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TNO report

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Thermoelectric conversion of waste heat to power and process heat

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Contents

1 Introduction

This project is carried out with help of subsidy of the Ministry of Economic Affairs and Climate Policy, national scheme EZ-subsidies, Topsector Energy, carried out by the Rijksdienst voor Ondernemend Nederland (RVO).

Data project

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Contact and availability report

Copies of this report can be obtained through the repository of public TNO reports: https://repository.tudelft.nl/tno/.

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2 Background and objectives

Background
In order to maintain the competitive position of the process industry in Europe, highest energy efficiency, lowest CO_2 emissions and high economic efficiency of the production processes are a must. Consequently, the process industry is constantly looking to improve in these fields under the boundary conditions that the investments are cost efficient with a pay-back time of less than 3 years whilst having minimum impact on the production process itself. Waste heat recovery is considered a crucial opportunity with respect to energy efficiency improvement.

Production processes in industries like the steel, glass, aluminum and ceramics, as well as waste incineration, involve high temperature processing and therefore inevitably large amounts of high-temperature waste heat. Recovering part of the energy stored in waste heat will significantly lower production costs and CO_2 emissions. In the high temperature range > 400°C, the options for feasible technologies have been quite restrictive so far. In this temperature domain, thermoelectric generation will add a new option and disclose a potential for waste heat recovery that has not been available thus far.

Thermoelectric power generation is the direct conversion of a heat flux into electricity. It is based upon the fact that a thermal gradient in a semiconductor material causes the generation of an electrical voltage by the Seebeck effect (an effect that is also used in thermocouples and Peltier cooling), see Figure 2.1. This effect can be applied in many areas where thermal gradients exist with the technical advantage that due to its semiconductor nature, these conversion systems have no moving parts, since they are not based on a thermal cycle in which a substance has to be transported between a high and low temperature zone.

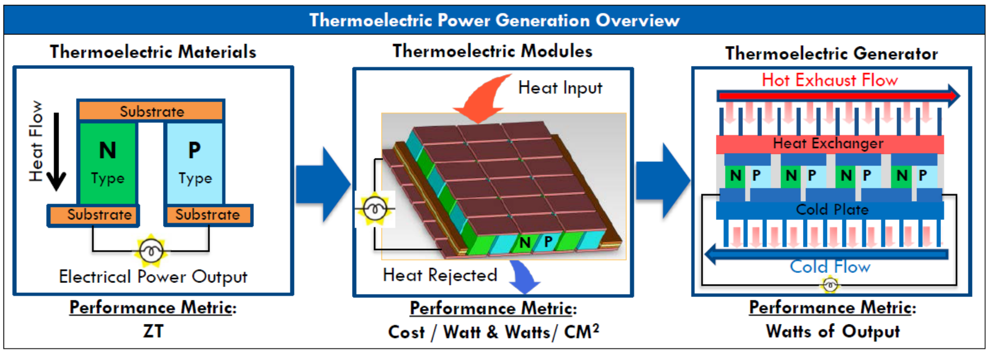

Figure 2.1 Thermoelectric principle (left), typical module lay-out (middle) and application in a car exhaust environment (right). Source: GMZ presentation Energy Harvesting, Berlin April 2014

Based on its silicon sheet casting process, RGS Development has composed a Thermagy TEG module solution which suits the high temperature range at a module cost perspective of 2-3 €/We. Compared to competitive solutions, the RGS solution is distinctive for the following reasons:

- Use of very low cost and stable silicon-based materials. Other alternative materials like telluride or skutterudites are considerably more expensive, cannot withstand the high temperatures and/or show degradation.

- Use of the single step RGS continuous casting method to produce thermoelectric legs in the form of strips. Alternative methods require many process steps in a batch type processing.
- Ability to apply a simple strip stacking method to assemble a module.

To extend the application potential of this technology, a number of problems can be identified and should be tackled.

- First, these TE panels have mainly been applied in radiation conditions in a steel mill. Other high-temperature sectors like glass, glass wool, stone wool, and ceramics would also possibly benefit from this technology. Therefore, the application of TE panels in these sectors should be explored.
- In addition, the value generated by the panels could be increased by coproduction of steam and electricity. The panels are currently cooled with water, which results in lukewarm water which has low value. The generation of steam will result in a somewhat lower electrical efficiency, but this is more than compensated by the production of usable process heat.
- The panels are presently designed to absorb radiation heat. However, considerable heat losses at very high temperatures can be found in exhaust gas flows, e.g. in glass ovens, blast furnaces, ceramic industry and waste incineration. The current panels are not capable of collecting heat by convection instead of radiation. The heat transfer at the front side needs to be improved for the system to be applied in high temperature exhaust gas flows.
- The use of water/steam as cooling medium may be problematic in situations where the presence of water poses possible safety issues. Preferably, the TE panels should be cooled by air. This is presently not possible.

Objective

The overall objective of this project is the development of economically feasible concepts for the conversion of high-temperature waste heat into electrical power and process heat. This technology can be applied in high-temperature sectors like steel, glass, ceramics, glass wool, stone wool, cement, and possibly the chemical sector.

More specifically, the following objectives are pursued:

- Extend and evaluate the application of TE panels to multiple high-temperature sectors (steel, ceramics, glass, glass wool, ..). Verify the performance of the thermoelectric panels under specified severe conditions, both with respect to temperature (400-1200°C front side, 40-180°C back side) and operating conditions (steel, glass, glass wool).
- Valorize the non-converted heat by coproduction of steam. The TE panels should be tested under a variety of temperature conditions at both the heat source and heat sink side. On the heat sink side, steam conditions up to 10 bar steam will be tested.
- Extend operating range of thermoelectric panels to convective heat transfer conditions. This option will explore the functionality of the TE panels in the temperature range 400°C-800°C.
- Evaluate the energy saving potential and market potential.
- Assess the business cases for multiple industrial end-users.

3 Results

3.1 Boundary conditions

The boundary conditions & requirements of the two end-users are defined to select cases for the experimental activities. Most promising options for integration of the thermoelectric system in the end-user processes are identified with respect to expected savings potential and expected costs for integration. Main conditions are the waste heat temperatures, gas composition and flow. These conditions will be used to prepare a global system design and the TE modules for the system to be developed.

An overview of the preferred modes of TEG integration is presented in Table 3.1. Due to the fact that Ardagh does not use steam, and in addition wants to avoid the use of water near the glass furnace, Ardagh focuses more on air cooling (furnace) and water cooling (exhaust gas). On the other hand, Tata needs steam for its steam system, making radiative to steam the preferred mode, with radiative to water cooling as a second best option.

Table 3.1 Preferred mode of TEG integration

	Front	Rear	Integration options Ardagh	Integration options Tata
TEG#1	radiative	Water cooling	-	Hot slabs (800°C) Hot sheet rolls (600°C) Hot plate (1100-1000°C)
TEG#2	radiative	Steam	-	Hot slabs (800°C) Hot sheet rolls (600°C) Hot plate (1100-1000°C)
TEG#3	radiative	Air cooling	Forehearth (1250°C-1130°C)	-
TEG#4	convective	Water cooling	Exhaust gas furnace (regenerative 450°C, recuperative 800°C, oxyfuel 1450°C)	-

3.2 Development of thermoelectric panels

The TE panels consist of several TE modules. These modules to be developed in the present project consist of 3 components; the high temperature heat transfer component (TE-heating component), the TE elements themselves and the low temperature cooling component (TE-cooling component). TNO designed and manufactured the thermal components of the module (TE-heating and TE-cooling components), while RGS Development is responsible for the TE-elements part of the module.

The following restrictions are imposed on the thermal design, based on the current RGS technology:

- Temperature heating side; should preferably be as high as possible to optimize the electrical yield, but may not be higher than 650°C, due to temperature limitations of the TE elements.
- Temperature cooling side is a compromise between optimal electric yield (requiring low temperature output) and usable thermal yield (requiring high temperature output). The temperature at the lower side of the TE elements may not be higher than 200°C, because of temperature limitations of the glue used by the manufacturer of the electric insulation.

Four different TE panels, consisting of TE-elements and TE-cooling components, will be developed according to four different configurations, identified by the application conditions, see Figure 3.1. Three of these panels are modified compared to the original design. The modifications relate to heat transfer issues, both at the front & back side. Heat transfer analyses are carried out to design for optimal heat transfer. The thermal panels are manufactured according this optimized design after which the TE elements are manufactured and connected.

Front side ↓ Back side →	Water cooling	Steam cooling	Air cooling
Radiation	X	X	X
Convection	X		

Figure 3.1 Condition at front and back side for 4 difference cases

Each of these 4 cases is analyzed with a model to predict the performance of a TE-panel. The modelling results will be compared with the experimental results in the section on discussion of the results.

The thermal model is a 2D model, calculating the temperature distribution along both the thickness of the panel and the flow direction. The following thermal resistances were taken into account:

- the radiative resistance between source and radiation shield (if present),
- the conductive resistance of the radiation shield (if present),
- the radiative resistance between radiation shield and TE module (or convective resistance for the flue gas case),
- the conductive resistance of the TE elements,
- the conductive resistance of the electrical insulation,
- the heat transfer resistance to the cooling medium.

Specific models are developed, depending on the configuration. Subsequently, the TE panels were manufactured, according the optimal design following the simulation model. Figure 3.2 till Figure 3.5 depict the different panels that are manufactured. Panel #4 contains only 1 row of TE-elements, since the amount of heat that could be delivered by the testing infrastructure (flue gas heating) was limited.

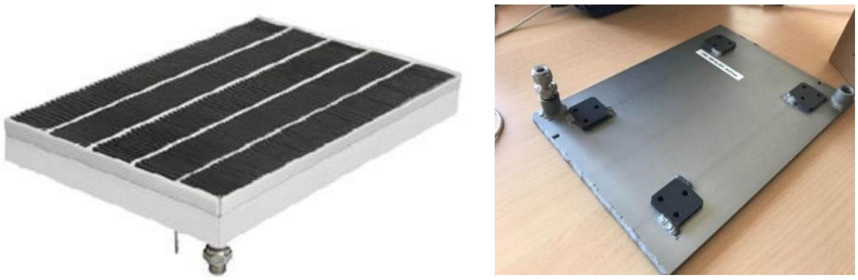

Figure 3.2 TEG panel #1, base case radiation heat source, water cooling

Figure 3.3 TEG panel #2, radiation heat source, steam production cooling

Figure 3.4 TEG panel #3, radiation heat source, air cooling

Figure 3.5 TEG panel #4, flue gas heat source, water cooling

3.3 Lab testing

The four TE panels that are developed are tested in the lab. An experimental setup is realized at TNO that measures the electrical and thermal performance of the various panels. An experimental program is carried out under a variety of (temperature) conditions to measure performance in terms of electricity and heat production. As an example, Figure 3.6 shows the setup that is used to do measurements on panel #2. The TE-panel is on the bottom of the picture, while the steam vessel, collecting the steam produced, is at the top of the picture.

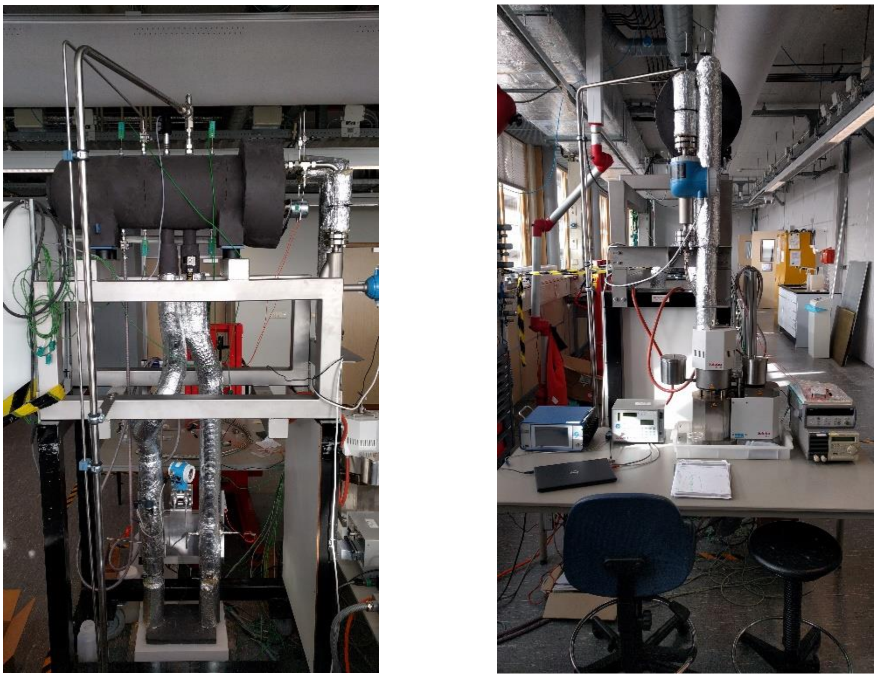

Figure 3.6 Lab setup for testing TEG panel #2

Results TEG panel #1

Figure 3.7 shows the measured thermal and electrical power produced by the reference panel (#1) depending on the top temperature of the TE-panel at different cooling water flow rates. The temperature of the radiation source varies from about 650°C to 750°C. As could be expected, both thermal and electrical power increase with increasing source temperature. The influence of the cooling water flow rate on the thermal and electrical power is rather limited. The measured electrical power measured is generated by 3 rows of TE-modules, instead of the regular 5 rows. To obtain the regular electrical output, the electrical power data from Figure 3.7 should be multiplied with 5/3.

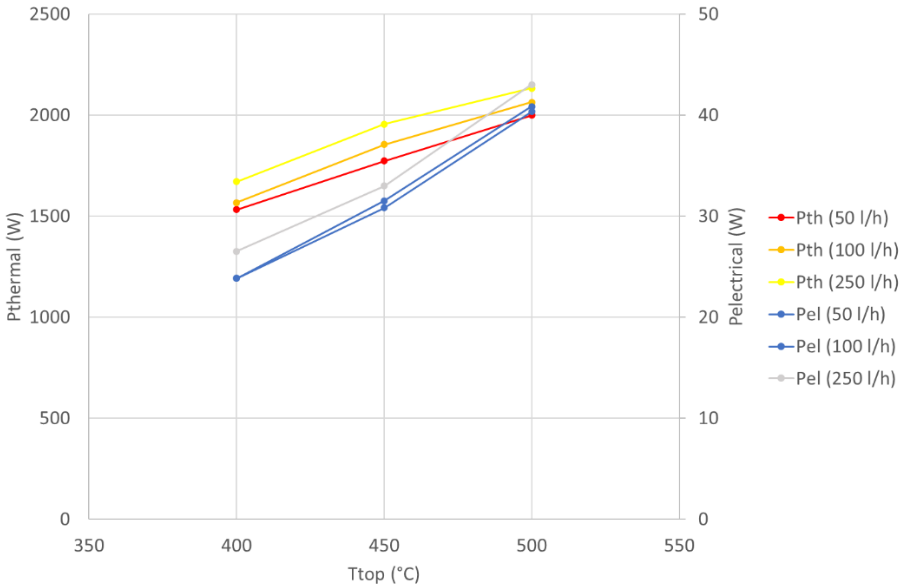

Figure 3.7 Measured thermal and electrical power for TEG#1 for different top temperatures and different cooling water flow rates at a cooling water temperature of 25°C

Results TEG panel #2
The performance of panel #2 was tested for 3 different steam pressures at the cooling side, being 3.5, 6, and 10 bara. A higher steam pressure means a higher temperature at the back end of the TE-panel and therewith a lower electrical efficiency. This can be observed in Figure 3.8.

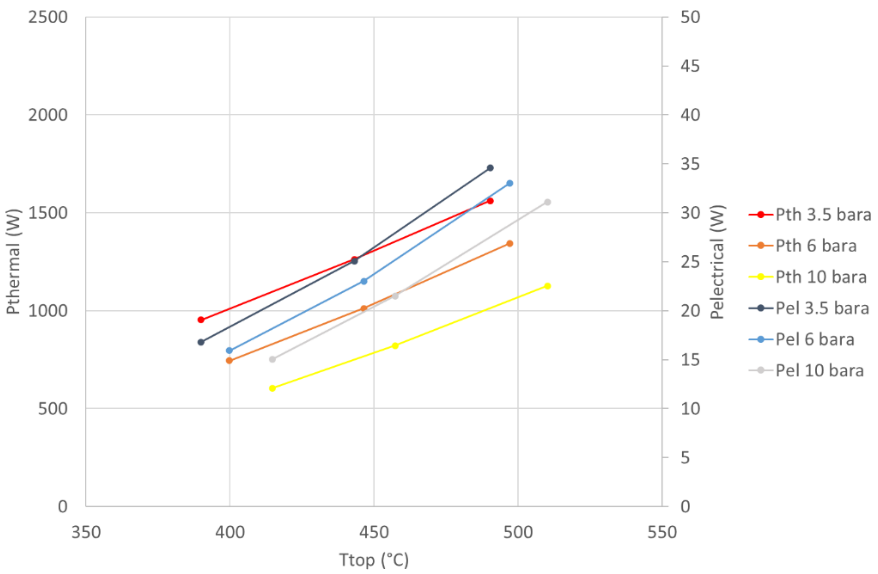

Figure 3.8 Thermal and electrical power of the TEG#2 thermoelectric panel for different top temperatures and different steam pressure levels

Since the experimental setup is at a rather small scale, heat losses will have a bigger impact on the thermal power results than in real scale systems. Therefore, the experimental results have been corrected for these heat losses. The thermal power depicted in Figure 3.8 concerns the measured steam production plus the measured heat losses from the steam collection vessel.

Results TEG panel #3

Panel #3 uses air cooling at the back-end of the panel. Cooling fins are added to the back side of the panel to improve the heat transfer. The performance was measured with a radiation source temperature of nearly 800°C and 3 different air flow rates, being 60, 80, and 110 Nm^3/hr. Cooling with air means a lower heat transfer at the back-end of the panel and therewith a higher back-end temperature resulting in a lower efficiency. This can be observed in Figure 3.9.

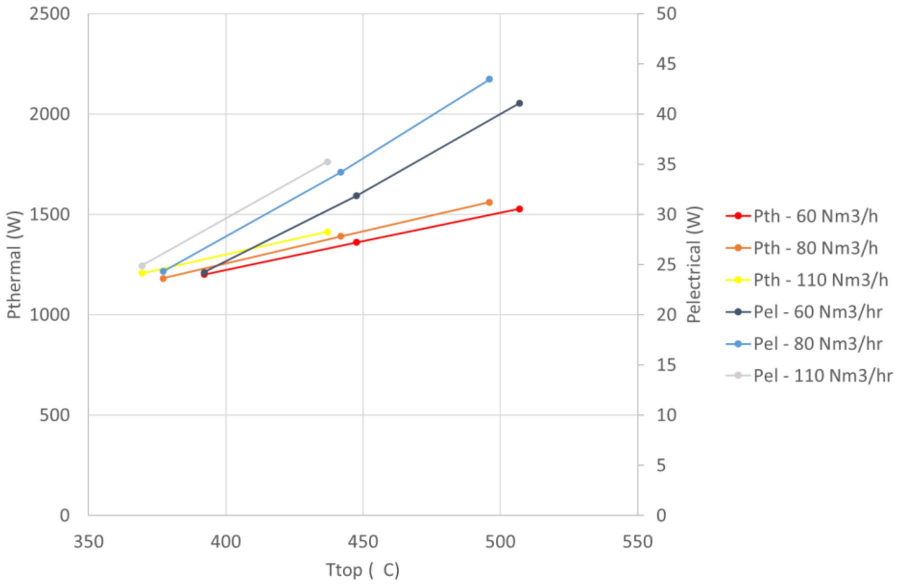

Figure 3.9 Thermal and electrical power of the TEG#3 thermoelectric panel for different top temperature and different air cooling flow rates

Results TEG panel #4

TEG panel#4 uses heated air to up about 750°C to simulate flue gas streams. A hot heat exchanger with fins is used to transfer the heat from this air to the TE-panel. A flue gas flow of 50 Nm^3/hr with varying temperature was applied to 1/5 of a complete panel. Unfortunately, no electrical performance results could be obtained since the electrical part broke during the experiments. Figure 3.10 presents the measured thermal and calculated electrical results for this panel.

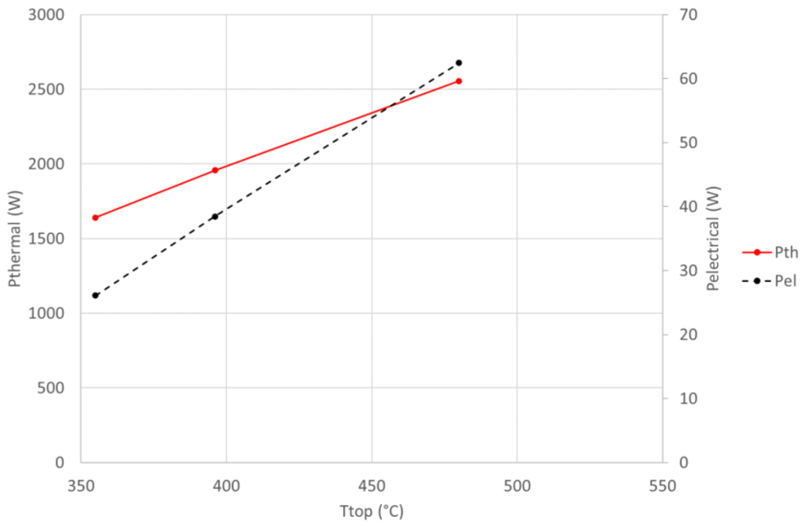

Figure 3.10 Thermal and electrical power of the TEG#4 thermoelectric panel for different top temperatures

3.4 Field testing

To examine the performance and behaviour of the TE-panels under actual industrial conditions, 1 panel was installed at the Ardagh glass production site in Dongen. The panel is installed above the feeder, just after the furnace and has been operating for more than 3 months. Measurement data was obtained during this period and collected locally. The data was extracted after the measurement period and analysed. Mainly temperature and power data are obtained.

Figure 3.11 shows the TE panel installed in a feeder at the Ardagh site. By lowering the panel towards the molten glass, a top temperature of 500°C could be achieved. The back side of the panel is cooled by water leading to a temperature of around 100°C at the back end of the TE-elements. This field testing was completed without any interference with the glass production process. The TE-panel was still intact after 3.5 months of exposure to the harsh environment of the feeder of a glass furnace. All data could be recovered from the localized storage. Unfortunately, the panel could not be moved closer to the feeder which would have led to higher top temperatures and therewith a higher power output. Furthermore, the protection of the soldered contacts was not sufficient, leading to failed electrical wiring and no measured power output. If the panel wiring would have stayed intact, an electrical power production of to 1500 W/m^2 is expected under the current temperature conditions.

Figure 3.11 TE panel installed @ Ardagh

3.5 Business & market

The business case for the industrial end-user has been calculated based on the expected price of the TE-panel, estimated by RGS to about 11 k€/m^2 (panel and integration) and the value of the expected electricity and steam production (if applicable). Two energy price scenarios have been evaluated, since these have undergone large changes in 2021. The low price scenario uses the average price of 2020 and adds the CO_2 tax of 2021. The high price scenario uses the current (October 2021) price and the expected CO_2 tax in 2030. This leads to the following energy prices.

- Low price (2020 price average + 2021 CO_2 tax):
  Gas: 21.5 €/MWh
  Electricity: 47 €/MWh
- High price (2021 current price + 2030 CO_2 tax):
  Gas: 141 €/MWh
  Electricity: 170 €/MWh

The payback time of an electricity-only panel depends strongly on the top temperatures that can be realized. With the energy prices of 2020, the payback period is in the order of 10 years at a top temperature of 600°C. This is improved greatly by the current rising energy prices and CO_2 taxes to payback times less than 3 years. Producing steam at the same time, reduces payback time to about 2 years for 2020 energy prices and to less than 1 year for high energy prices and CO_2 taxes.

The business case will be further improved if the maximum top temperature of the TE-panels can be increased above the current 650°C. The electrical efficiency will increase with higher top temperature, leading to more electrical power from the same module. RGS is currently proceeding to 1000°C top temperature.

The market potential is estimated by considering the production of high-temperature solid products (steel, glass, cement, ceramics, aluminum) that show large heat losses by radiation. Only solid bulk products that lead to TEG top temperatures >500ºC are taken into account. Nearly 1700 PJ of waste heat is available at these high temperatures in the studied sectors on a global scale.

A total of 50% of the waste heat from the solid products is assumed to be captured by the TE-panels. The other half is lost to the ambient. In addition, RGS technology is assumed to be able to cover 100% of the Dutch market, 25% of the EU market and 5% of the world market. The total area of TE-panels that could be sold by RGS is then estimated as 2014 + 12580 + 27050 = 41644 m^2. With a sales price of 11 k€/m^2 (panel + integration), this results in a total turnover over 458 M€.

4 Contribution to the objectives of the Topsector

Sustainability
The impact on the energy system is estimated based on the results of the market study. The waste heat potential at high temperatures in the steel, glass, ceramics, cement, and aluminum industry are given in Table 4.1. This is the total waste heat that is released by cooling down the hot products. Waste heat from hot flues gases has been excluded. Next, the assumption is that 50% of this heat is captured by the TE-panels and converted to electricity and steam. Steam production is only assumed for the steel and cement industry.

Table 4.1 High-temperature waste heat potential in industrial sectors and electrical and steam yields from TE-panels

	HT waste heat (PJ/y)			Steam yield (PJ/y)			Electrical yield (PJ/y)		
	NL	EU (-NL)	World (- EU)	NL	EU (- NL)	World (- EU)	NL	EU (- NL)	World (- EU)
Steel	4.1	84.4	947.9	1.4	28.4	318	0.08	1.56	17.4
Glass industry	0.8	24.6	106.9	0	0	0	0.03	0.92	4
Ceramics	1.2	9.4	116.2	0	0	0	0.05	0.36	4.4
Cement		23.0	331.1	0	12	174	0	0.52	7.6
Aluminium	0.0	0.8	11.8	0	0	0	0	0.04	0.4
Total	6.2	142.1	1513.9	1.4	40.4	492.0	0.16	3.40	33.80

Primary energy savings are calculated for both the electricity production and the useful heat (steam) production. The electricity production is compared with conventional production from the electricity grid (7.7 MJ/kWh), while the steam production is compared to a regular gas-fired boiler with an efficiency of 90%. The CO_2 emission reduction is calculated is a similar way. The CO_2 emission of natural gas combustion is 56 kton/PJ. The CO_2 emission of electricity production is 0.49 kg/kWh, assuming the electricity production of TE-panels will replace electricity produced by fossil fuels.

Primary energy savings in the Netherlands, based on 1.4 PJ/y steam production and 0.16 PJ/y electricity production, amounts to 1.9 PJ/y. The corresponding CO_2 emission reduction results in 109 kton/y. These numbers will increase if heat recovery from hot flue gases will also be taken into account.

Knowledge position
Thermoelectric waste heat recovery and conversion is attractive due to the scalability of the technology, the low impact on the regular production process and the low maintenance costs since it is a solid state device. Large scale introduction has not yet occurred due to relatively high costs of materials and modules. The Thermagy thermoelectric module solution which has been developed at RGS is based on the unique semiconductor material casting method. The RGS casting process can produce the active materials in a single step as compared to the multi-step process used today. This material manufacturing capability in combination with an innovative TEG module design, allows a breakthrough in module manufacturing costs. The overall benefit of the RGS thermoelectric modules as compared to other thermoelectric modules is estimated as a factor 3-5 lower in module costs, besides the advantage of the high temperature applicability.

This project has demonstrated that this technology can also be applied for simultaneous electricity and steam production at the expense of only a small drop in electrical efficiency but with large gains in process heat production. The project also showed that air cooling is possible, specifically for applications where water cooling is preferably not used. The use of flue gases as a heat source is technically also feasible but will require more development work on heat transfer between the source and the TE-panel and the materials used to transfer this heat.

5 Spin off

The production technology for producing the TE-material that is used in this project, is also suitable for the production of nano-porous silicon anodes for Li-ion batteries. This material results is a higher energy density and a faster charging rate.

6 Publications

The consortium has contributed to the Projectenschouw of RVO, Projectenschouw TKI Energie en Industrie | Topsector Energie

7 Signatures

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on 2021-12-22 09:50:39

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