"INTEGRATED" Project Report (RP2)

(SUMMARY FOR PUBBLICATION)

Summary of the context and overall objectives of the project

InTEGrated (Grant Agreement-899248, 2020-2023) is the continuation of the THERELEXPRO project (EUR 29536, 2013-2016). InTEGrated research develops innovative thermoelectric generation prototypes based on the concepts of compactness, modularity, and overheating protection systems, as highlighted by the experience gained from the former project. New prototypes were optimized for energy harvesting from EAF off-gas cooling water and high temperature radiative waste heat, designed to be integrated within new or existing plants. A dedicated finite-element "system model" was created, able to simulate the performance of thermoelectric systems. InTEGrated addressed key improvements aimed to raise the technology up to TRL 7.
The project produced five different types of thermoelectric systems, two types for the exploitation of hot water with temperature < 100°C (Prototype A), and three types for the exploitation of radiant energy from hot steel products with surface temperatures of approx. 900 °C (Prototype B).

Prototype A
This thermoelectric system has been called "water-to-water" type to indicate that heat is extracted from hot water (or other hot liquid) source and is then transferred to a cold water (or other cold liquid) sink, while simultaneously producing electricity.
The prototypes have been created in this project and are used for the exploitation of hot water in the form of square and circular section tubes. These two particular shapes were chosen with the aim of both improving heat-electricity conversion and making them modular and scalable. In fact, the tubular shape of the thermoelectric systems does not allow to disperse thermal energy in the environment (more efficiency) and allows many identical tubes to be placed side by side, enormously reducing the effort required for the design of large or small production plants (scalability).

Prototype B
The prototypes for the exploitation of radiant energy (so called Prototype B) followed different approaches, with the main target to protect the thermoelectric modules (TEM) from overheating, which could easily occur e. g. due to changes in production. The first approach was based on the use of phase change materials (PCM) within a heat absorber to absorb excessive radiative heat and to mitigate abrupt temperature gradients which may damage the TEMs. The second solution used water heat pipes (WHP) to transfer the radiative heat to the TEMs, enabling to install the TEMs at a safety distance from the radiative hot source. The third approach used high temperature heat pipes (HTHP) in combination with high temperature TEMs (temperature range 500 – 600°C) to investigate a system for higher waste heat temperatures. All three prototypes B were investigated in the laboratory to collect general performance data. Finally, the WHP-Prototype was investigated in a long-term online test at the cooling conveyor of the wire rod mill at Elbe-Stahlwerke Feralpi in Riesa, Germany.
The economic viability and the environmental footprint for such systems were assessed as well as required measures for future installations defined.

Modelling
Computational models have been developed based on COMSOL Multiphysics Simulation Software to provide theoretical tools for system simulation, design optimisation and performance prediction. Four specific models were constructed to account for the key prototypes developed in this project, including circular-section and square-section systems of Prototype A, phase-change protected, and water-heat-pipe protected systems of Prototype B. The models were validated using the experimental data obtained from this project and have been employed to investigate design optimisation and performance enhancement of the developed prototypes. A wide range of operating conditions and a vast amount of design variables of these developed prototypes have been investigated through model simulations, which would have been very difficult, costly and time consuming experimentally.

<u>CONCLUSION OF THE ACTION</u>:
The new prototypes developed in the InTEGrated project have shown their capability of producing electricity at a lower cost per kWh than those developed in the Therelexpro project.

Prototype A
Thermoelectric tubes with a square or circular section have shown different characteristics and manufacturing difficulties. For the creation of square section thermoelectric tubes, the objective was to use mainly materials available on the market and therefore reduce the production cost as much as possible, and consequently reduce the cost of the electricity produced. To create the circular section tubes, however, it was necessary to explore new construction techniques, mainly because it was necessary to create flexible thermoelectric modules capable of wrapping around the curved surface of the internal tube. This highly innovative and complicated path required a greater expenditure of design energy, producing a less performing result. Despite this, the idea of using flexible thermoelectric modules remains an interesting challenge and one that could lead to superior results. The two construction techniques have therefore led to different results, and it is difficult to assert which is the best solution. The square section tube quickly led to good results but can hardly be improved further in the future. The circular section tube, on the other hand, even if it will have to be further studied, especially to improve its reliability, could lead to the possibility of mass production and therefore to a reduction in production costs, which is in fact a key factor that has a greater impact on the development of this type of technology.

Prototype B
The online test of the water heat pipe approach of Prototype B has shown that the system works in principle, but an increase in the electrical resistance of the TEMs with progressive operation time and thus a power loss with ongoing operation time was observed. Subsequent CT scans of a used and a new TEM determined the formation of cracks and increasing damages to the solder connections because of the vibrations from the conveyor and of the highly discontinuous heating-up and cooling down of the prototype during the field test. Therefore, it must be stated that the TEMs used are not suitable for this application, despite the manufacturer's claim that they can be used up to 300 °C. Thus, more robust TEMs must be found for big scale installations in harsh environments with highly discontinuous waste heat arisings. The concluding economic calculation of a big scale industrial implementation at a cooling conveyor of a hot wire rod mill resulted in a payback period of 12 years for such an installation. Therefore, the cost for the system must be reduced to approx. 25 - 50 % of the current cost before it can be an option for industrial application. Possible cost-saving potential could be identified in using more cost-efficient materials for the heat absorbers (e. g. aluminum instead of copper) and the water coolers (steel instead of brass) as well as in using cheaper TEMs and heat-pipes. However, without automated mass production of TE materials and entire TE systems as well as standardization the required cost reduction cannot be reached.

Overall conclusion
The InTEGrated project (2020-2023) successfully refined thermoelectric generators developed during Therelexpro project (2016-2020). These advancements resulted in more compact, modular, and heat-resistant prototypes. Furthermore, a dedicated finite-element "system model" was created, able to simulate the performance of thermoelectric systems and thus to save a large amount of time in the development phase due to the possibility to predict future design iterations.
The new thermoelectric systems (Prototype A: water-to-water systems for cooling water exploitation, Protoytpe B: radiation-to-water systems for radiative source exploitation) demonstrate encouraging conversion efficiencies, transforming low-temperature hot water into electricity at 1 - 1.6 % (Prototype A) and radiant energy at 1.5 - 2.5 % (Prototype B).
However, these efficiencies are still insufficient for widespread industrial use.
Low conversion efficiency translates to high production costs, leading to an acceptable Levelized Cost of Electricity (LCOE) only after an extended period (20-30 years). The payback periods for both prototypes were calculated with more than 12 years. This timeframe is impractical, especially considering the desired cost recovery period of around three years for new technologies in the steel industry. In comparison established heat-to-electricity conversion systems offer superior efficiencies. Even for low-temperature sources, Organic Rankine Cycle (ORC) systems achieve 5 – 8 % of conversion efficiency, significantly exceeding what developed thermoelectric generators can currently deliver.
Given these limitations, the developed thermoelectric generators for waste heat conversion require significant advancements to become economically viable.
This can be achieved through:

- reduced manufacturing costs, e.g. by automated mass production of TE materials and entire TE systems.

- increased conversion efficiency by new/improved materials
- standardization of TE systems
- commercially available complete TE systems with proven long-life service even under harsh environmental conditions
- reduction in cold water consumption

Furthermore, the field tests of both prototypes showed weaknesses which have to be overcome to reach a long-life service of such systems:

- Prototype A: Sealing problems between the cold side hydraulic part and the electrical part, calcium and dirty deposition.

- Prototype B: Formation of cracks in the TE material and solderings with progressive operation time and thus, power losses with ongoing operation time.

Overall, it must be stated that the current investment costs combined with the low potential for electrical recovery and the not proven long-life services in industrial environments limit the industrial scope of big scale waste heat recovery by TEG in the steel industry. There may be future applications probably in SME fields or in special applications like the power supply of sensors.

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far.

WORK PERFORMED:

- Review of the state of the art on thermoelectric issues, particularly concerning the state of the art of thermoelectric materials, general application of thermoelectric systems and application of thermoelectric systems in the steel industry.
- Definition of the environment in which the two thermoelectric generators prototypes will work.
- Definition of the main specifications of the two types of thermoelectric generators prototypes necessary to start the detailed design of the components.
- Theoretical work in support of analysing operation requirements and design specifications.
- Modelling and simulation using the multiphysics model.
- Design of TEG prototypes:
    - Six Prototypes A were designed: three in the shape of a square section tube and three with a circular section. The square section tubes used thermoelectric modules that can be purchased on the market and the internal tube was made of aluminium. Each prototype differs from the others due to some different design choices, mainly regarding the design of the heat exchange between the hot liquid and the thermoelectric module. The circular section tubes were made starting from the assembly of pellets in thermoelectric material and was made with internal stainless steel metal tube. This fact required fine-tuning the welding procedure which took a long time and certainly still requires improvements. The greater difficulty of construction of circular section tubes led to a lower reliability of the thermoelectric generator and for this reason the project, in the final part, concentrated on square section tubes.
    - Three prototypes B were designed: one prototype based on the utilization of a phase change material (tin), one based on the usage of water heat pipes for the heat transport from the heat absorber to the TEMs, and one solution using high temperature heat pipes for the heat transport from the heat absorber to high temperature TEMs.
- Prototypes manufacturing for laboratory tests and long-term tests.
- Prototypes industrial on-line installation and tests:
    - Laboratory tests of the Prototypes A were carried out in the second half of 2022. Unfortunately, a circular-section thermoelectric tube had an irreparable failure during laboratory tests. Therefore, five of the six prototypes A created were installed at the Ferriere Nord industrial plant in Osoppo to test their reliability in an industrial harsh environment. Online testing began in late January 2023 and ended in August 2023.
    - Prototype B: After evaluating the laboratory tests, it was decided to investigate the prototype B's WHP approach in a long-term test (from March 2023 to December 2023) at the cooling conveyor of the wire rod mill at ESF site. Main target was to determine the long-term performance and the feasibility of such a system for waste heat recovery in harsh environments.
- Continuous data analysis during the online tests of prototypes A and B.
- Economic calculations (LCOE) for the long term-tested prototypes.
- Life Cycle Assessment (LCA) of the long term-tested prototypes.

- Exploitation plan for the tested prototypes and the simulation models.

MAIN RESULTS ACHIEVED:

Prototype A

The tube shape of a water-to-water thermoelectric generator has been shown to increase the conversion efficiency and scalability of the system compared to the prototype developed in THERELEXPRO project. Furthermore, by using components available on the market it is possible to reduce their costs and reduce the cost of the electricity produced. However, it has also been demonstrated that some aspects of the systems need to be improved. Three of five prototypes installed at the industrial plant suffered from sealing problems between the cold side hydraulic part and the electrical part. This aspect must be taken into maximum consideration when designing this type of thermoelectric generator. Excluding this aspect, it was possible to demonstrate that square section tubes provided better performance as well as better reliability. The possibility of using industrially made thermoelectric modules has provided the square section thermoelectric tubes with lower manufacturing costs and better construction reliability. Square section tubes showed conversion efficiency from 1 % to 1.6 %, electrical power/tube volume ratio of 2.5 W/L, production cost of €20/W, and electrical power per volume of thermoelectric material equal to 0.5 W/cm^3. The levelized cost of electricity was calculated at €0.60/kWh for a plant active for 5 years and at €0.25/kWh for a production plant that has been active for 20 years. Furthermore, the feasibility of making flexible thermoelectric modules that can be wrapped around a curved surface was demonstrated.

Prototype B

Overall, the laboratory tests of the PCM and WHP-Prototypes were successful, while the HTHP-Prototype test delivered no usable results, due to the destruction of the heat pipes. The PCM-Prototype worked almost in the expected range, but the overheating protection time due to the used PCM was only approx. 40 s and furthermore, the PCM melts prematurely, before the hot side of the TEM has reached the critical failure temperature. The power output of the WHP-Prototype was slightly lower than expected due to a lower hot side temperature of the TEMs. However, the power output of the TEMs was also in the range as the supplier reported for this temperature. Finally, after evaluating the laboratory tests, it was decided to use the WHP-Prototype for the long-term test at the cooling conveyor of the wire rod mill at ESF, since this approach is the more promising approach, due to the wider field of application, the possible adaptation also for high-temperature TEG without fundamentally system changes, and the higher overheating protection time compared to the PCM approach.

Results of the subsequent online test of the WHP-Prototype at ESF site showed that the system works well but with progressing operation time significant losses in the power output and efficiency were determined. CT scans of a used and a new TEM showed that failures in the soldering and in the TE material induced cracks in the TE material, which resulted in the observed losses. Finally, according to the long-term test results, specifications of typical industrial installations and required design improvements were defined by the partners and the economic and ecological impact of the WHP-Prototype was assessed. The prototype efficiency varied in a range of 0.5 – 2.5 %, depending on the hot side temperature of the TEMs. Excluding the efficiency losses with progressing operation time (see above) a power production of approx. 400 W/m^2 seems to be possible by this system. The prototype showed an electrical power/tube volume ratio of 8.1 – 11.4 W/L, production cost of 21.9 – 31.0 €/W, and an electrical power per volume of thermoelectric material equal to 6.3 -9.0 W/cm^3. The levelized cost for electricity of the WHP-Prototype was calculated at 0.86 €/kWh for a plant active for 5 years and at 0.38 €/kWh for 20 years. The payback period for an industrial installation in bigger scale was calculated with more than 12 years, so that significant cost savings by using more cost-efficient materials, using cheaper TEMs, automated mass production of TE materials and entire TE systems as well as standardization are mandatory for such installations to reach economic viability.

Modelling

The model simulation confirms that the prototypes developed in this project have achieved good design, which approaches their respective optimal design. The experimental results obtained from these prototypes represent the state-of-the-art performance available from these practical operating conditions. They can be used as the benchmarks for evaluation of the realistic economic benefit from respective thermoelectric energy harvesting applications. The simulation study also shows that a further improvement in the power output and conversion efficiency by about 25% is possible in Prototype B by developing advanced materials (segmented legs).

The developed models proved to be a powerful simulation tool that has applications beyond this project. They are capable of exploring a wide range of design variations, system parameters and extreme operating conditions of thermoelectric systems using both fluidic and radiative heat sources. They can be readily modified and adopted for studying many other thermoelectric systems, such as predicting the improvements of new designs and potential performance of incorporating new advanced materials.

LCA results
The results show that the electricity production with prototype A has a slightly greater impact on the environment than the production with prototype B, except for Marine Aquatic Ecotoxicity.
In terms of climate warming, both prototypes can be considered low-carbon renewable energy production systems, with a carbon footprint of 125 and 124 kg CO2 eq. on CML-IA baseline.
Regarding the emission of toxic material into the environment, it should be kept in mind that electrical production using thermoelectric generators produces such materials only during the processing phase, and not during the working period. Therefore, assuming that each power plant has a comparable impact during the production phase, TEGs should be considered a green technology similar to wind, hydroelectric or solar generation and much better, for this impact category, than traditional production methods based on combustion technologies.
From an environmental point of view, no recommendation can be made to favor one prototype or the other. In fact, they were designed to operate in two completely different conditions, with advantages and disadvantages each. Prototype A works as a chiller capable of simultaneously cooling water and producing electricity, prototype B works as a heat recovery system capable of converting lost radiant energy into electricity. Therefore, the two prototypes have two different objectives, and it is not advisable to use one over the other.
The only general recommendation, valid for both prototypes, is to try to use thermoelectric materials made of less toxic and possibly very widespread materials on the earth's crust.

Exploitation
In the frame of the exploitation measures the partners evaluated the planned and achieved results and as well as the developed technologies in InTEGrated. Furthermore, possible application areas for waste heat recovery by TEG were identified. Identified possible waste heat recovery applications for prototype A included cooling water and/or off gas usage of e. g. EAFs, production lines of the nonferrous metals industry and for refractory materials, cement kilns, domestic gas burners, internal combustion engines, combined heat and power plants as well as water usage from hot springs or steam boilers. Possible application cases for prototype B were seen in radiation from casting lines, forges and in the nonferrous metals industry.

Dissemination
Throughout the research period, the partners took steps to publish articles in specialized journals and disseminate the results of the InTEGrated project in conferences. A total of 13 publications were published by the partners during the project: 8 conference presentations (at the European Conference on Thermoelectrics, ESTAD, ESTEP meeting, Thermoelectric Network UK Meeting, Dissemination Day RFCS Projects), one journal paper (Energy Environ. Sci.) and several presentations at the InTEGrated workshop.

Progress beyond the state of the art, expected results until the end of the project and potential impacts (including the socio-economic impact and the wider societal implications of the project so far)

By drawing on the successful results of the THERELEXPRO project, InTEGrated developed new TEG systems characterized by an innovative design and optimized materials, enabling to achieve key improvements in terms of performance and economic viability. Specifically, the prototypes developed feature the following innovative aspects:

- ✓ An ad hoc finite element “system model” able to simulate the performance of the prototypes intended as complete systems. Thus, it can be easily adapted to other thermoelectric systems independently from their application.
- ✓ New dedicated TEMs manufactured from optimal TE pellets, selected through the ad hoc finite element “system model”.
- ✓ Special adhesives (used to fix the new TEMs to the inner pipe) and resins (for TEMs insulating coating) for prototype A application were optimized to attain improved thermal coupling, enhanced electrical insulation and protection against water wear.
- ✓ A highly innovative heat pipe-based heat extraction (which works also as an overheating protection system) for heat transfer to the TEMs (one based on water heat pipes, and one based on high temperature heat pipes) and a PCM based overheating protection of the TEMs. Especially the water heat pipe approach makes high temperature waste heat also usable for common TEMs. Due to their

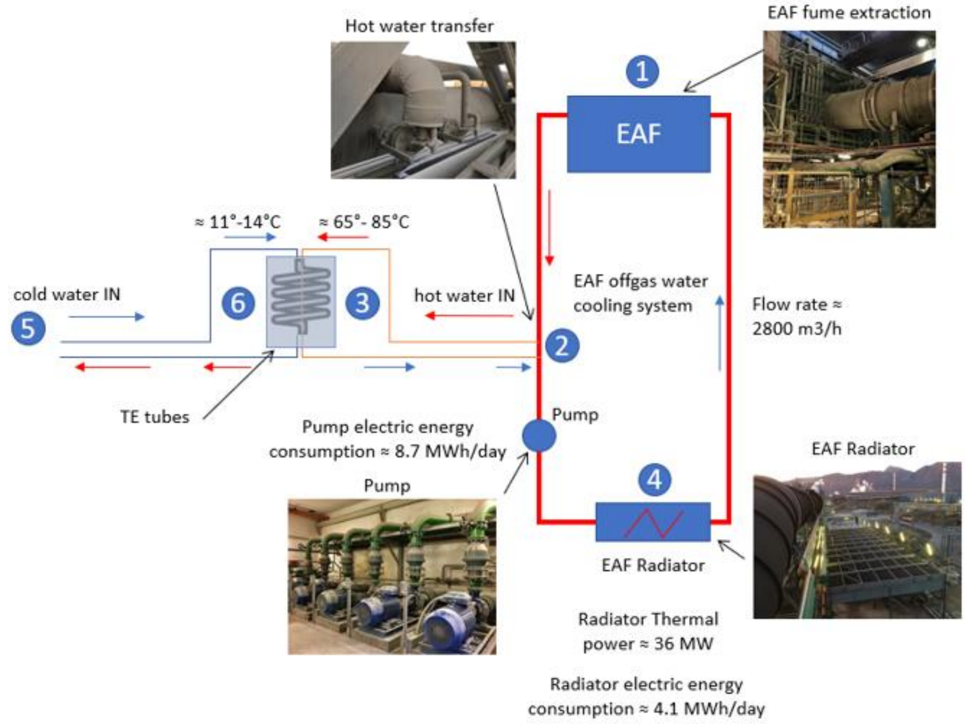
generic nature, both systems can be easily transferred to other thermoelectric waste heat applications.

- ✓ During prototype design and construction, a cost-effective, production-oriented assembly procedure was developed to address economically viable, full-scale TEG systems, in view of an effective transfer of project results at the industrial level.

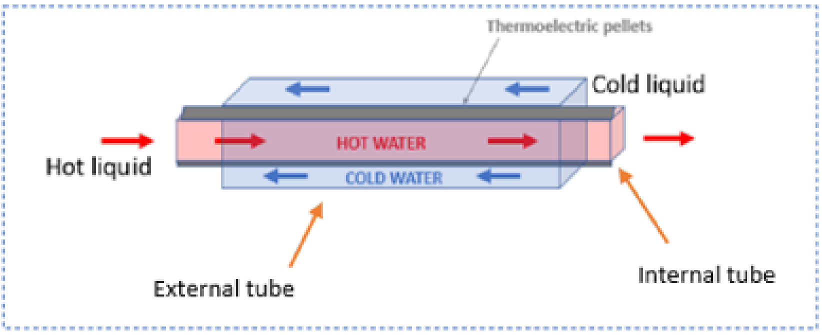
Address (URL) of the project's public website

www.integrated-euproject.eu

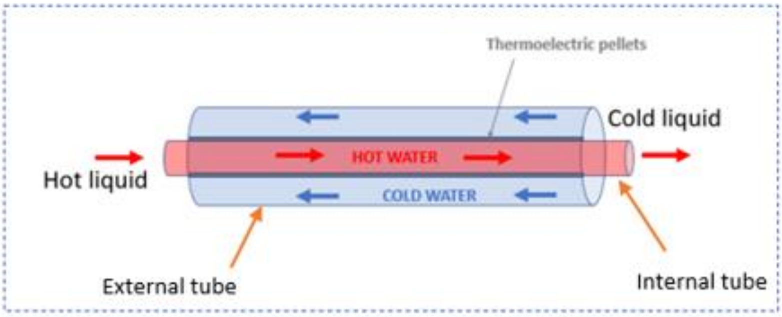
Images attached to the Summary for publication.



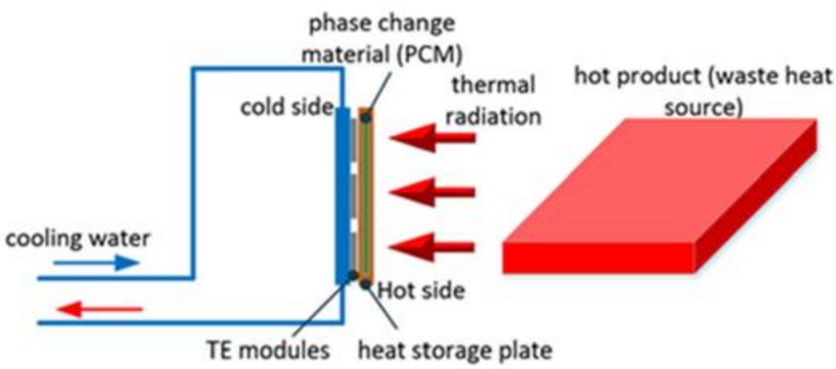
Scheme of *water-to-water* thermoelectric tubes installation at Electric Furnace plant



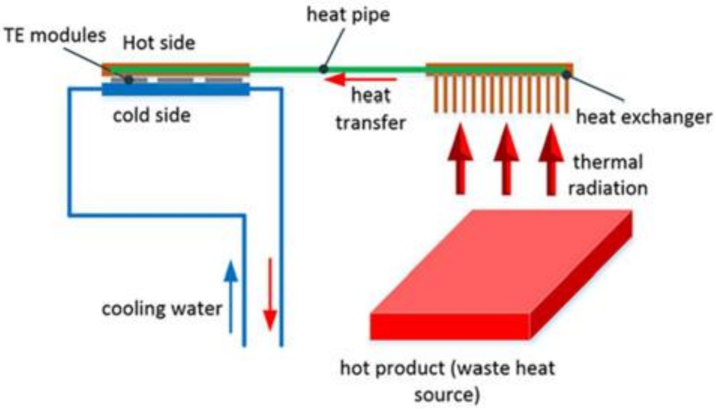
Scheme of *water-to-water* thermoelectric tubes with square section



Scheme of *water-to-water* thermoelectric tubes with circular section



Scheme of *PCM-Prototype*

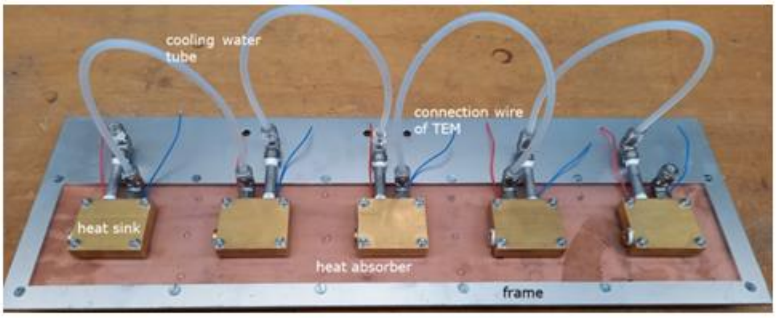


Scheme of *WHP-Prototype*

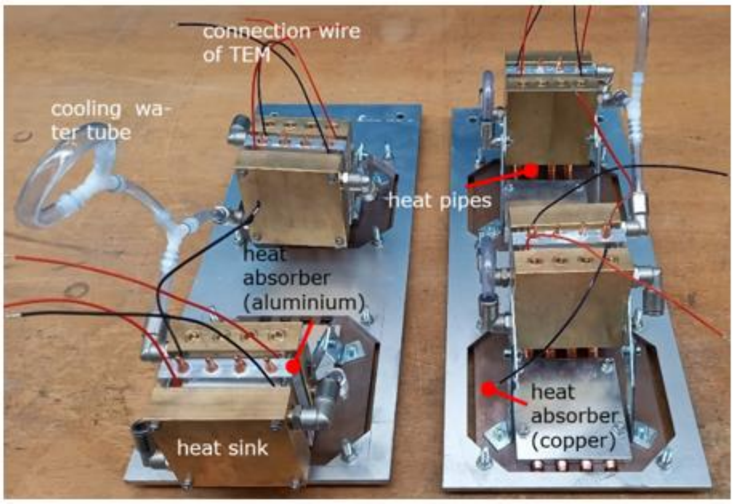
Thermoelectric tube with square section

Thermoelectric tube with circular section

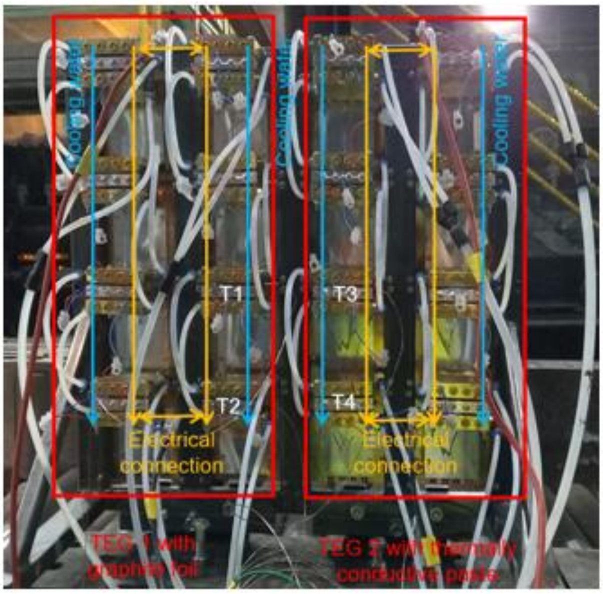
Prototype A installed at Ferriere
Nord Osoppo plant



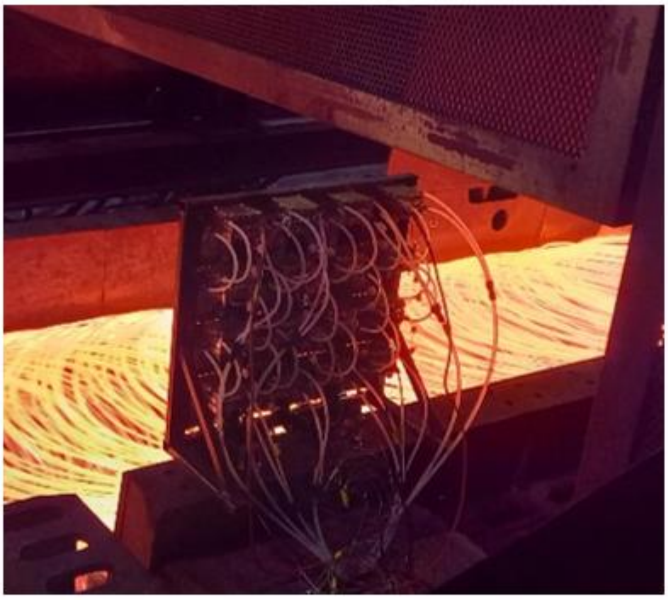
Laboratory test of small PCM-Prototype



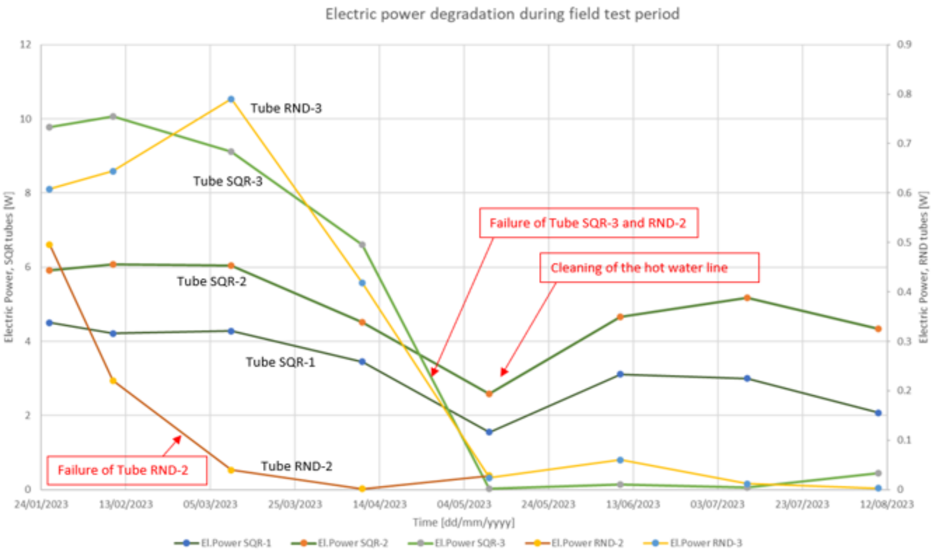
Laboratory test of small WHP-Prototype



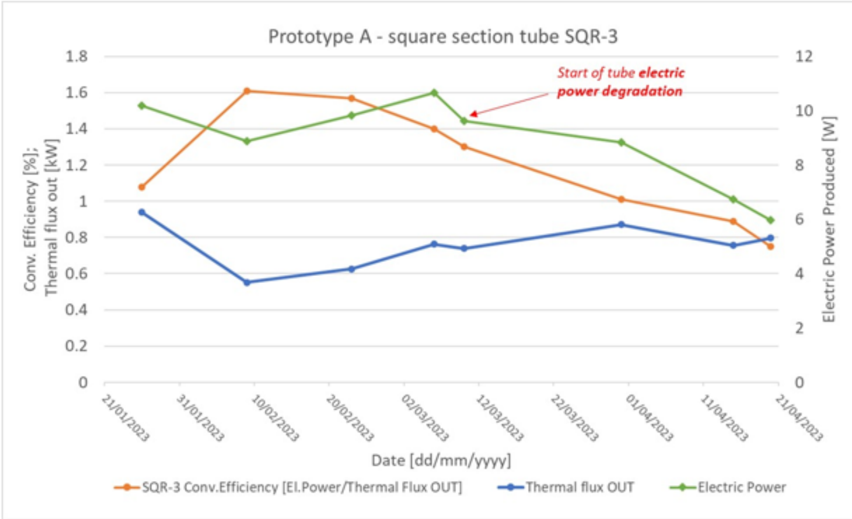
Final WHP-Prototype



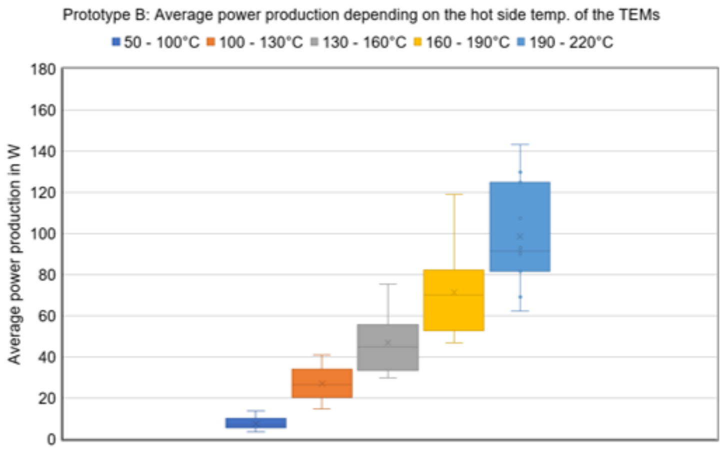
Installed WHP-Prototype at the hot wire rod mill of ESF site



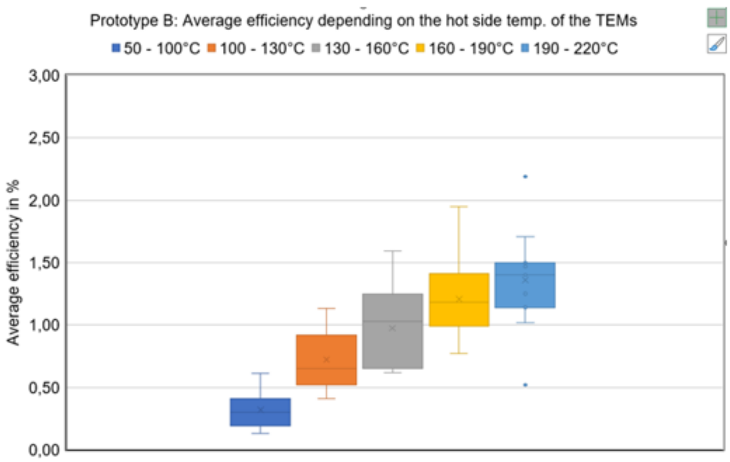
Electric power production of prototypes A at Ferriere Nord plant



Square section thermoelectric tube conversion efficiency



Overall average power production of the WHP-Prototype at different temperature ranges of the TEM hot side



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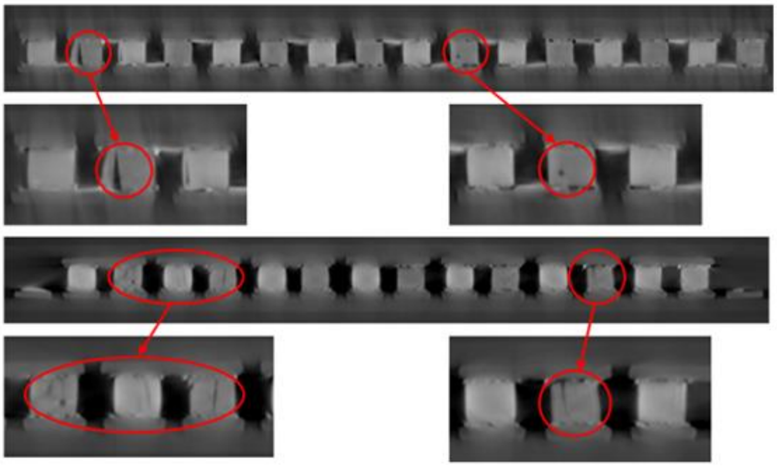

CT scans of a used TEM of the WHP-Prototype