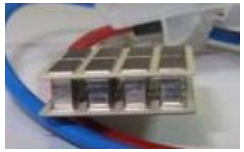


Module efficiency ~5,4 %
(dT~530 K; T_{hot} ~550 °C)

<u>Tunable Module design parameter:</u>
Module geometry: **16 x 16** mm² or **20 x 20** mm²
variable height: 3 … 5 mm

Thermal resistance: **4 …. 40 K/W** ; (dT~490 K; T_{hot} ~550 °C)

Open circuit voltage: **245 µV/K per unicouple** (dT~490 K; T_{hot} ~550 °C)



=> U_0 = ~0,9 V for module with 7 unicouples
and dT~490 K; T_{hot} ~550 °C

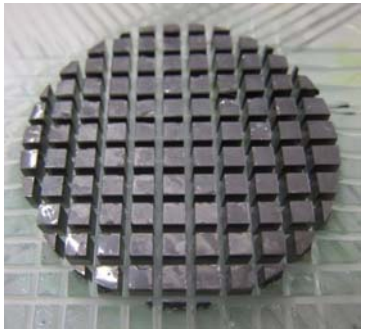
High Temperature Module Fabrication

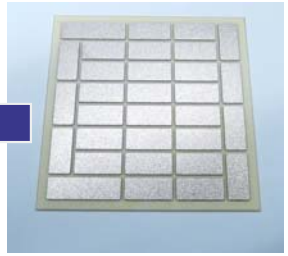
Manual Module Production Process

sintering

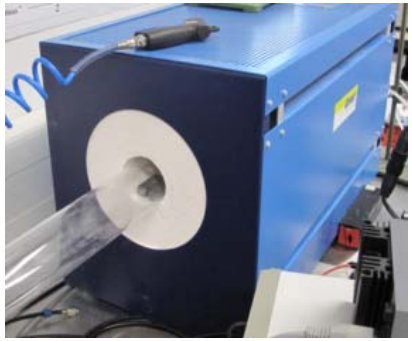
polishing

& dicing



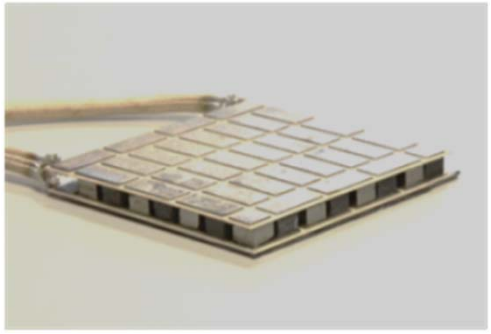


brazing



electric.

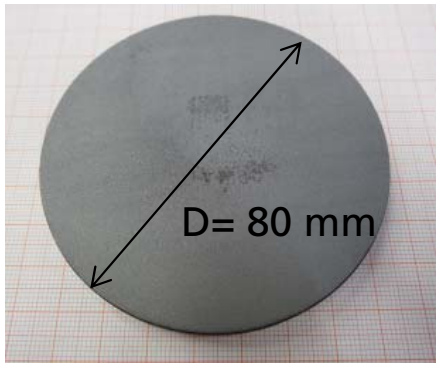
connected



High Temperature Module Fabrication

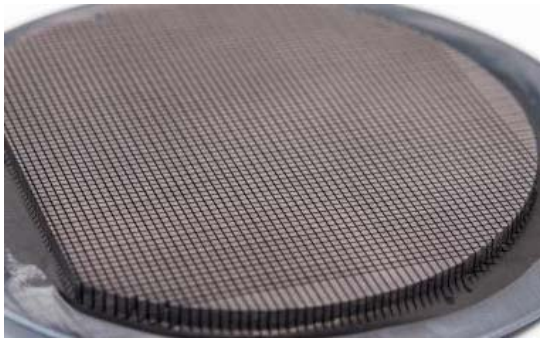
Semi-automated Module Process

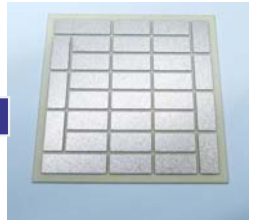
sintering



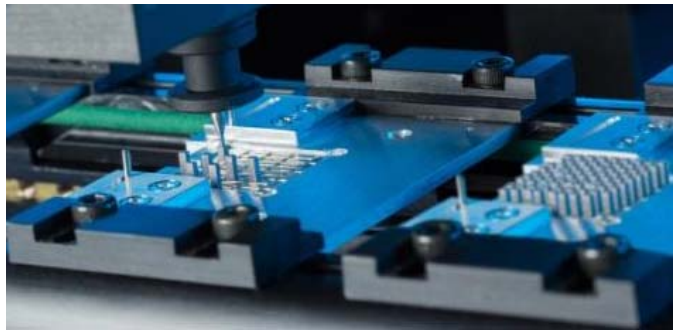
polishing

& dicing





pick & place



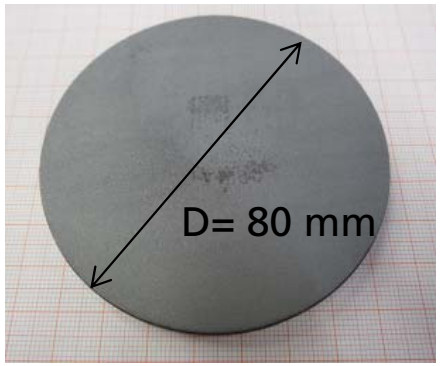
High Temperature Module Fabrication

Semi-automated Module Process

High Temperature Module Fabrication

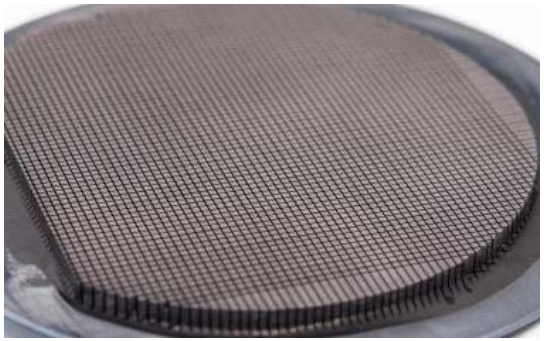
Semi-automated Module Process

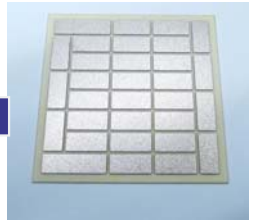
sintering



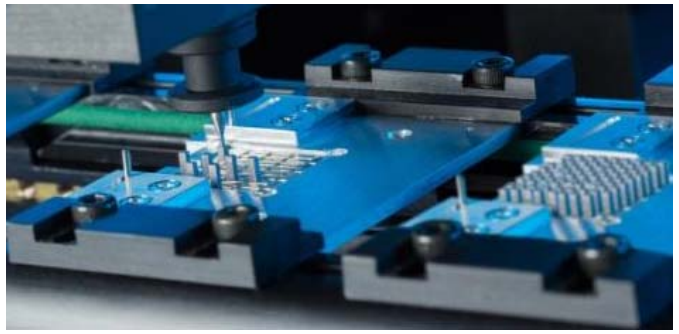
polishing

& dicing





pick & place



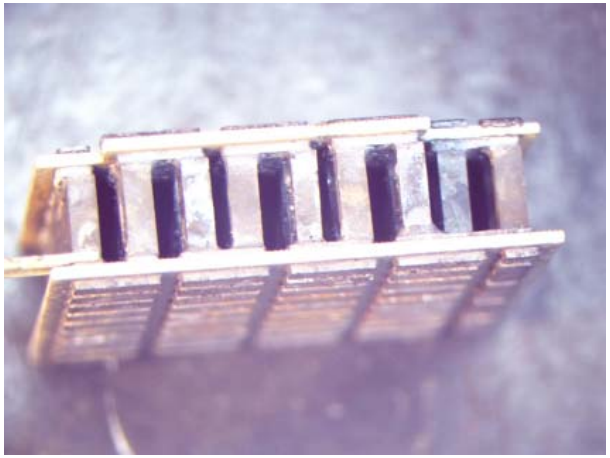
brazing

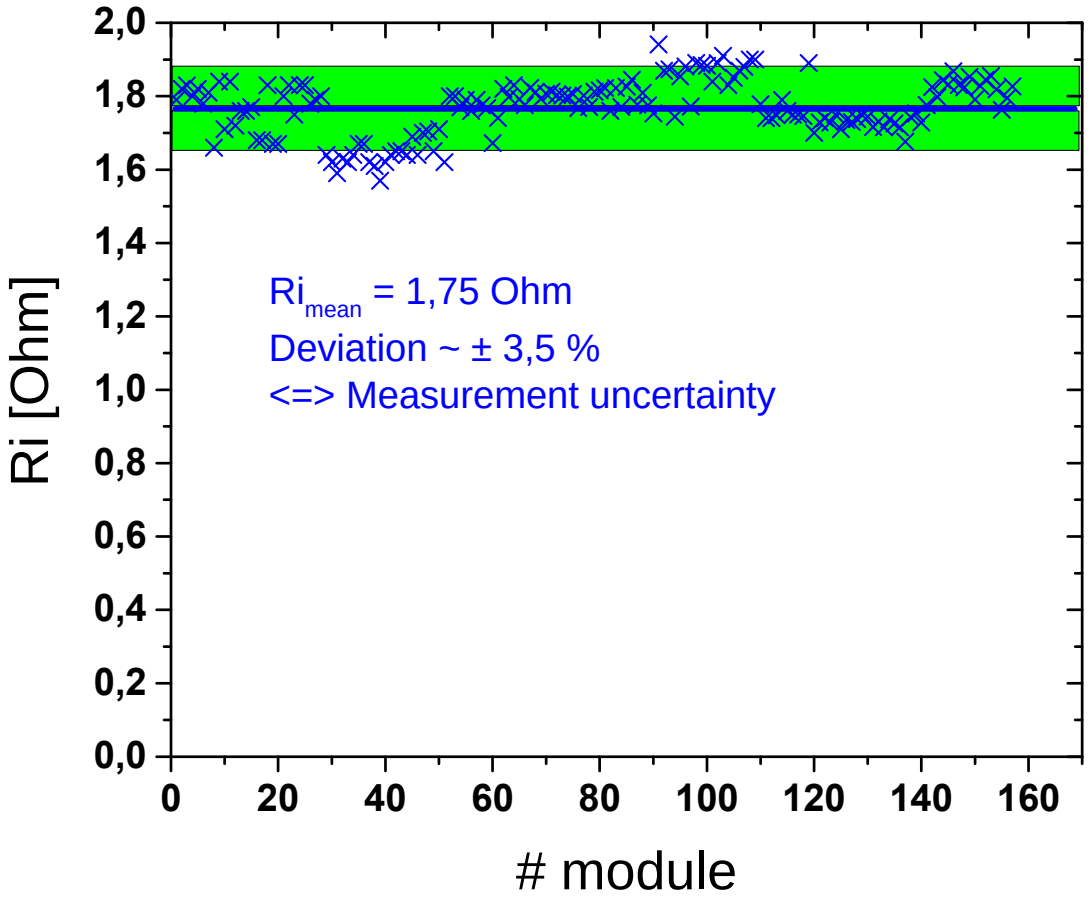
quality

control

High Temperature Module Fabrication

Semi-automated Module Process





High Temperature Module Fabrication

Semi-automated Module Process

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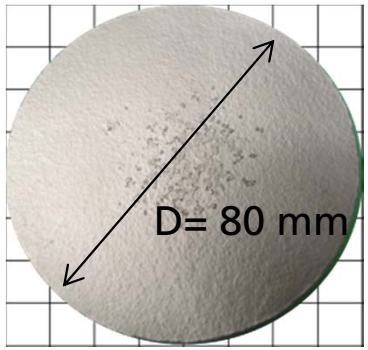

polishing

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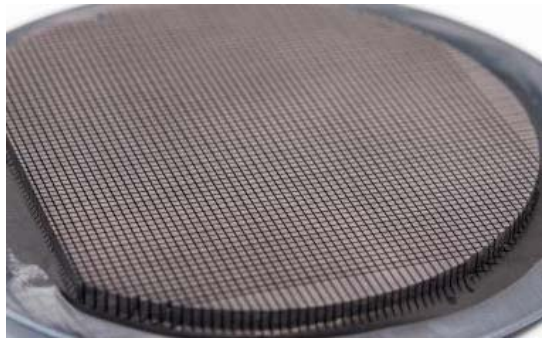
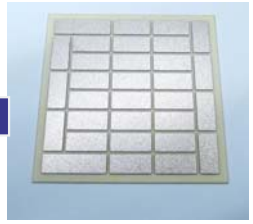
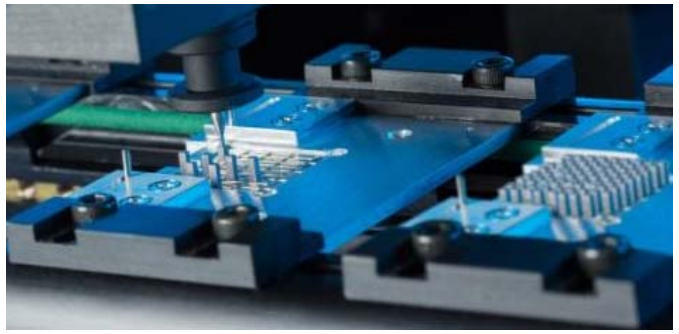




pick & place



brazing

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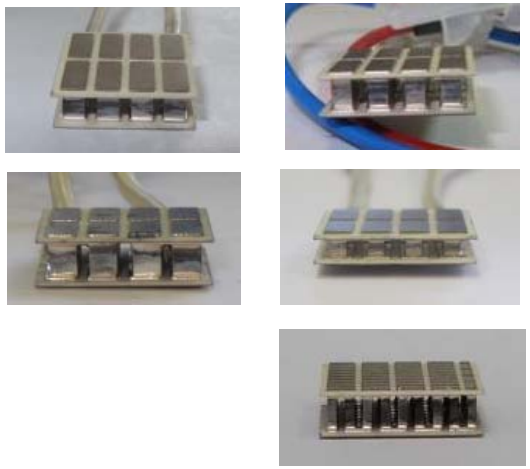
control

High Temperature Module Fabrication

Customized Half-Heusler Module designs



Module efficiency ~5,4 %
(dT~530 K; T_{hot} ~550 °C)

<u>Tunable Module design parameter:</u>
Module geometry: **16 x 16** mm² or **20 x 20** mm²
variable height: 3 … 5 mm

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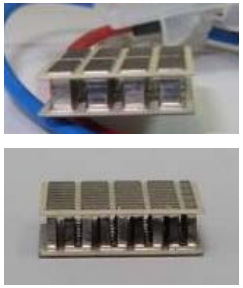
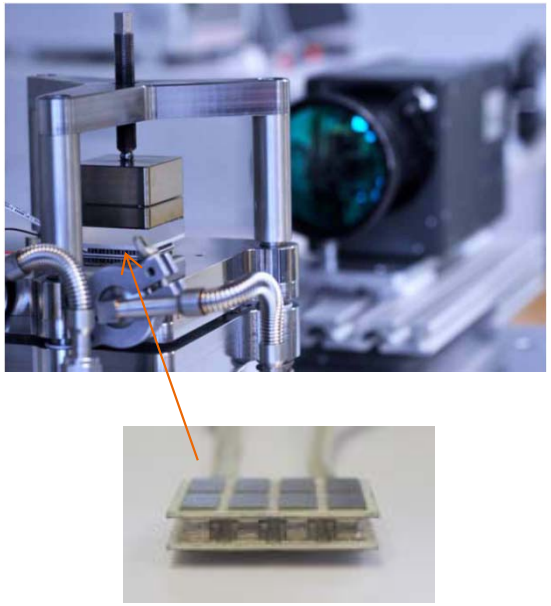


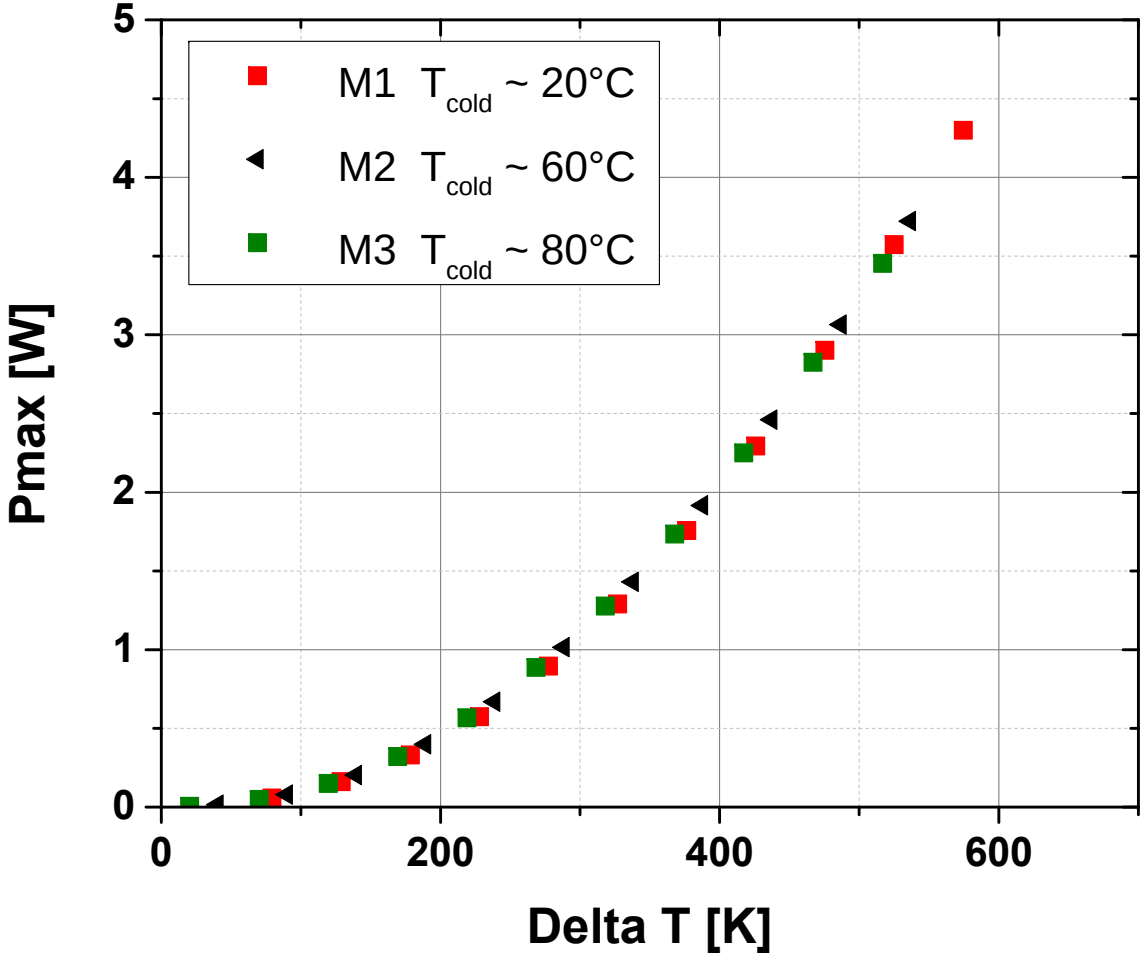
=> U_0 = ~0,9 V for module with 7 unicouples
and dT~490 K; T_{hot} ~550 °C
=> U_0 = ~5 V for module with 39 unicouples
and dT~490 K; T_{hot} ~550 °C

High Temperature Module Fabrication

Performance of Half-Heusler Modules

Electrical Power output of a new high temperature Half-Heusler Module (1.6 x 1.6 cm²)





High Temperature Module Fabrication

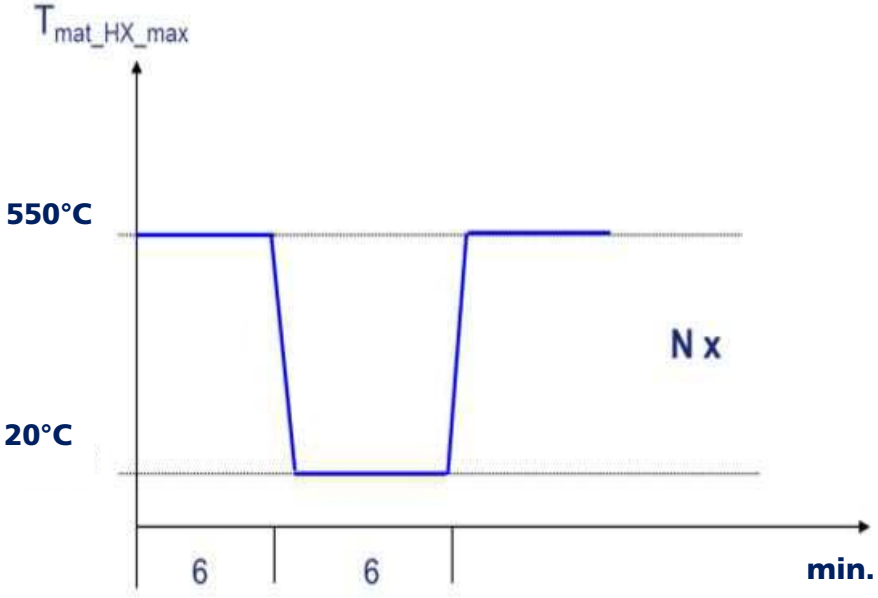
Reliability of Half-Heusler Modules

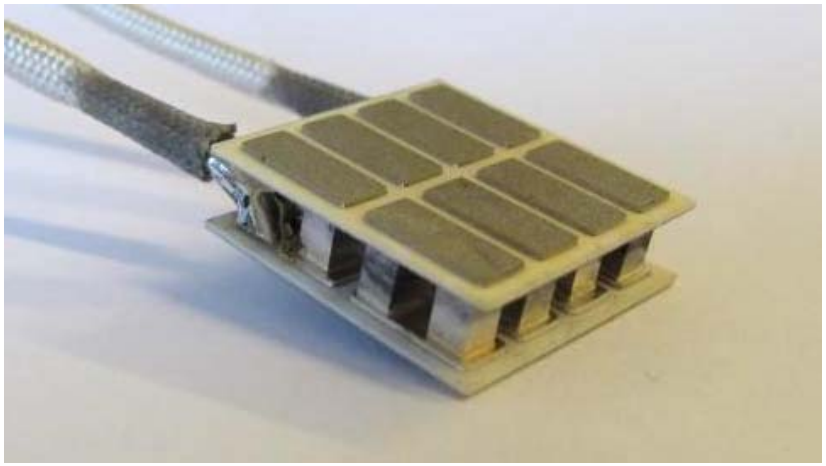
faurecia
Emissions Control Technologies

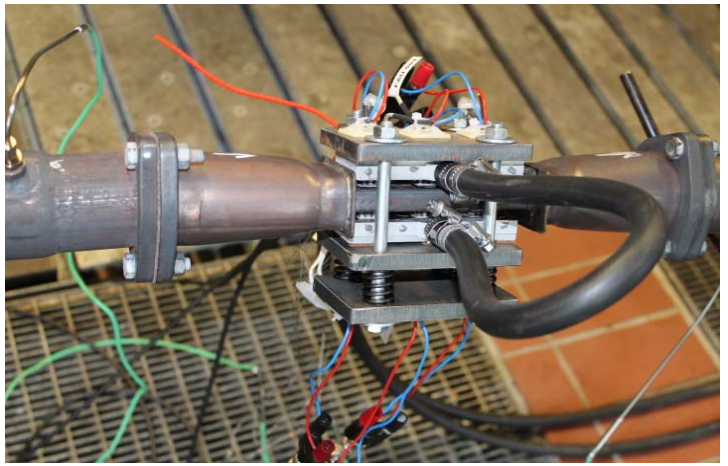
Thermal shock testing at Faurecia ECT

- T_H = 550 °C <-> 20 °C
- T_C = 20 °C
- >1,000 Cycles in Air

→ No significant degradation!







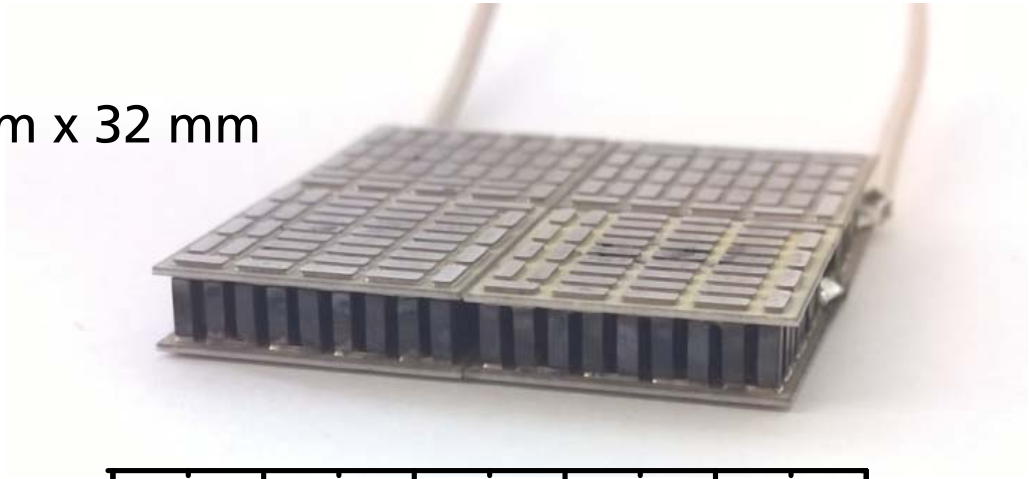
High Temperature Module Fabrication

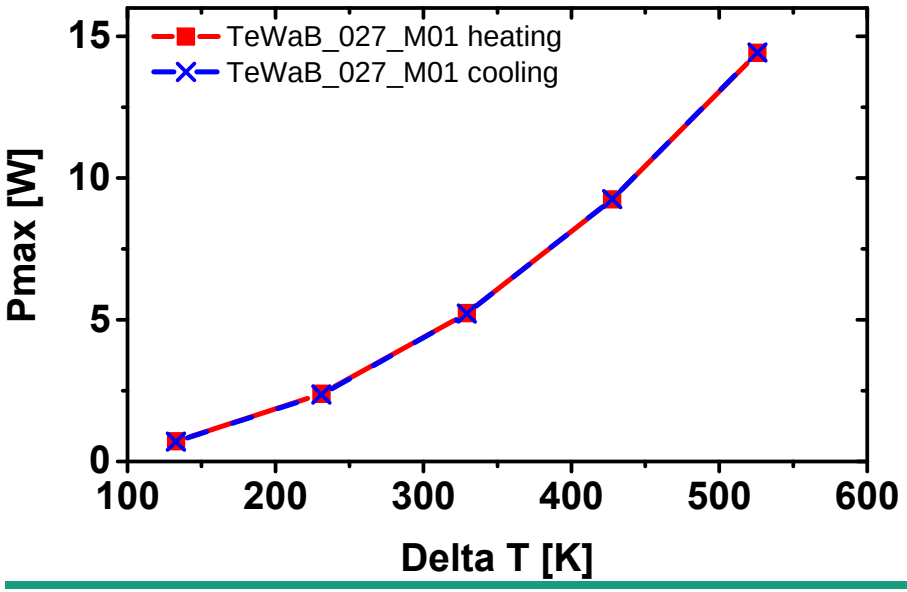
Half-Heusler Module Arrays

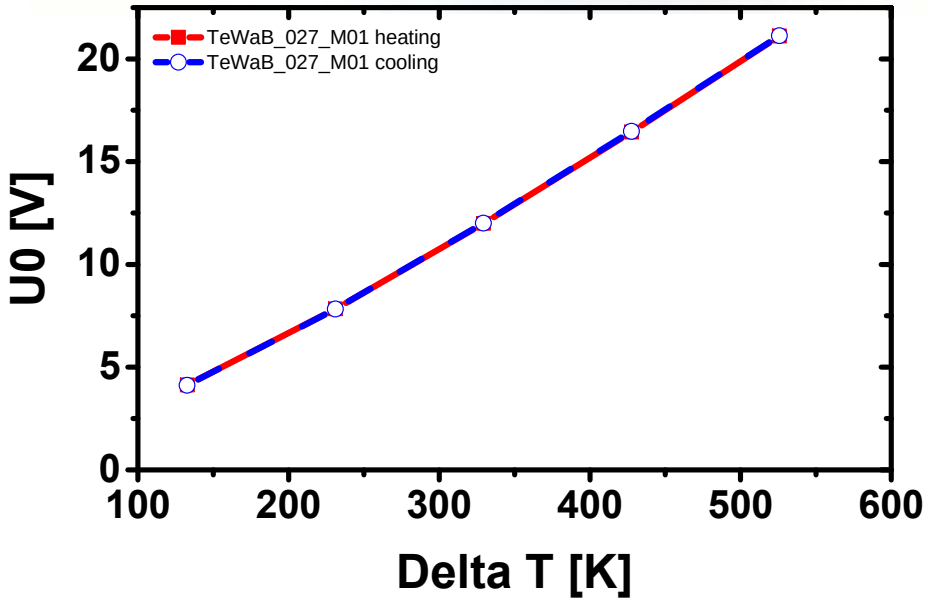
badenova
Energie. Tag für Tag

2 x 2 Module Array

- Interconnection of 4 modules = 32 mm x 32 mm
- 156 unicouples => High voltage
- 1.46 W/cm^2 @ ΔT = 530 K, T_{hot}= 550°C
- 5.4% @ ΔT = 530 K, T_{hot}= 550°C







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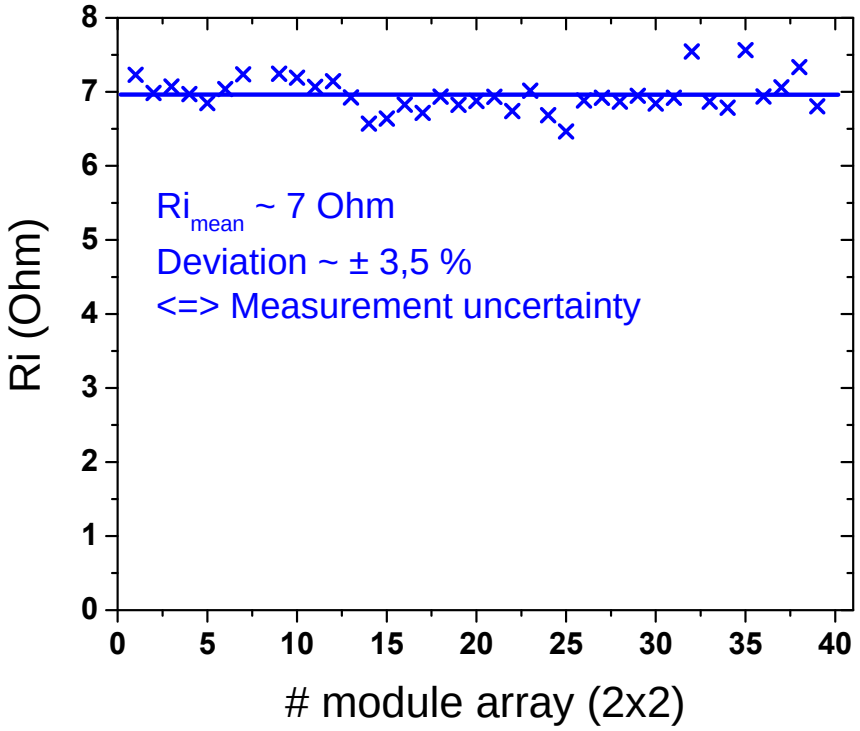
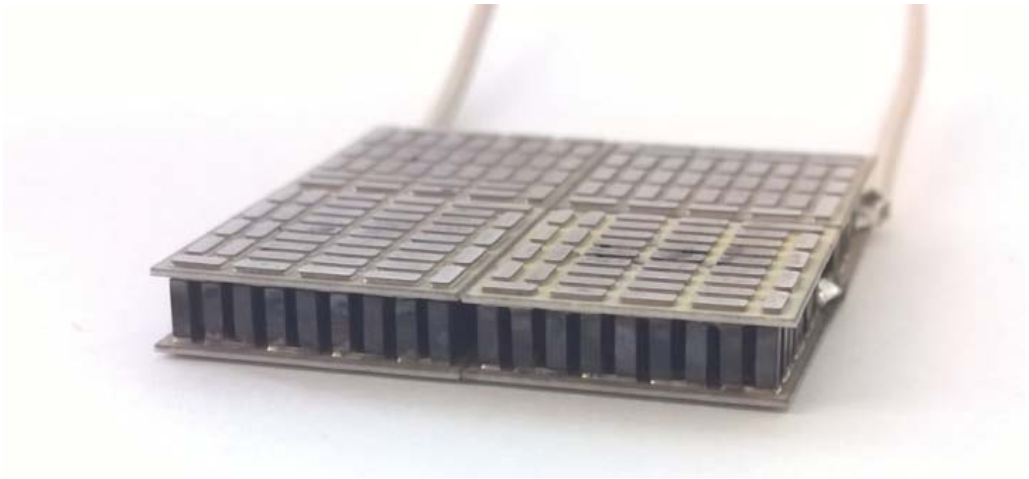
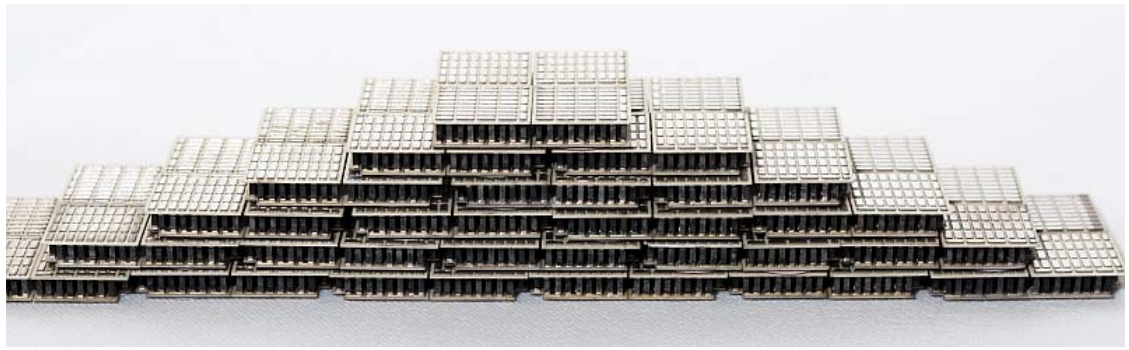






High Temperature Module Manufacturing

Half-Heusler Module Arrays

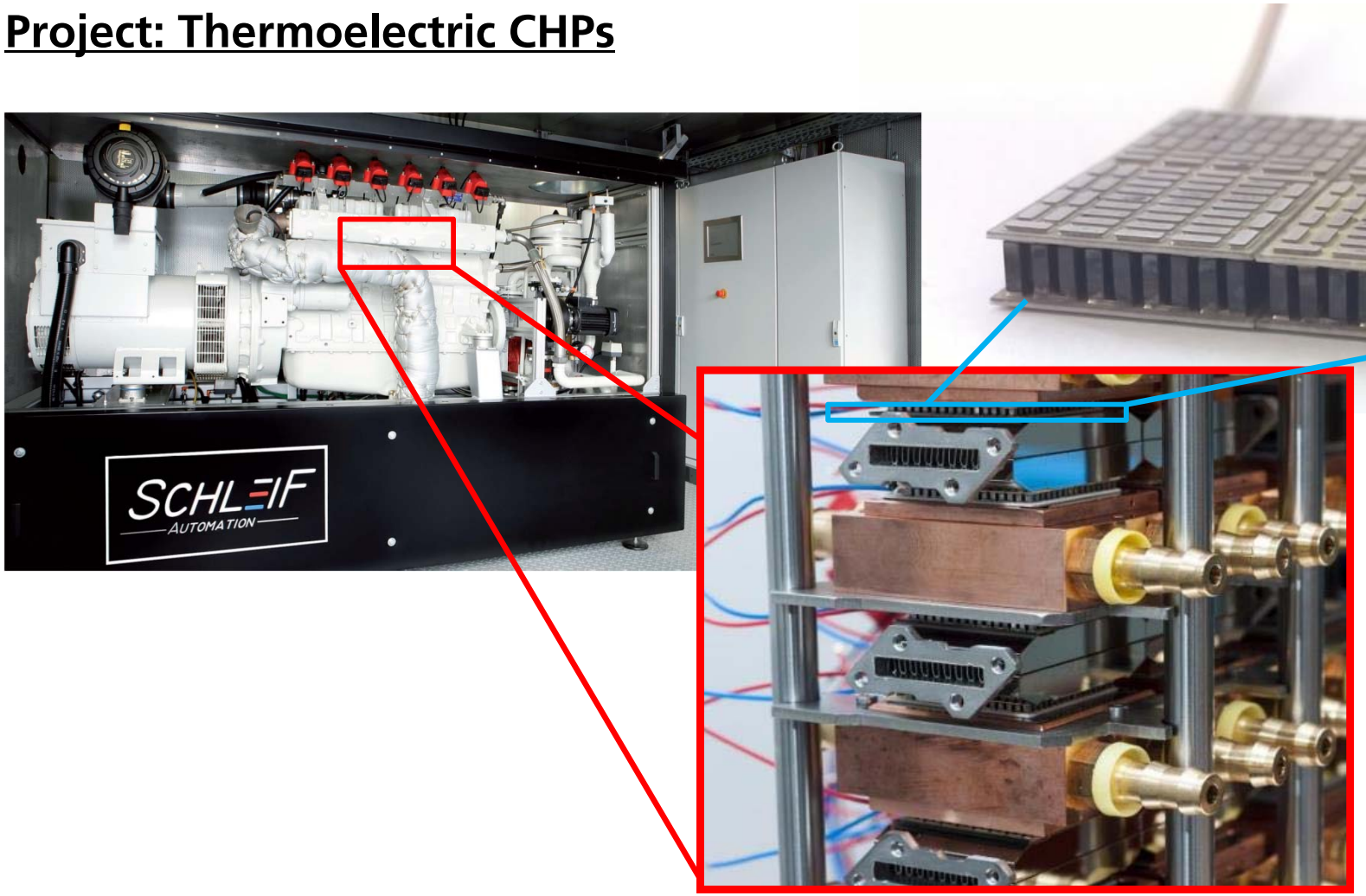
Baden-Württemberg

EFRE Investition in Ihre Zukunft.

EUROPÄISCHE UNION

badenova Energie. Tag für Tag

Project: Thermoelectric CHPs

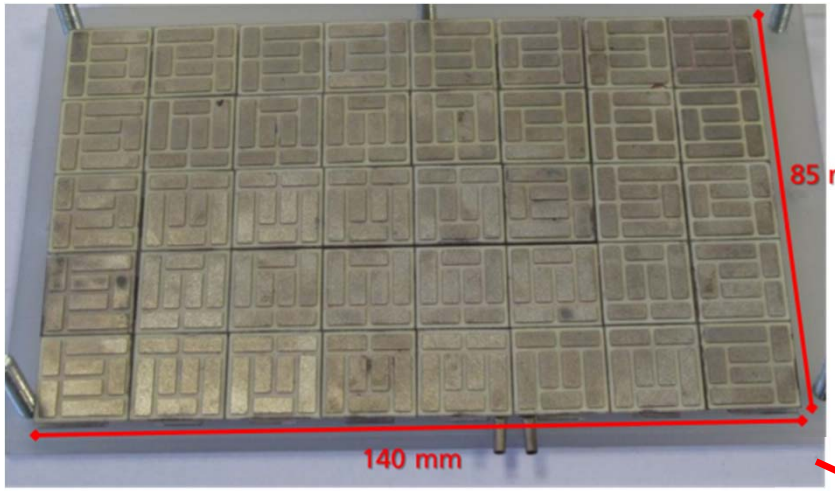


High Temperature Module Manufacturing
Half-Heusler Module Arrays

Bundesministerium für Wirtschaft und Energie

TÜVRheinland® Genau. Richtig.

Interconnection of 40 single modules



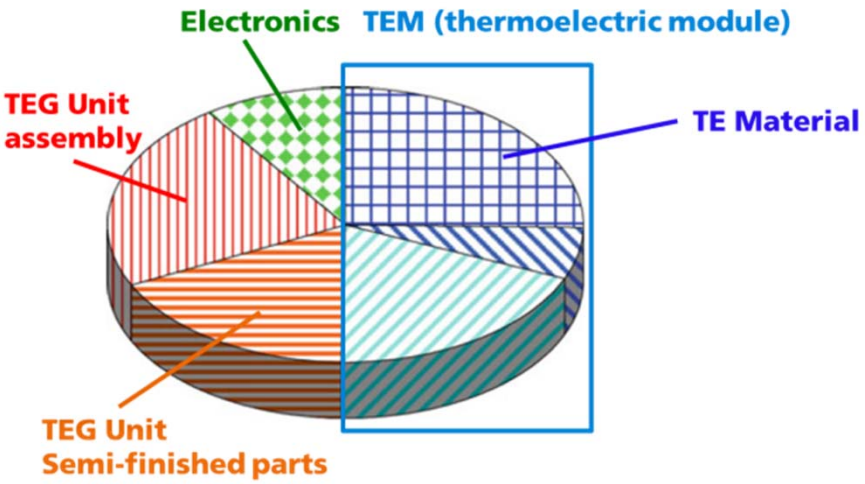
Thermoelectric waste heat recovery on the way to mass production and into applications

Content

- On the way to applications
- Module Fabrication
- New Half-Heusler Modules and Arrays
- **Cost Considerations**
- Summary

Cost Considerations

Thermoelectric system (TEG) cost allocation



ment. Nevertheless it is assumed that currently pending issues can be solved, thus most effective production steps for the shaping of the legs, making the electrical contacts, as well as the assembly and testing of the modules and safe thermal contacting at low compression levels can be realized. The result of the cost assessment for these assumptions indicates that system target costs for mass production of 1 €/W to 2 €/W are still realistic. The related cost

K. Salzgeber (AVL), et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

Cost breakdown:

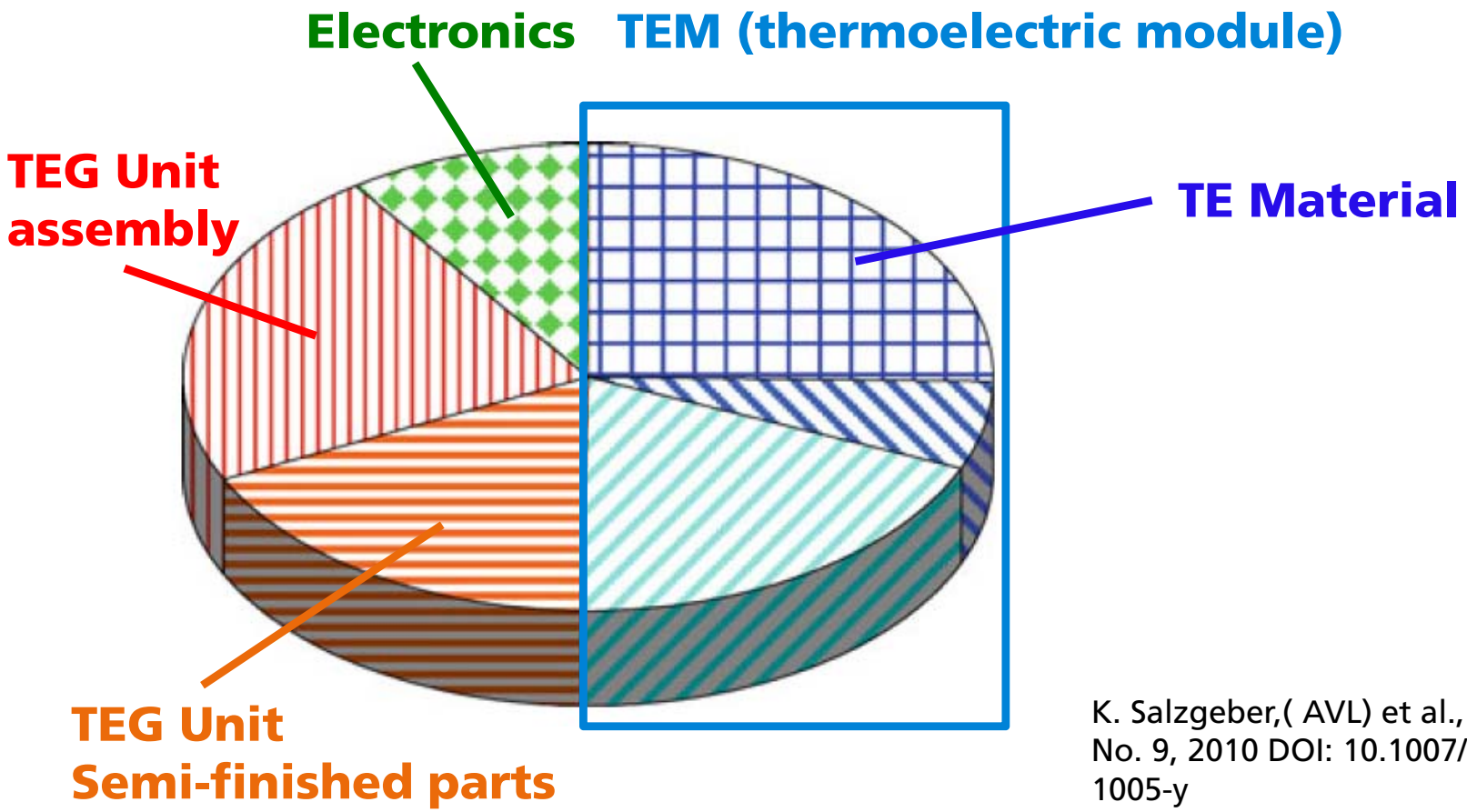
- In car price: 110 € (CM to End user)
- TEG cost: 80€ (Valeo to CM)
- Mean output P(W): 80 W (NEDC)

→ **Cost target 1€ / W**

Dr. Cédric de Vaulx et al. TRA2014, Paris 14-17 April 2014

Cost Considerations

Thermoelectric system (TEG) cost allocation



K. Salzgeber,(AVL) et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

Cost split for a TEG Unit designed for gasoline engines for Hybrid electrical vehicles (Cost assessment for mass production)

High temperature modules
made by Fraunhofer IPM

Material class	Material availability	Power density (module)		Module efficiency	Pros / Cons
		[W/cm²]	[W/g]		
Lead telluride	>kg	0.5	?	?	+ high ZT - contains Pb + Te
Silicides	kg	0.6	0.6	5.0 %	**+ low density** **+ good n-type** **- capsulation needed** **- poor p-type**
Skut-terudites	>kg	0.74	0.5	**8 %**	**+ high ZT** **+ high reproducibility** **- capsulation needed** **- mechanical stability**
Half-Heuslers	>kg	**1.1**	**1.0**	5.4 %	**+ stable** **+ high reproducibility** **- Contain Hf**

Cost Considerations

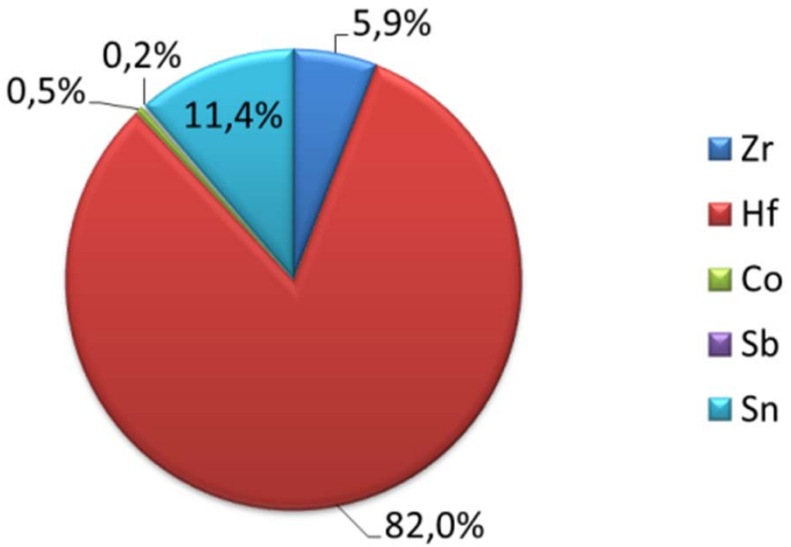
Hf-based Half-Heusler Modules

Bundesministerium für Wirtschaft und Energie

TÜVRheinland® Genau. Richtig.

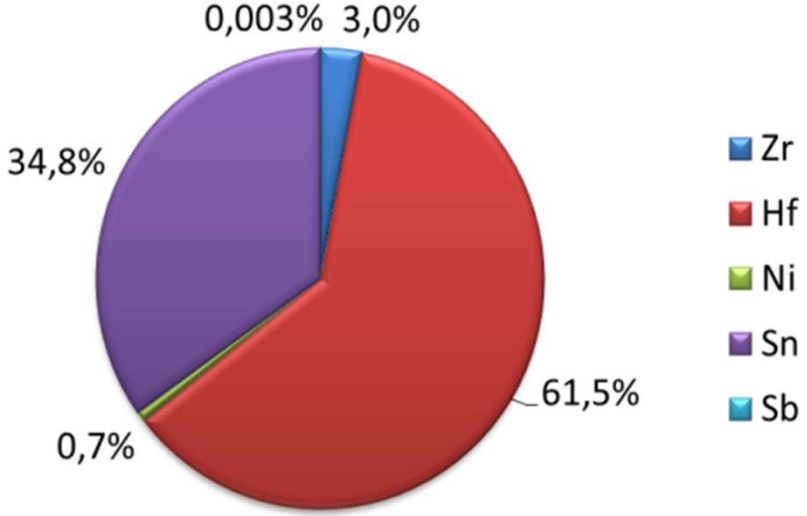
Raw material costs (2016)

p-type $Zr_{0,5}Hf_{0,5}CoSb_{0,8}Sn_{0,2}$



226 € /kg

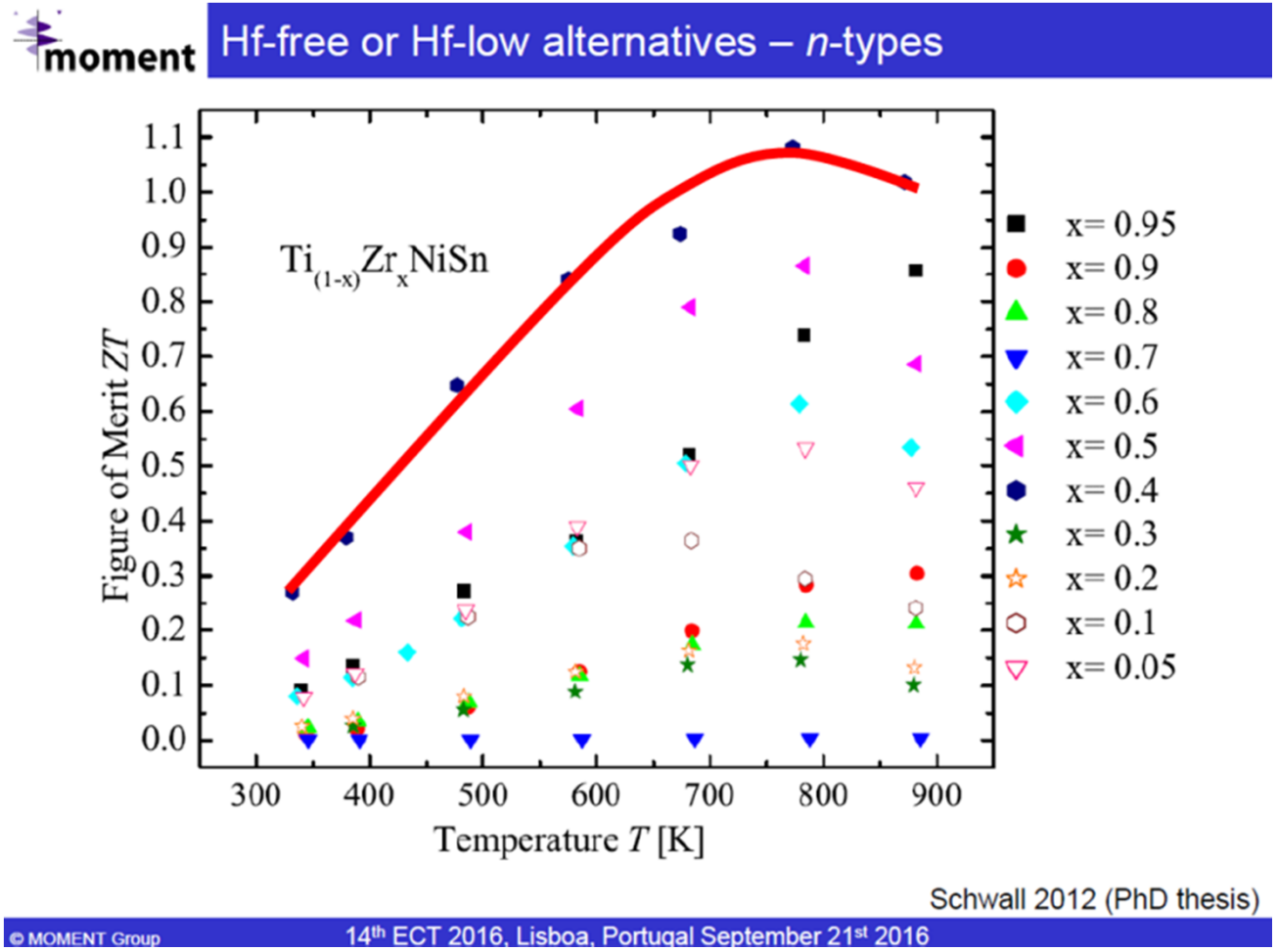
n-type $Zr_{0,4}Hf_{0,6}NiSn_{0,98}Sb_{0,02}$



262 € /kg

=> Hf- free Half-Heuslers

Cost Considerations
Hf-**free** Half-Heusler Modules



Benjamin Balke, ECT 2016, 21.09.2016

Cost Considerations
Hf-**free** Half-Heusler Modules

Material	cost [€] / kg material	Hf-% on material price	ZT @ 600°C 700°C
$Ti_{0.6}Zr_{0.4}NiSn$ (p)	13.7	0	1.02
$Ti_{0.5}Zr_{0.5}NiSn_{0.98}Sb_{0.2}$ (p)	14.0	0	1.19
$Ti_{0.2}Nb_{0.8}FeSb$ (n)	30	0	0.95
$Zr_{0.14}Nb_{0.86}FeSb$ (n)	31.5	0	0.85

Cost reduction of Half-Heusler raw materials by **>90% !!!**

Benjamin Balke, ECT 2016, 21.09.2016

High temperature modules
made by Fraunhofer IPM

Material class	Material availability	Power density (module)		Module efficiency	Pros / Cons
		[W/cm²]	[W/g]		
Lead telluride	>kg	0.5	?	?	+ high ZT - contains Pb + Te
Silicides	kg	0.6	0.6	5.0 %	**+ low density + good n-type - capsulation needed - poor p-type**
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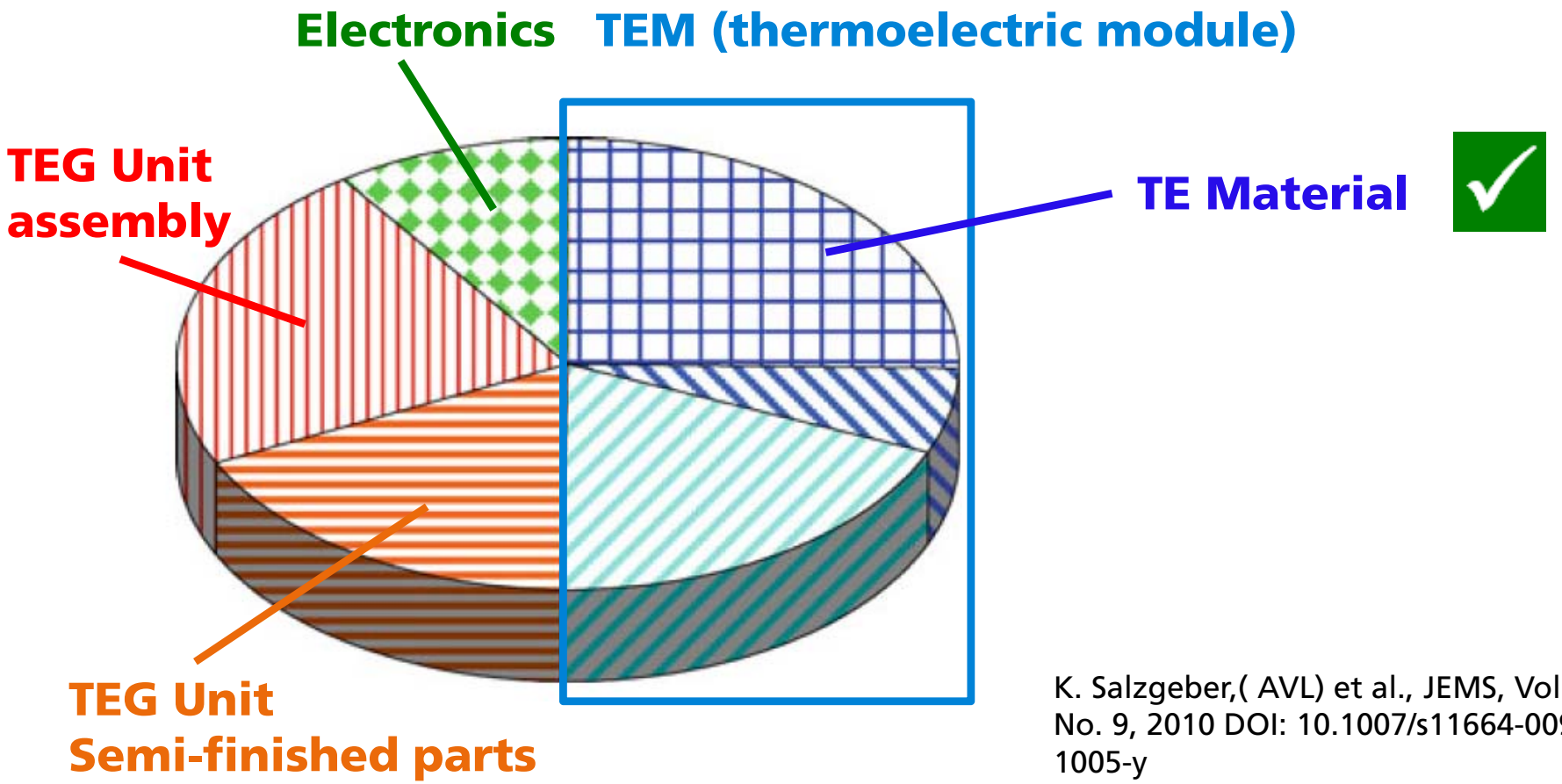
Cost Consideration

Based on commercially available Bi_2Te_3 modules

Module	**commercial Bi_2Te_3**	**Half-Heusler**
Raw material costs (2016):	~ 44 $/kg	22 - 50 $/kg (Hf-free)
Synthesized material costs	~ 300 $/kg	<=> 300 $/kg possible !?
	3-5 kg batch synthesis by THM in mass production	***> 8 kg batch synthesis realized >> 8 kg possible***

Cost Considerations

Thermoelectric system (TEG) cost allocation



K. Salzgeber,(AVL) et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

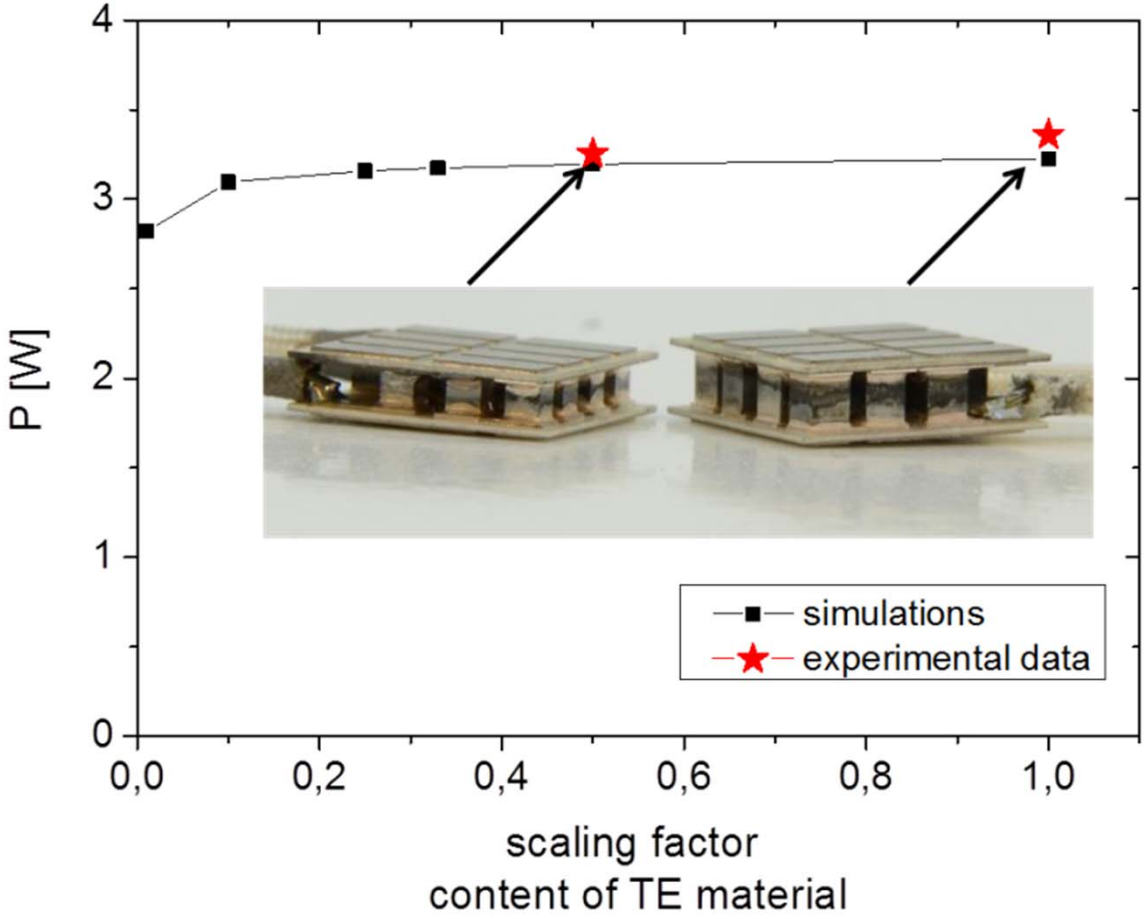
Cost split for a TEG Unit designed for gasoline engines for Hybrid electrical vehicles (Cost assessment for mass production)

Cost reduction
Thermoelectric Downsizing

50 % material reduction
without changing the module properties like
- thermal resistance
- electrical resistance

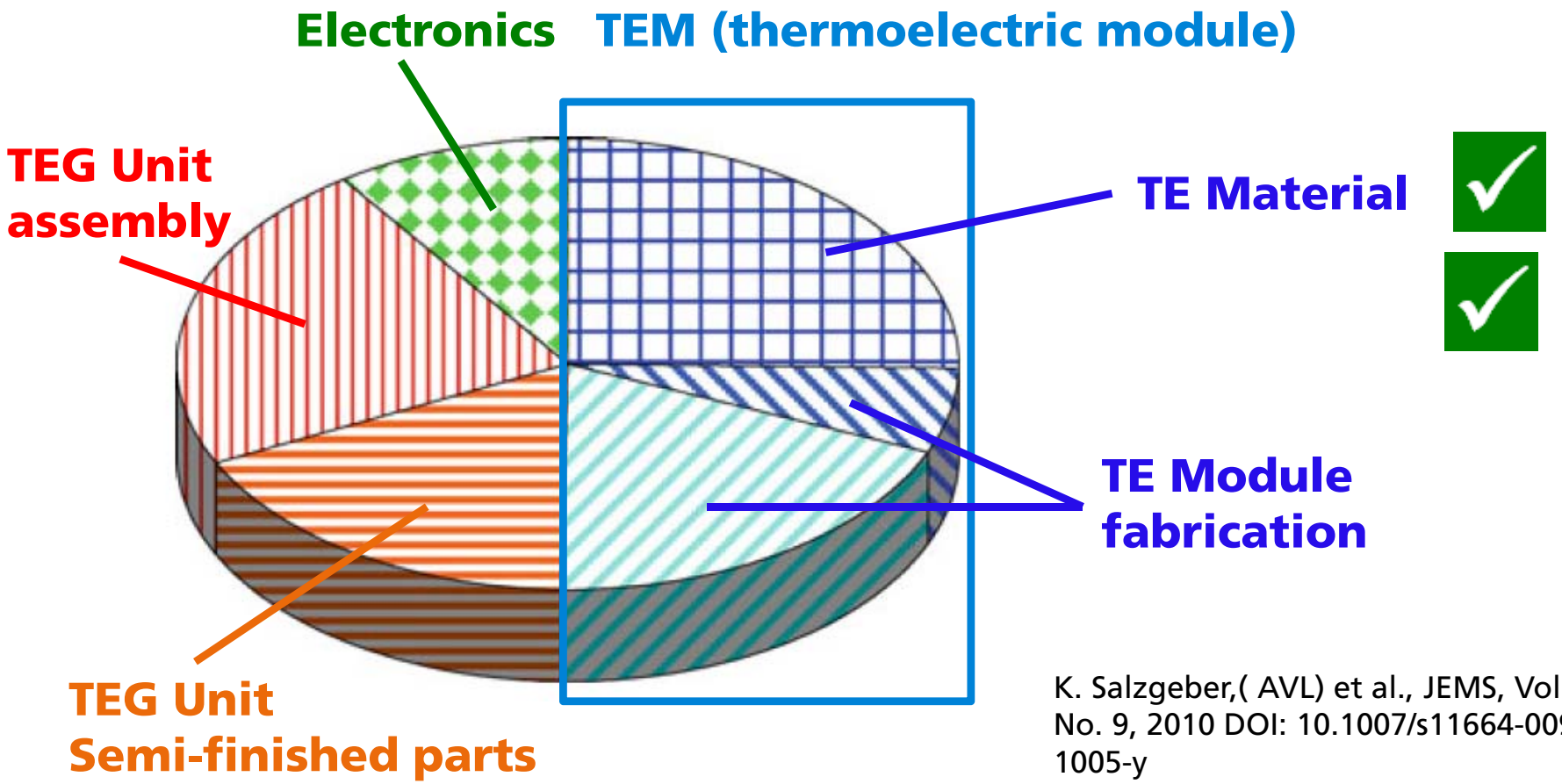
Possible due to the very good mechanical properties of Half-Heusler materials

(Bi_2Te_3 is very brittle -> not possible)



Cost Considerations

Thermoelectric system (TEG) cost allocation



K. Salzgeber,(AVL) et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

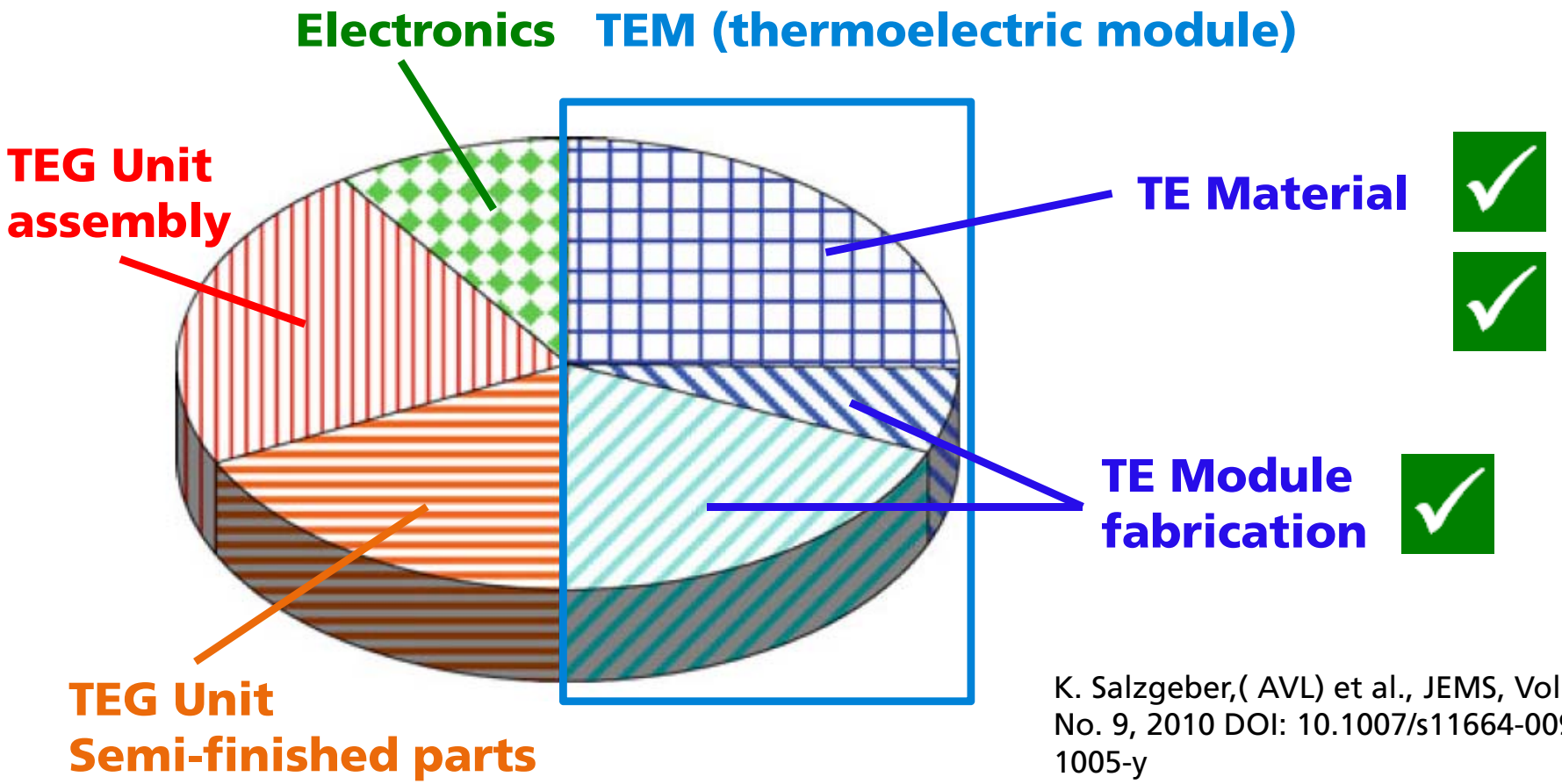
Cost split for a TEG Unit designed for gasoline engines for Hybrid electrical vehicles (Cost assessment for mass production)

Cost reduction due to mass production

fully automated production process is possible

Cost Considerations

Thermoelectric system (TEG) cost allocation



K. Salzgeber,(AVL) et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

Cost split for a TEG Unit designed for gasoline engines for Hybrid electrical vehicles (Cost assessment for mass production)

Cost Consideration

Based on commercially available Bi_2Te_3 modules

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mass production of thermoelectric modules (TEM) possible:

> 100.000 TEM (40x40 mm^2) 1 - 4 $/TEM

Cost Consideration

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	3-5 kg batch synthesis by THM in mass production		*> 8 kg batch synthesis realized >> 8 kg possible*

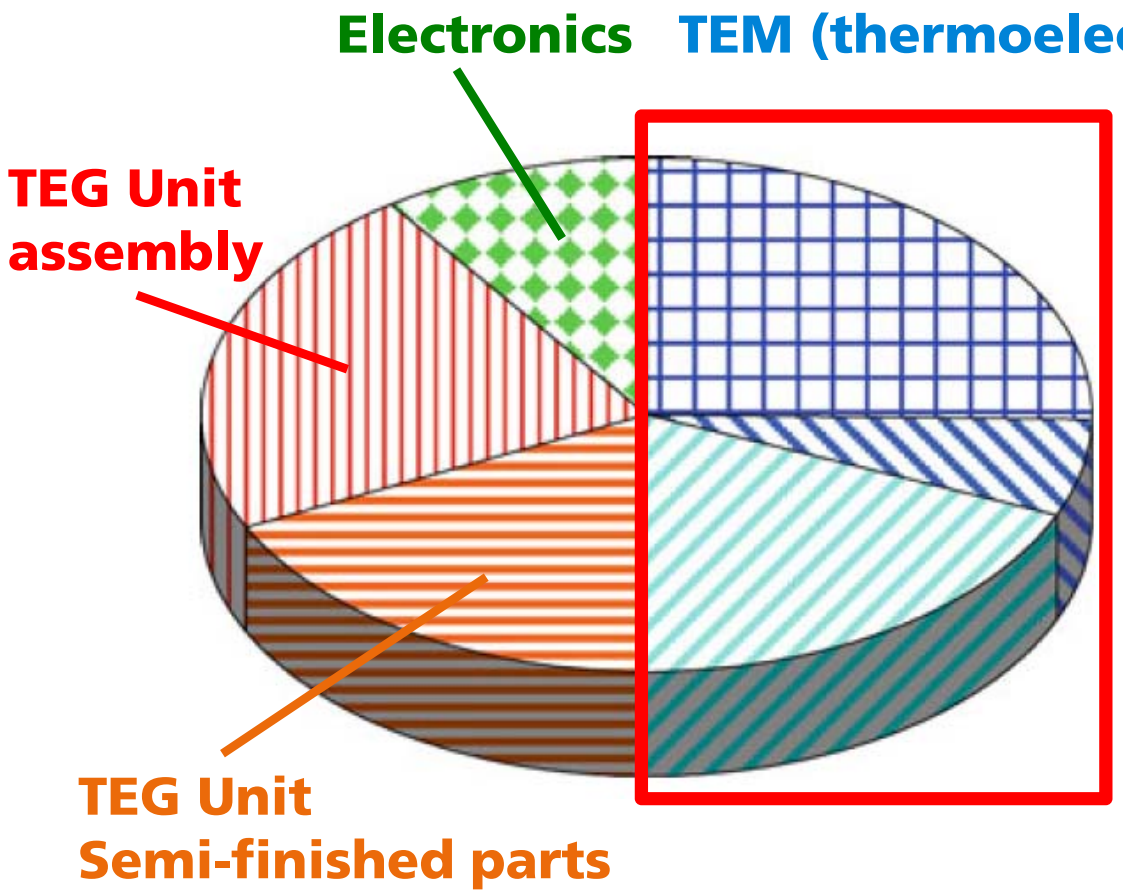
mass production of thermoelectric modules (TEM) possible:

> 100.000 TEM (40x40 mm^2)	1 - 4 $/TEM	⇔	**5 $/TEM** realistic*
$P_{out, peak}$ / TEM (40x40mm^2)	4 - 9 W		**18 - 22 W shown**
	=> **~1 - 0.5 $/W**		**~0.25 $/W ***

**assumption: TEM fabrication process for Half Heusler similar to Bi_2Te_3 TEM fabrication*

Cost Considerations

Thermoelectric system (TEG) cost allocation



~ 0.25 $/W

K. Salzgeber,(AVL) et al., JEMS, Vol. 39, No. 9, 2010 DOI: 10.1007/s11664-009-1005-y

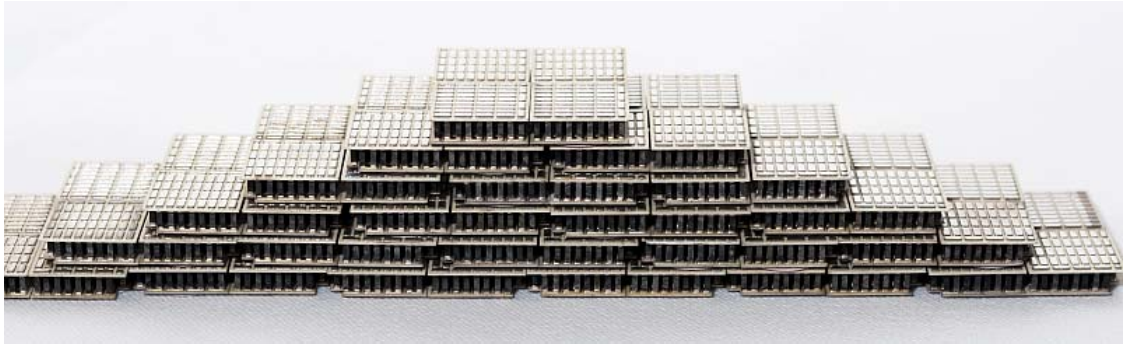
Cost split for a TEG Unit designed for gasoline engines for Hybrid electrical vehicles (Cost assessment for mass production)

Thermoelectric waste heat recovery on the way to mass production and into applications

Content

- On the way to applications
- Module Fabrication
- New Half-Heusler Modules and Arrays
- Cost Considerations
- **Summary**

Summary



Achievements:

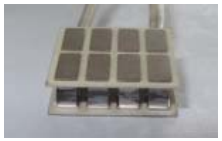
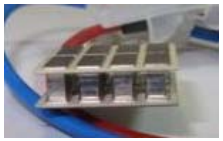
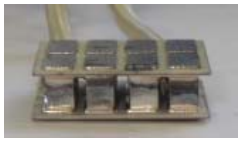
- **Custom designed Half-Heusler modules** with high power densities made of kg-batch material
- **Fabrication of Half-Heusler modules with high reproducibility** and reliability is possible
- **Semi-automated fabrication** of Half-Heusler modules **demonstrated**
- **Mass production** of Half-Heusler modules is **possible**

- Cheap Half-Heusler modules possible in mass production !!!

- Fraunhofer IPM provide **Half-Heusler-modules for prototype systems**

High Temperature Module Manufacturing

Customized TE-Module designs

TEM Properties		Unit	IPM-Type 1	IPM-Type 2	IPM-Type 3	IPM-Type 4	IPM-Type 5
TE module dimensions	base area	[mm²]	16±0.5 × 16±0.5	16±0.5 × 16±0.5	16±0.5 × 16±0.5	16±0.5 × 16±0.5	16±0.5 × 16±0.5
	height	[mm]	5.0±0.15	5.0±0.15	4.0±0.15	3.5±0.15	5.0±0.15
weight (without wires)		[g]	~4	~3	~3	~2	~4
number of thermo-couples		[#]	7	7	7	7	39
wire with thermal isolation ~80 mm long			500 mm long; blue: minus, red: plus				
Internal resistance at room temperature (without wires)		[Ohm]	0.04±0.01	0.06±0.01	0.03±0.01	0.05±0.01	1.4±0.1
Following module properties were achieved under the conditions ΔT ~530 K; T_{hot} ~550 °C; T_{cold} ~20 °C; p_{con} = 2 MPa, atmosphere: nitrogen							
thermal resistance (K_{th})*		[K/W]	~9	~7	~7	~9	~8
open circuit voltage (U_0)		[V]	1.0±0.1	1.0±0.1	0.9±0.1	1.0±0.1	5.3±0.5
internal resistance (R_i)		[Ohm]	0.07±0.01	0.10±0.01	0.05±0.01	0.08±0.01	2.0±0.1
power (P_{max})		[W]	3.1±0.3	2.4±0.2	3.5±0.3	3.0±0.3	3.5±0.3
efficiency (η)*		[%]	~5.3	~3.2	~4.6	~5.1	~5.3
* calculated data							

Acknowledgment

RexTEG

thermoHEUSLER
thermoHEUSLER²

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"Innovationsfonds Klima- und Wasserschutz" by badenova AG & Co.KG

Thanks!

Gefördert durch:

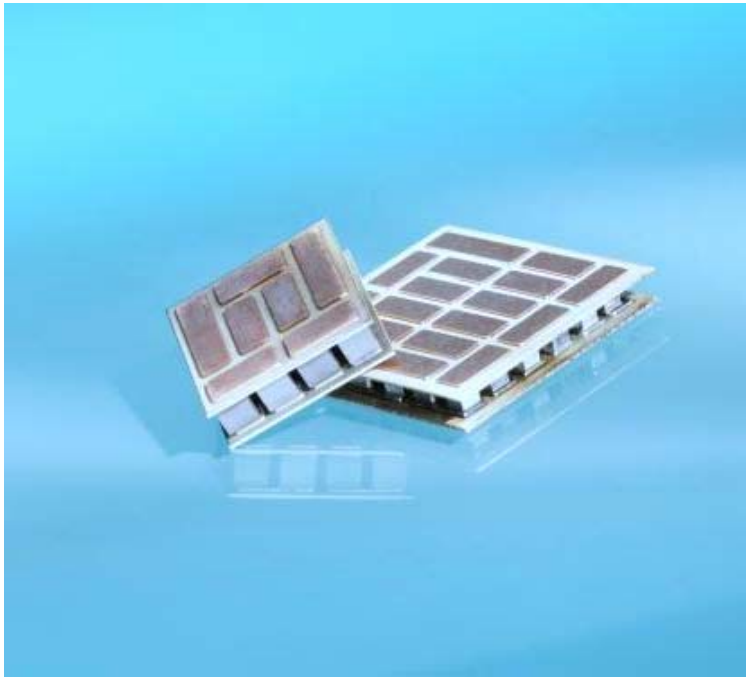
Bundesministerium für Wirtschaft und Energie

Federal Ministry of Education and Research

Projektträger Jülich Forschungszentrum Jülich

SEVENTH FRAMEWORK PROGRAMME

Good ideas for better solutions



Thank you for your attention!

➡ Contact

Jan.koenig@ipm.fraunhofer.de

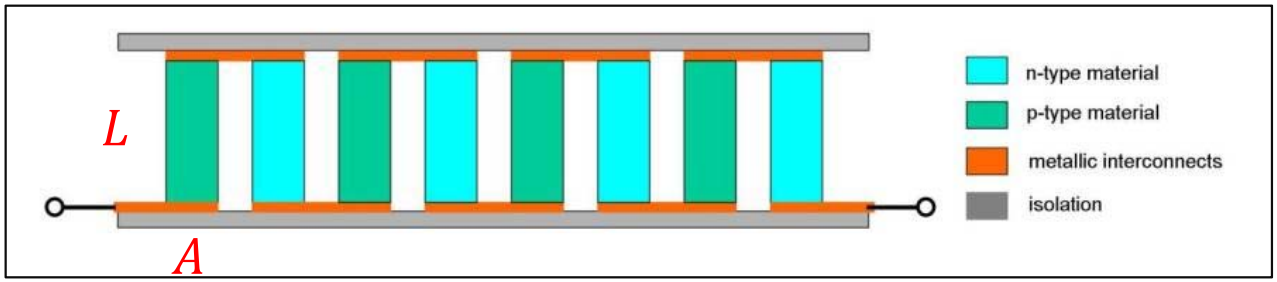
➡ Visit us on the Internet at
www.ipm.fraunhofer.de/en

Cost reduction

Optimization of module geometry

Idea: ***"thermoelectric downsizing"***

Reduce amount of TE material while keeping thermal and electrical properties of TE module



- electrical resistance of TE module:

$$R^{el} = nR_{TE}^{el} + \mathcal{O}(R^{contact}) \approx n\rho\frac{k\,L}{k\,A}$$

- thermal resistance of TE module:

$$R^{th} = \frac{1}{n}R_{TE}^{th} + \mathcal{O}\left(\frac{R_{TE}^{th}}{R^{bp}}\right) \approx \frac{1}{n\lambda}\frac{k\,L}{k\,A}$$

Identical scaling k of L and A leaves thermal and electrical properties of module unaltered!

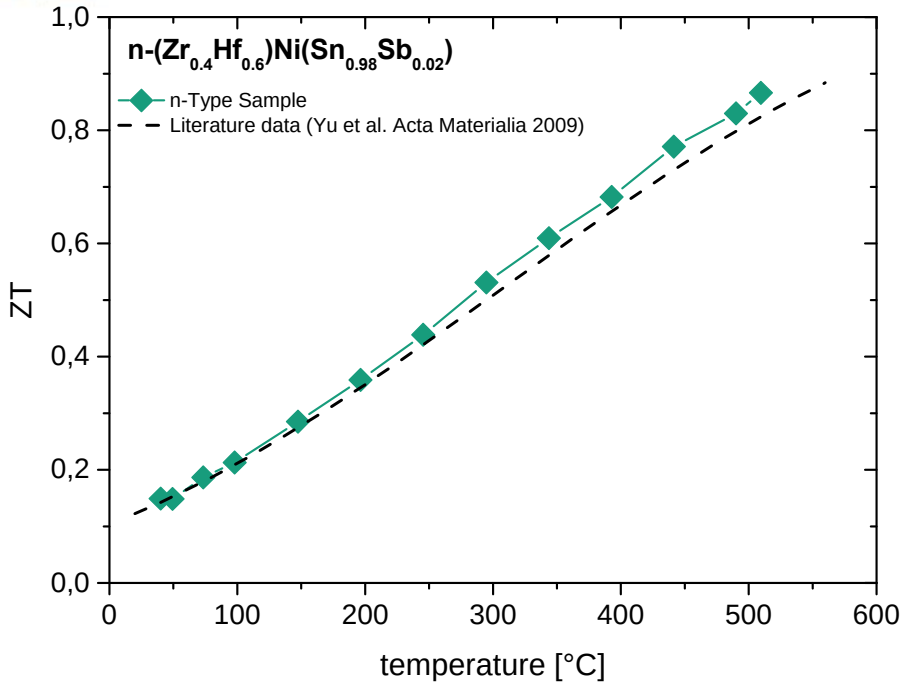
High Temperature Module Manufacturing

The Half-Heusler Alloys (>kg production)

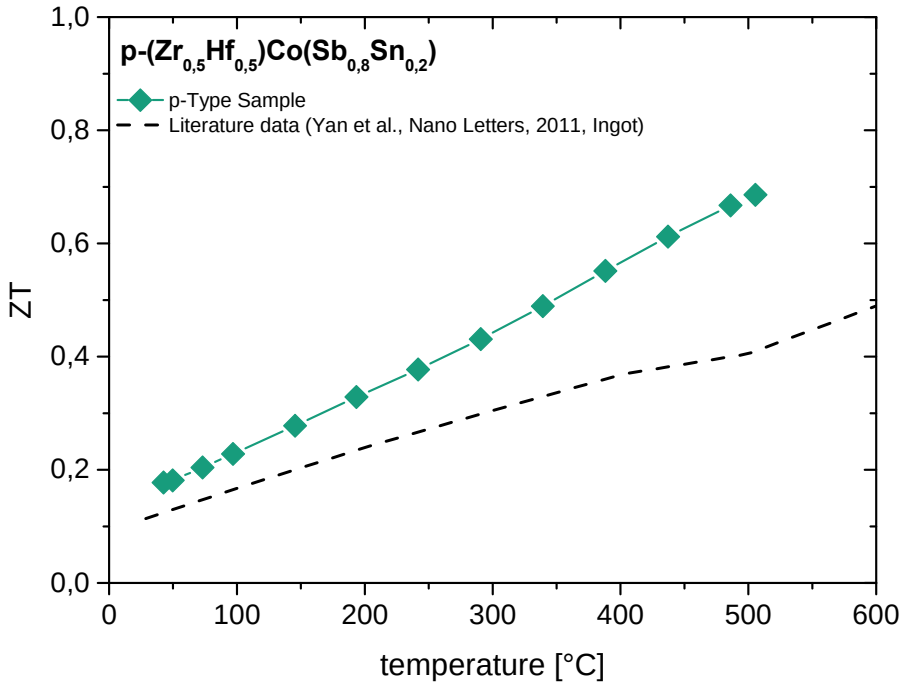
ISABELLENHÜTTE
Innovation by Tradition

VAC
VACUUMSCHMELZE

n-type



p-type



- Data in very good agreement with literature*,**
- Good reproducibility of material properties in >kg production (typically ~10% deviation from batch to batch)

*C. Yu, T.-J. Zhu, R.-Z. Shi, Y. Zhang, X.-B. Zhao and J. He, Acta Materialia **57** (9), 2757-2764 (2009).
**X. Yan, G. Joshi, W. Liu, Y. Lan, H. Wang, S. Lee, J.W. Simonson, S.J. Poon, T.M. Tritt, G. Chen, Z.F. Ren, Nano Letters, 11 (2011) 556.

Thermoelectricity

Performance of commercial Bi_2Te_3 module

Performance data of a commercial TEG (4x4 cm²) up to hot side temperatures of 250°C