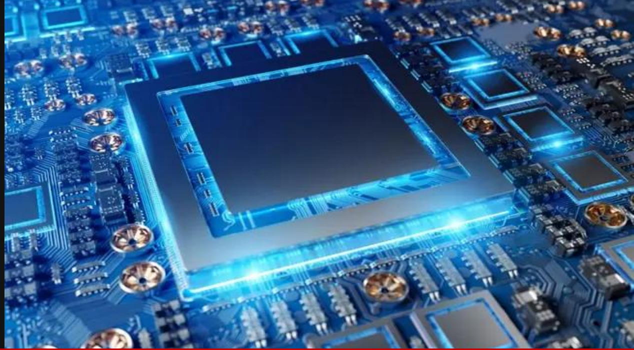
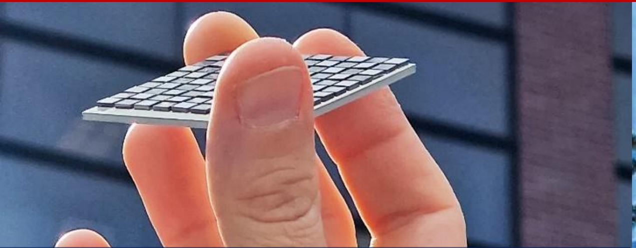


# Thermoelectric technologies for power generation, cooling and sensor applications





## Krzysztof T. Wojciechowski

Thermoelectric Research Laboratory
Faculty of Materials Science and Ceramics
AGH University of Krakow
wojciech@agh.edu.pl
http://www.thermlab.agh.edu.pl/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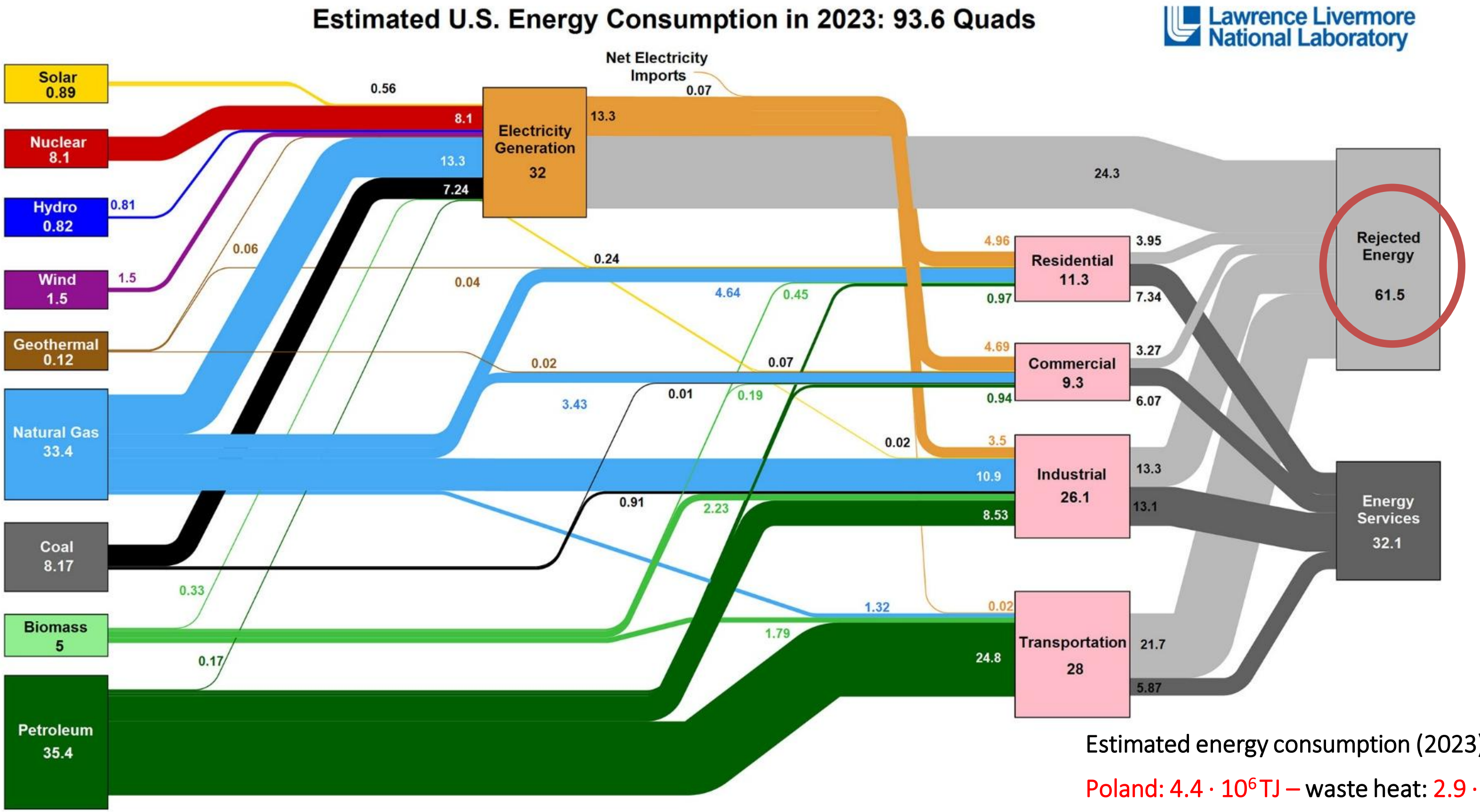
# Global problem: waste heat and greenhouse gasses emissions

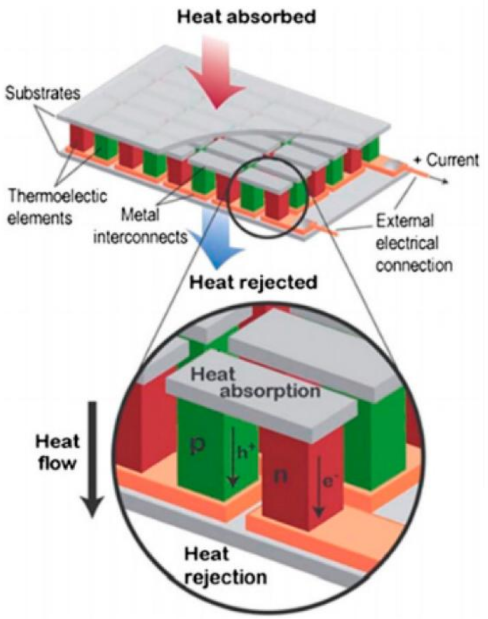



**Waste heat and related $CO_2$ emissions**

Estimated energy consumption (2023): USA: $99 \cdot 10^6$ TJ

Poland: $4.4 \cdot 10^6$ TJ – waste heat: $2.9 \cdot 10^6$ TJ

# Solution: thermoelectric technologies for cooling and power generation




**Modern thermoelectric converter**

**Advantages:**

- semiconductor technologies,
- low weight
- no mechanical moving parts,
- simple design,
- high reliability,
- no need for maintenance

**Applications in the space and military technologies for power generation and IR sensors, such as:**

- **Mars rovers:** *Curiosity* (2012) and *Perseverance* (2020)
- **Space probes:** *Voyager 1* and *Voyager 2* (1977)
- **many other space and terrestrial applications**

# Goal of the project

The Thermoelectric Research Laboratory (TRL) at AGH stands at the forefront of thermoelectric innovation in Poland, combining pioneering research with advanced technological development. The team has not only introduced novel semiconducting materials but also engineered breakthrough devices for direct heat-to-electricity conversion and thermoelectric cooling. Our solutions demonstrate a high level of technological maturity, with an estimated average **Technology Readiness Level (TRL) of 6+**, underscoring their readiness for real-world applications.

**The primary objective of this project is to transition these cutting-edge thermoelectric technologies into large-scale industrial production, driving advancements in renewable energy solutions.**

**Pioniering thermoelectric technologies developed at TRL, AGH:**

1. **Low-cost semiconductor TE materials with high efficiency ($\eta_{max}$ = 17 %)**
2. **Thermoelectric converters with exceptional power density (> 3.2 kW/m$^2$)**
3. **Miniature TE batteries for dual-use applications**
4. **Thermoelectric generators for waste heat recovery**
5. **Thermoelectric microscope for precise hydrogen content analysis**

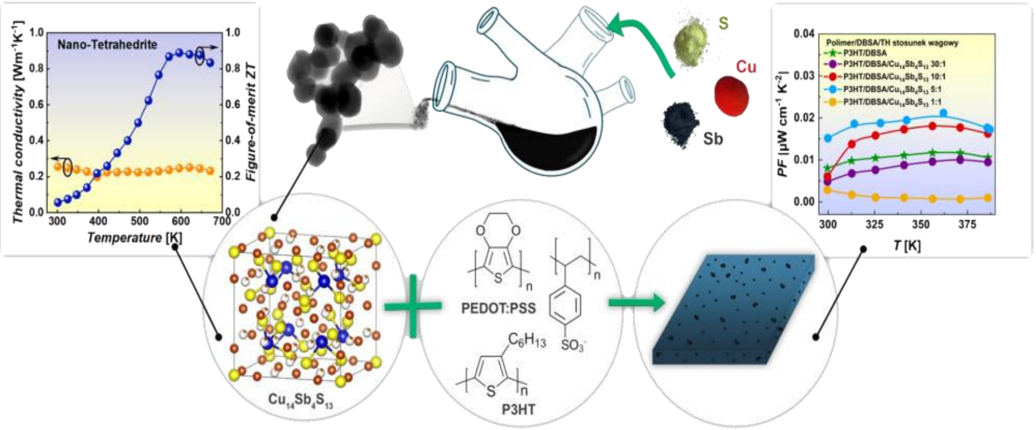
# 1. Low-cost semiconductor TE materials with high efficiency ($\eta_{max}$ up to 17 %)

The team's work focuses on developing advanced thermoelectric materials that offer significant competitive advantages in the thermoelectric technology market. Our materials are designed to meet key criteria essential for practical applications, including: **high efficiency, cost-effectiveness, durability and environmental sustainability.**

By integrating these attributes, our innovative thermoelectric materials enhance **the performance and market competitiveness** of our thermoelectric converters and devices, setting **new industry standards**.

In particular, we have pioneered novel material types:

- **Composite** materials(AES-MPS)
- **Graded** materials (DT-FGTM)
- **Flexible** polymer-inorganic thermoelectric materials **for biosensors and microgenerators**

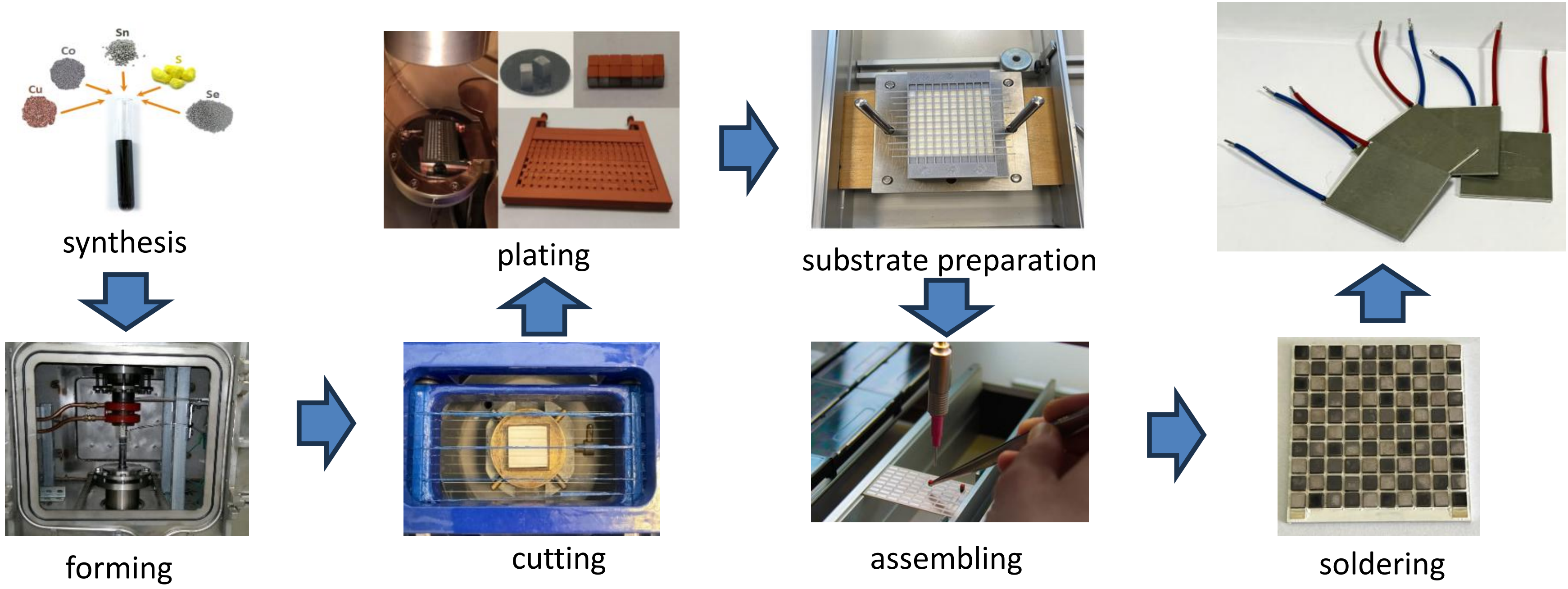



**Related patent applications:**

1. K. Wojciechowski, T. Parashchuk, O. Cherniushok, *Gamma-argyrodite structure material for thermoelectric conversion and the method of obtaining the same,* EP4292982A1 (2023)
2. O. Cherniushok, T. Parashchuk, K. Wojciechowski, EP24219360 (P.450136), *Cu, Te, and S-based material for thermoelectric conversion and method of preparation thereof* (2024)
3. *K. Wojciechowski, A. Kosonowski, A. Słyś, Method of obtaining Cu-Sb-S group compounds with a tetrahedral structure, patent* PL 243015 B1, (2023)

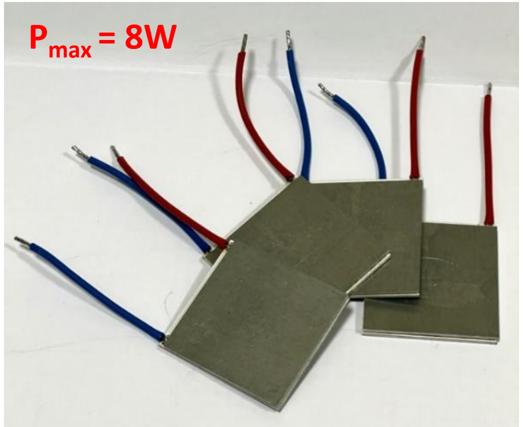
# 2. Thermoelectric converters developed @ TRL AGH

The **TRL team**, in collaboration with partners under the **TECHMATSTRATEG2/408569/5/NCBR/2019** project, has developed a **new technology for manufacturing unique, low-cost thermoelectric converters** with a target price of **<1 USD/W**. Our first TE modules are designed for **low-grade heat conversion** (up to **200°C**) and achieve a **very high power density** exceeding **3.2 kW/m²**. The technology has been **validated at TRL 6+**, including the **assembly of a laboratory-scale thermoelectric converter production line**.

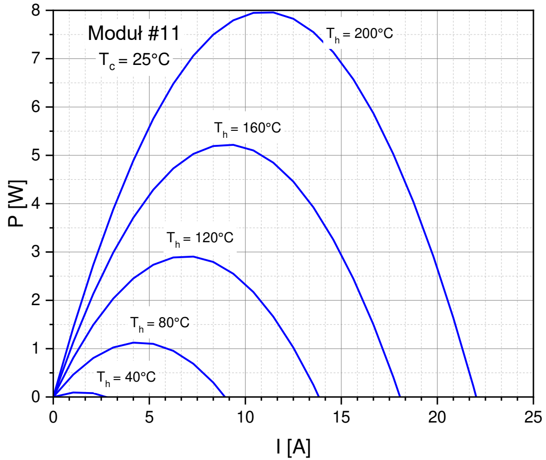


# 2. Thermoelectric converters developed @ TRL AGH

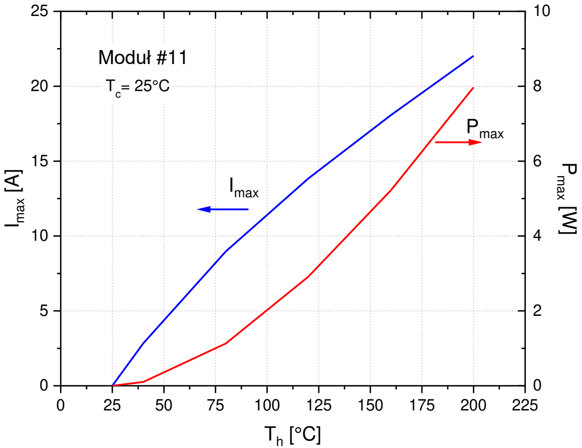
The thermoelectric converters developed at AGH feature unique structural and material solutions that minimize heat losses and enable high power density. **This project aims** to further advance the technology by extending the operational temperature range **to 500°C** and increasing power density above **10 kW/m²** and efficiency **beyond 12%.** These advancements will make the modules a breakthrough in the thermoelectric industry.




Thermoelectric converters, $T_{max}$ = 200 °C




Current-voltage characteristics



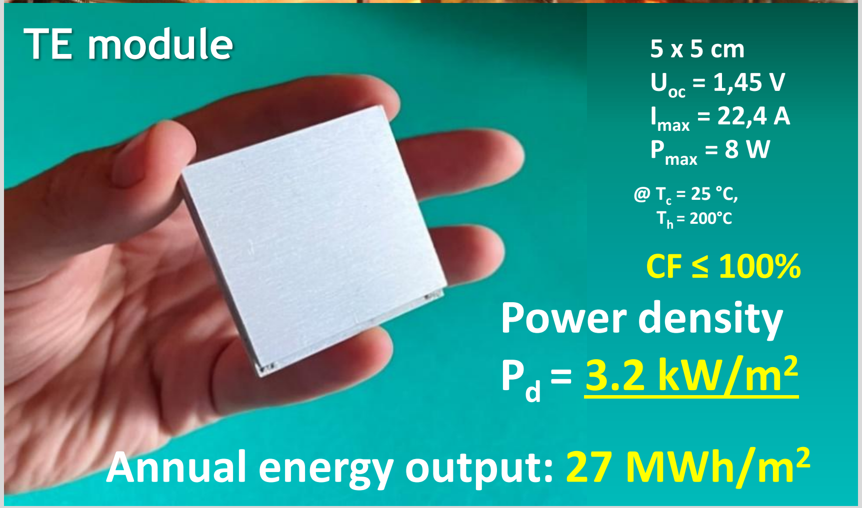

Temperature characteristics

**Related patent applications:**

1. K. Wojciechowski, T. Parashchuk, M. Maksymuk, *Thermoelectric converter based on functionally graded materials,* EP23190983A, (2023)
2. M. Musiał, K. Wojciechowski, *Cascaded thermoelectric converter, utility model* PL73351Y1, (2023)
3. K. Wojciechowski, M. Musiał*, System for generating electricity, especially from waste heat,* PL444457A1, (2023)

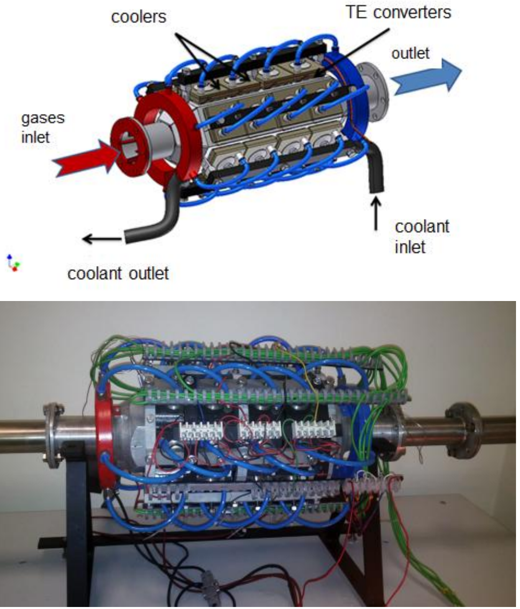
# Thermoelectricity vs. Photovoltaics





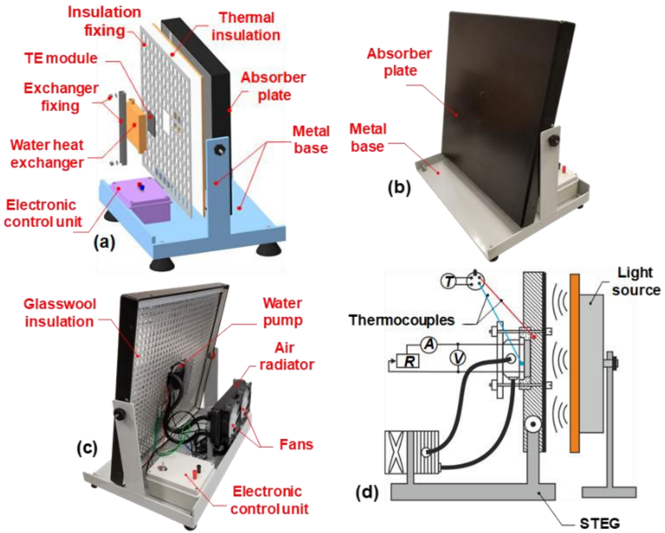

# 3. Prototypical thermoelectric generators

The **TRL team** has developed several **unique designs** of thermoelectric generators and heat pumps for **domestic and industrial applications**. The prototypes demonstrate **potential applications** such as **waste heat recovery from automotive exhaust gases, enhancement of solar energy conversion, energy flow control in chemical reactors, and powering electronics in domestic heaters**. The Technology Readiness Level **(TRL) ≈ 6.**




200 W TEG for waste heat recovery from automotive exhaust gases

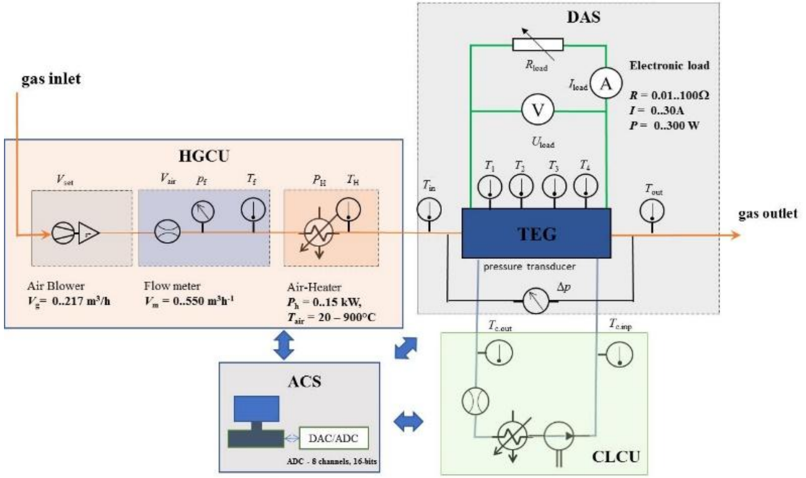
MicroTEG for powering the control system of a domestic heater

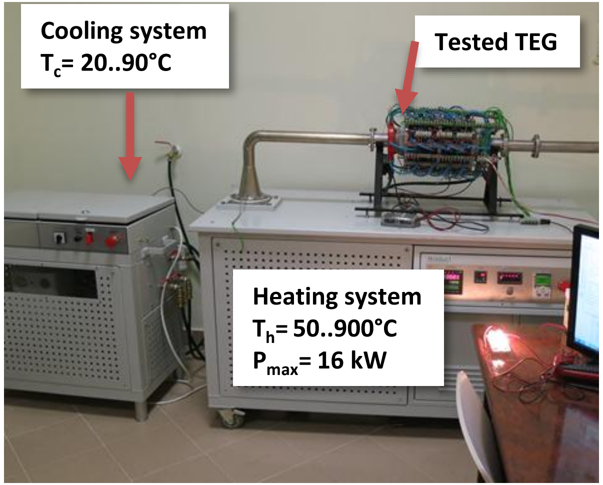



TEG prototype for converting solar energy or from infrared (IR) heat source

# 3. Prototypical thermoelectric generators

The TRL laboratory is equipped with **unique** testing apparatus, developed by our team, for evaluating new types of thermoelectric generators and heat pumps. This **cutting-edge equipment** enables highly detailed research under conditions closely resembling real-world operation, ensuring accurate and reliable performance assessment




Test setup for evaluating various TEG prototypes.

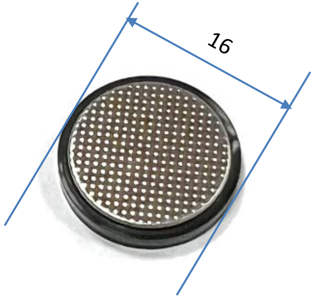
**Related patent applications:**

1. K. Wojciechowski, K. Marszalek, *A hybrid solar energy converter, EU patent* EP2827383B1 (2017)
2. K. Wojciechowski, *Method for control of energy flow in a thermal object, in particular a chemical reactor* PL243914B1 (2020),
3. K. Wojciechowski, Tadeusz Wójcik, Karol Sztekler., *Method for transformation of gas heat energy in electrostatic filter,* PL228901B1, (2017)

# 4. MTEB battery for dual-use applications

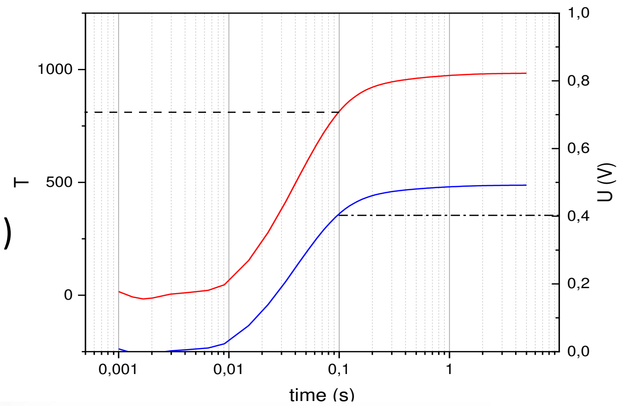
Our team is developing **innovative dual-use microgenerators** for standalone IoT devices (e.g., sensors, control systems) and **battlefield IoT applications**. Utilizing **advanced thermoelectric materials** and an **original internal architecture**, our **miniature thermoelectric batteries (MTeB)** offer **ultrafast response times** and **high overload resistance**. These unique features enable their use in **extreme environments**, such as **rotating machinery, artillery shells, rockets**, etc., where conventional power sources fail.

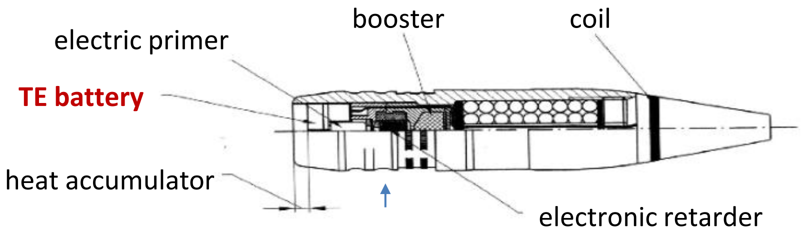
## Multipurpose Thermoelectric Battery (MTeB) developed at AGH

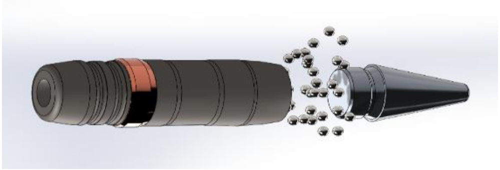



### Advantages

- small size and compact design (CR1632 case)
- rapid response time (< 100ms)
- high durability and resistance to accelerations (>$10^5$G)
- safety of operation and storage (no aging effects)



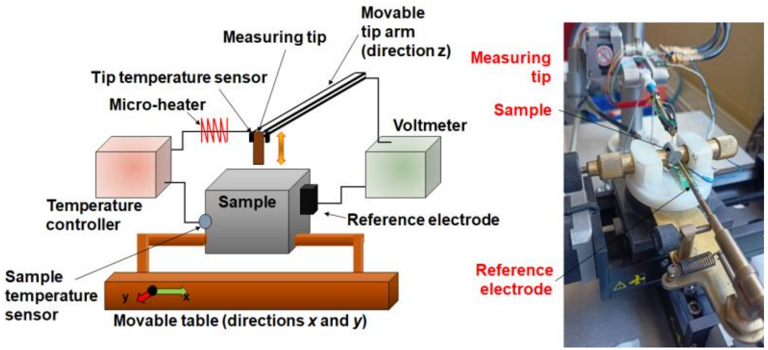



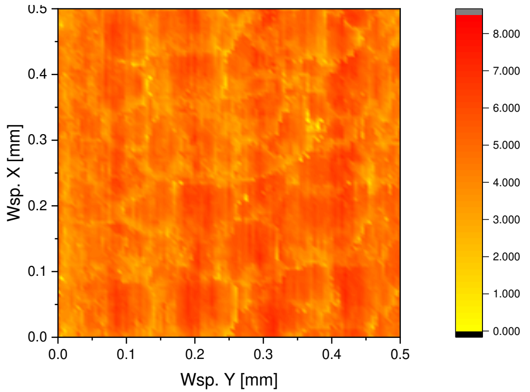
Example of application: 23x151mm APBSL cartridge with TE battery

# 5. Thermoelectric microscope for hydrogen content analysis

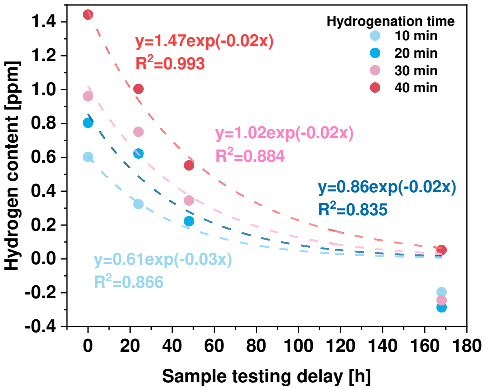
The TRL team has developed a **fast, non-destructive measurement technique** and a **scanning thermoelectric microscope SthM** for analyzing the surface distribution of hydrogen in steel and electrochemical coatings. This innovative method and device are also suitable for assessing hydrogen content in other materials, as well as for **quality control of products on the production line** and monitoring **operational hydrogen transmission and hydrogen storage systems**.




Scanning Thermoelectric Microscope (SThM)




Surface hydrogen distribution map in electrochemical Cr coating




Kinetics of dehydrogenation

## Related patent applications:

1. K. T. Wojciechowski, M. Sajdak *Thermoelectric indenter and measuring system for determining hydrogen content and microhardness*, EP23215081.3, (2024)
2. K. Wojciechowski, *Method for measuring properties of thermoelectric materials and the measuring probe for this method,* PL238822B1 (2021),

# Market Readiness and Scalability

Thermoelectric modules and devices are increasingly **market-ready** due to advancements in materials, manufacturing techniques, and cost reduction. Key factors influencing their scalability and adoption include:

- **Applications**: Thermoelectric technologies are rapidly expanding across sectors such as miniature power sources for IoT devices, electronic cooling systems, infrared sensors, waste heat recovery, cryogenic gas-free heat pumps, and portable cooling devices. Applications range from 10 mW in consumer electronics to **multi-kW** systems for industrial use.
- **Market Size**: The global thermoelectric market is projected to reach **USD 3.6 billion by 2027**, with a **CAGR of 9.4%** from 2020 to 2027.
- **Manufacturing Scale**: Manufacturing capacity for thermoelectric modules is increasing, with production expected to reach **several hundred MW per year** in the next 5 years.
- **Cost Reduction**: The cost of thermoelectric modules for power generation is anticipated to decrease from **3 USD/W** to **< 1 USD/W** within the next decade.

# Alignment to SV and the US in Key Sectors

Thermoelectric technologies align with several United Nations Sustainable Development Goals (**UN SDGs)**, contributing to **energy efficiency**, **sustainability**, and **climate action**:

1. **Affordable and Clean Energy (SDG 7)**: Thermoelectrics enable **waste heat recovery**, improving energy efficiency in sectors like industry, transportation, and power generation.
2. **Industry, Innovation, and Infrastructure (SDG 9)**: These technologies support **clean energy infrastructure**, fostering innovation in energy conversion and cooling systems.
3. **Responsible Consumption and Production (SDG 12)**: Thermoelectrics promote **circular economy** practices, reducing waste and encouraging sustainable energy solutions.
4. **Climate Action (SDG 13)**: By improving energy recovery and reducing reliance on fossil fuels, thermoelectrics help **lower carbon emissions**.
5. **Decent Work and Economic Growth (SDG 8)**: The development of thermoelectrics stimulates **job creation** in clean energy, research, and manufacturing sectors.

These technologies also support U.S. efforts to reduce environmental impact, optimize energy use, and promote a **green economy**, contributing to a **net-zero** future.

# TRL AGH team potential and readiness

TRL AGH UST in Krakow

## International cooperation

- The Thermoelectric Research Laboratory **team** is recognized **worldwide**. Members of our international team have collectively published **over 500 scientific papers and conference presentations**.
- In **2024**, the team organized the joined **40th International Conference on Thermoelectrics** and the **20th European Conference on Thermoelectrics** in **Kraków (ICT2024).**
- The **team leader, Prof. Krzysztof Wojciechowski**, is a **board member** of both the **International Thermoelectric Society** and the **European Thermoelectric Society**.

The TRL team collaborates on TE solutions with numerous international partners, including:

1. **Michigan State University, East Lansing, USA** (Group of Prof. Alexandra Zevalkink)
2. **Northwestern University, Evanston, IL, USA** (Group of Prof. G. Jeffrey Snyder)
3. **Colorado School of Mines, Golden, USA** (Group of Prof. Eric Toberer)
4. **German Aerospace Center (DLR), Cologne, Germany** (Groups of Prof. Eckhard Mueller and Prof. Johannes de Boor)
5. **JPL NASA, Pasadena, USA** (A. Chmielewski)
6. **Max Planck Institute of Chemical Physics of Solids, Dresden, Germany** (Group of Prof. Yuri Grin)
7. **University of Caen Normandy, France** (Group of Prof. Franck Gascoin)
8. **Kumamoto University, Kumamoto, Japan** (Groups of Prof. Tsutomu Mashimo and Prof. Akira Yoshiasa)

# Team potential and readiness

TRL AGH UST in Krakow

## Collaboration with Industry

The team has extensive experience in collaborating with industry. In the past, it has carried out projects with partners such as **Honda LTD**, **Sasol Technology Ltd**, **EDF Poland**, **Synthos S.A.**, **Collins Aerospace Poland**, **General Electric Aviation Poland**, and **Mesko S.A.**

For its inventive activities, the team has been recognized with several awards, including the **Gold Medal** at the **International Invention Show & Technomart (INST)** in Taipei, the **Gold Medal** awarded by the **National Research Council of Thailand**, the **Platinum Medal** at the **International Warsaw Invention Show 2015**, and the **Minister of Higher Education of Poland Award** in 2016.

## Selected grants on thermoelectric technologies:

- **IMPRESS-U NAWA, BNP/NSF/2023/1/00010/DEC/01** – *"Decoupling Structure and Composition with Zintl Phases"*, National Agency for Academic Exchange, Partners: **Michigan State University**, **University of Lviv** (2024-2026), **~ 250,000 USD**
- **OPUS-2023/51/B/ST11/00329/R** – *"Diamond-like Semiconductors as Low-Cost Thermoelectric Materials for Direct Conversion of Waste Heat into Electricity"*, National Science Centre (2024-2027), **~ 180,000 USD**
- **MAITEG, WEAVE-UNISONO 2022/04/Y/ST5/00139** – *"Entropy Engineering and Interface Optimization in Materials for Highly Effective Thermoelectric Energy Conversion"*, National Science Centre and German Research Foundation, Partners: **German Aerospace Institute (DLR)** and **University of Duisburg-Essen (UDE)** (2024-2027), **~ 500,000 USD**
- **TEAM-TECH/2016-2/14** – *"New Approach for the Development of Efficient Materials for Direct Conversion of Heat into Electricity"*, Foundation for Polish Science (2018-2022), **~ 900,000 USD**
- **TECHMATSTRATEG2/408569/5/NCBR/2019** – *"Development of a Technology for the Production of a New Type of Thermoelectric Modules for the Conversion of Low-Parameter Waste Heat into Electricity"*, National Centre for Research and Development (2019-2022), **~ 2,500,000 USD**

## Total funding: > 6 million USD

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Thank you for your attention

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# 40th International Conference on Thermoelectrics
# 20th European Conference on Thermoelectrics

**June 30 to July 04, 2024 Krakow, Poland**

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**Krzysztof Wojciechowski & Janusz Tobola**