Final report

1.1 Project details

Project title	Hybrid Solar Panel
Project identification (program abbrev. and file)	EUDP journal nr. 64012-0155
Name of the programme which has funded the project	Energiteknologisk udvikling og demonstration
Project managing company/institution (name and address)	PeltPower (formerly PowerPipe) Storkevænget 14, DK 4653, Karise
Project partners	PeltPower – entire project DTU Byg – entire project DTU Energi – entire project LOKE – left project in July 2013 Batec – was declared bankrupt in December 2014 1st Mile – joined project April 2013, left in June 2014
CVR (central business register)	DK33864752 [PeltPower]
Date for submission	2012-03-06

1.2 Short description of project objective and results

The initial goal of project "Hybrid Solar Panel" was to develop a special version of a flat plate solar collector that would integrate thermoelectric generators (TEG) into a unit that would be able to supply a household with both hot water and electrical power. The expected project outcome was a hybrid solar panel that would produce hot water and electrical power with a payback time of less than 10 years when used in a single family home.

We designed, built and characterized a hybrid solar panel. It turned out that the mechanical construction of the hybrid solar panel was very complex due to difficulties associated with mounting the TEGs directly on the absorber in the solar collector and due to the required significant increase in absorber thickness compared to normal solar collectors. A higher absorber thickness will result in a significantly higher price for the solar collector. Furthermore, simulations showed that the efficiency of the hybrid solar collector was very low at operating temperatures required for optimal TEG performance.

The project was redefined to focus on a so-called hybrid heat exchanger (HHE), which would be able to convert the heat energy absorbed in the solar collector directly to electricity, but which did not have to be physically integrated with the solar collector. This would also allow the solar collector to operate at a higher efficiency. The HHE was designed, built and tested with good results.

Kort beskrivelse af projektets mål og resultater

Formålet med projektet Hybrid Solar Panel var at udvikle en speciel version af en plan solfanger med integrerede termoelektriske generatorer, således at produktionen af varmt brugsvand og vand til opvarmning kunne kombineres med en el-produktion. Det forventede resultat af projektet var en hybrid solfanger, der kunne producere varmt vand og elektricitet med en tilbagebetalingstid på højst 10 år, når enheden blev anvendt i et enfamilieshus.

Hybridsolfangeren blev udviklet, konstrueret og testet. Det viste sig, at den mekaniske konstruktion af hybridsolfangeren blev meget kompleks hovedsagelig på grund af problemer med montering af TEG'erne direkte på solfangerens absorber og på grund af behovet for en væsentlig større tykkelse af absorberen, hvilket vil fordyre solfangeren væsentligt. Desuden viste simulationer, at effektiviteten af solfangeren var meget lav ved den driftstemperartur, der var nødvendig for at opnå optimal ydelse fra TEG'erne.

Efterfølgende blev projektet redefineret til at udvikle, opbygge og teste en såkaldt hybrid varmeveksler, som ville kunne konvertere den absorberede varme i solfangeren direkte til elektricitet, men som samtidig ikke behøvede at være fysisk integreret i solfangeren. Hybrid varmeveksleren blev designet, konstrueret og testet med et godt resultat.

1.3 Executive summary

The idea in project "Hybrid Solar Panel" was to combine two commercially available products, i.e. a traditional flat plate solar collector and so-called thermoelectric generators (TEG) into a single unit capable of generating both hot water and electrical power. The target application for the system is a single-family house.

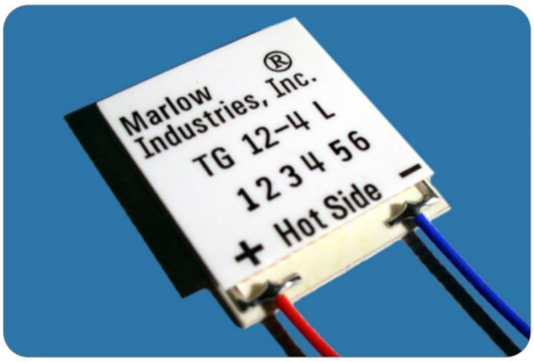

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Figure 1 The project idea is to combine thermoelectric generators and a solar collector into a so-called hybrid solar panel. The device to the left is a thermoelectric generator typically 40 x 40 mm. To the right three roof-mounted flat plate, solar collectors are shown. Dimensions are typically 1 x 2 m for each solar collector.

The original objective of the project was to design, build and test a hybrid solar panel system capable of generating heating and hot water along with electrical power.

It is assumed that the single-family house will have four hybrid solar panels mounted on the roof, each approx. 2 m^2.

Thermoelectric generators

Thermoelectric generators, TEGs, are devices that convert heat (temperature differences) directly into electrical energy, using a phenomenon called the Seebeck effect. Most commercially available devices use doped semiconductors made from bismuth telluride (Bi_2Te_3), lead telluride (PbTe), or combinations thereof, depending on temperature. These are solid-state devices with no moving parts. Due to their solid-state structure, the reliability is extremely high and the TEG itself has no need for maintenance. Typical efficiencies are around 5% for commercially available devices with a temperature difference of 200 °C, i.e. 5 % of the thermal energy in the heat is converted into electrical energy, when measured in the lab on a single device. When several TEGs are built into a larger system the typical overall efficiency is 2-3 %, due to thermal management issues.

TEGs are commercially available from several vendors today such as Marlow (www.marlow.com, US), MicroPelt (www.micropelt.com, DE) and Tecteg (www.tecteg.com, CA) .

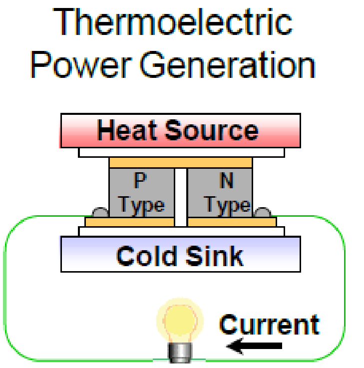
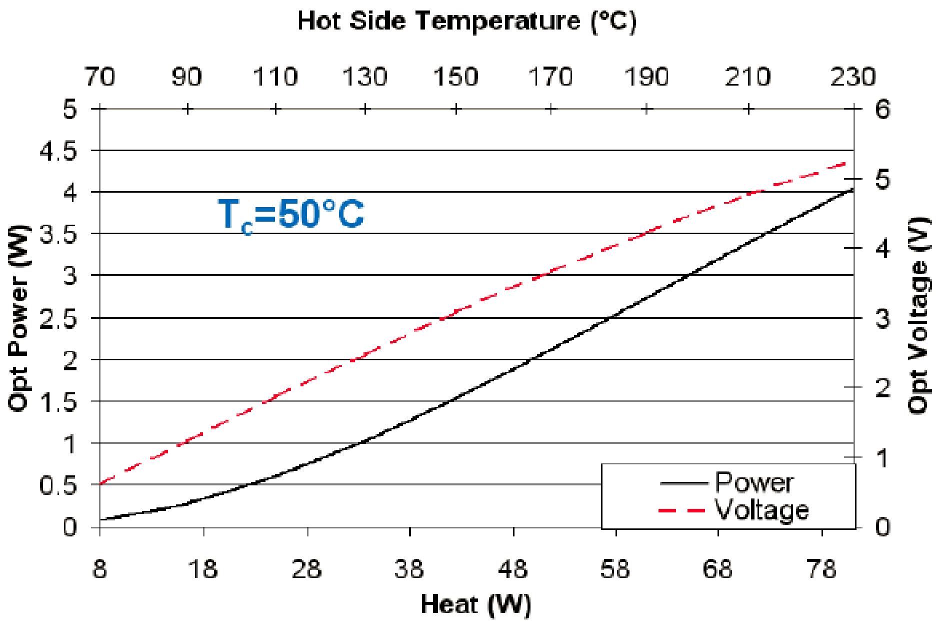


Figure 2 Thermoelectric generator. p- and n-type semiconductor pellets are connected in series and placed between two ceramic plates with a heat source on one side and a heat sink on the other side. The thermoelectric generator is based on the so-called Seebeck thermoelectric effect.

Most vendors use Bi_2Te_3 as the semiconductor material since this material is well characterized and show a very high stability with a lifetime expectancy in excess of 25 years. The Bi_2Te_3 -based TEGs have maximum operating temperatures below 250 °C. The TEG is able to produce electrical energy as long as there is a temperature difference between the 'hot side' and the 'cold side'. Typical maximum power for a 30 x 30 mm TEG is 4-5 W at a hot side temperature of 200 °C and a cold side temperature of 50 °C.



Figur 3 Output power (black) and voltage (red) from a TEG as a function of hot side temperature for a constant cold side temperature of 50 °C. For T_{hot} =70 °C and T_{cold} = 50 °C, the output power is almost 0 W compared to a maximum of 5 W at T_{hot} =230 °C and T_{cold}= 50 °C. Source Marlow 2015.

TEG elements require a high hot side temperature to produce maximum electrical power due to the relatively low efficiency of commercially available TEGs.

A number of very promising new thermoelectric materials are currently being studied for TEG applications. Examples from Fraunhofer and TU Wien are [9] and [10]:

- Half Heussler – max operating temperature ~ 550 °C; efficiency ~5 % (in lab)
- Skutterutides – max operating temperature ~ 500 °C; efficiency ~8-12 % (in lab)

For more details, see e.g. Refs. [3] and [10]. The most promising of these materials, skutterutides, have conversion efficiencies above 12% when tested in the laboratory.

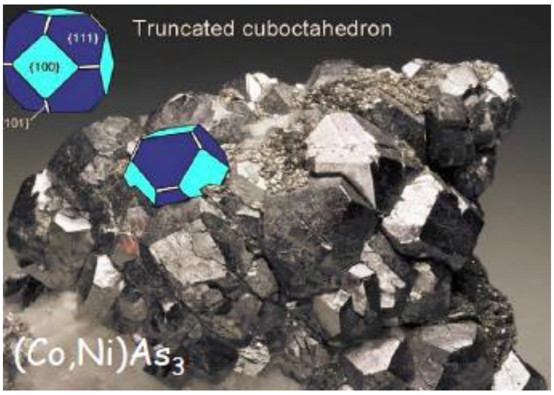


Figure 4 Skutterutide is a $CoAs_3$-based mineral (left) first mined in the Norwegian town of Skuterud in 1772. Originally used together with potash and quartz to form the cobalt blue pigment e.g. used for decoration of porcelain [10]. Skutterutide is available from mines in Norway, US, Canada and Morocco.

Great efforts are currently being made to investigate the industrial potential of new thermoelectric materials. In order to be useful for large-scale industrial applications, the materials must have the following properties:

- Available in large volumes
- Reasonable raw material prices, e.g. less than 50 USD/kg
- Non-toxic – current TE-materials often contain toxic elements such as Pb og Te
- Mechanical and thermal stability
- Long lifetime and long MTBF

Solar collectors

Solar thermal energy is generated from light and heat radiation from the sun. Each year the Earth receives many times more energy than all the people in the world can consume, and more than the total energy reserves on earth. The sun irradiates 174 PW (peta watts) or approx. 8,000 times more energy to the Earth's surface than the total human need for energy. Approximately 30% of the solar energy is reflected back into space while 70% is absorbed by clouds, oceans and land surfaces. The solar irradiance just above the atmosphere is 1400 W/m² at maximum. The solar energy at the Earth's surface depends on the location and number of hours with sunshine in the form of clear weather without clouds, also named sunshine hours.

In Europe, the maximum solar irradiance is around 1000 W/m² in summer, 800 Watt/m² in spring and autumn equinox, and 600 W/m² at the winter solstice. The annual solar radiation on horizontal in Europe varies from ca. 700 kWh/m² in the north to 1900 kWh/m² in the south. Modern flat plate solar collectors can utilize up to 90% of this solar energy in contrast to solar cells that typically utilize around 15% of the received solar energy.

Solar collectors convert the solar energy into heat in the form of hot water whereas photovoltaic solar cells convert solar energy directly into electrical energy, but at a significantly lower conversion efficiency.

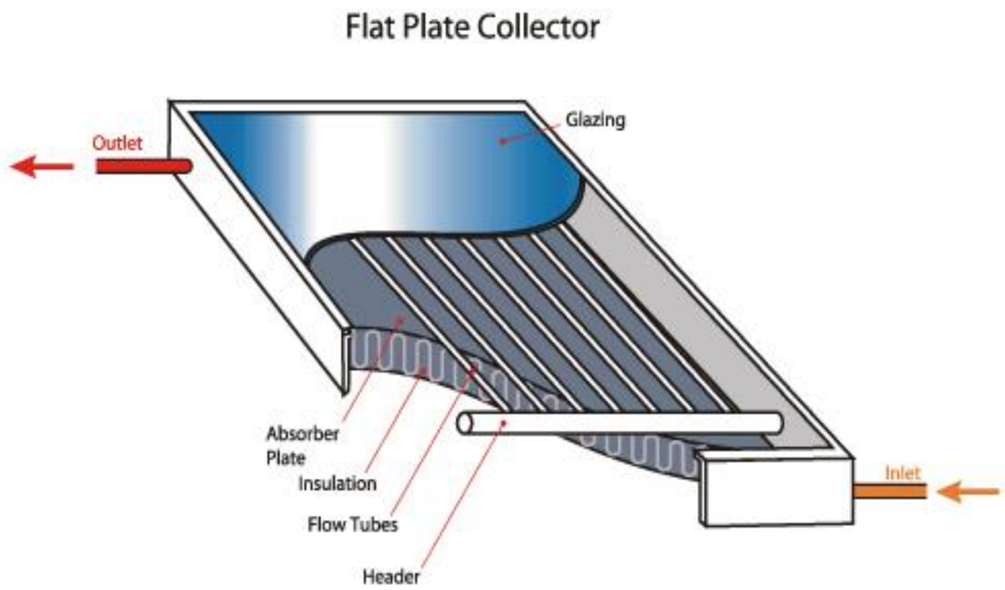


Figure 5 Design of a flat plate solar collector as manufactured by one of the partners in the project. Typical operating temperatures for a flat plate solar collector is 40 - 60 °C measured as the mean temperature between inlet and outlet when the solar collector is used for heating and hot water generation.

Market for TEG based products

Until today, the use of TEG-based power generators has mainly been limited to military applications and remote wireless sensors, as illustrated below. The sensors provide temperature or pressure measurements typically from locations where it is difficult to install a connection to electrical power from the grid. The data from the sensor are transferred via a wireless connection. The sensor including the radio transmitter is powered by a TEG taking advantage of a temperature difference typically between the measured object and ambient.

Figure 6 Wireless sensors powered by TEGs. Logimesh's vibration sensor and ABB's temperature sensor. Both products are commercially available today.

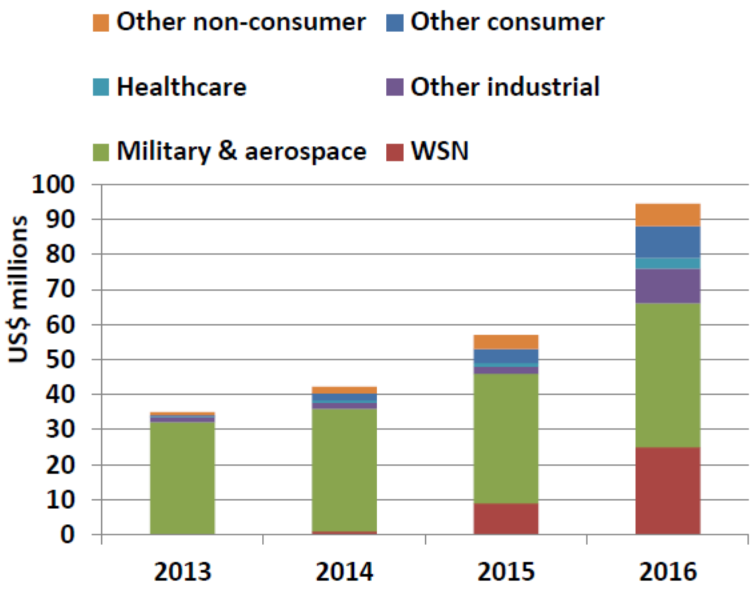


Figure 7 Market for TEG based products. As seen from the diagram, military and aerospace applications clearly dominates the market in these years. However, the market for wireless sensor networks (WSN) shows a very rapid projected growth along with 'other industrial applications'. Source IDTech 2014

In the automobile industry, great efforts are being spent on developing TEG-based systems that utilizes waste energy in the exhaust gas from combustion engines. Typically, a combustion engine utilizes around 30% of the energy available in the fuel to actually move the car [7]. The remaining energy is wasted as heat either in the exhaust gas or in the cooler. It is the hope that TEG-based energy harvesting from exhaust gas will become economically viable from around 2020 [11].

The more expensive it is to buy and transport fuel to a certain location, the better the business case for TEG-based solutions will be. As an extreme example, the US Army explains that the so-called "totally burdened cost" of delivering fuel into combat zones in e.g. Afghanistan could be higher than 100 USD/litre compared to a typical street cost of 1 USD/litre [12]. In such a scenario, the use of TEG-based generators to reduce fuel consumption will make a lot of sense.

High power niche applications
Most TEG based power supplies only generate limited amounts of energy, however, a few examples of TEG-based power generation at higher power levels have been indentified during the project.

The first example is Gentherm's 500 W power supply for remote locations. The system uses natural gas or propane burners to heat the hot side of the TEGs and cooling to the ambient on the cold side, see photo below. Each unit generates 500 W using 48 m^3 of natural gas or 76 litres of propane per day. Source: Gentherm model 8550 data sheet. Thermal energy in 48 m^3 natural gas corresponds to approx. 480 kWh equivalent to 20 kW - 24 hours/day. Gentherm's power supply converts 20 kW thermal power into 500 W electrical power, i.e. a conversion efficiency of 2.5%, which is pretty much state-of-the-art with Bi_2Te_3-based TEGs.

Figure 8 Gentherm power supply used e.g. for telecom radio link repeaters at remote locations, e.g. mountain tops, without access to the power grid. The photo shows a 2 kW system with four units each generating 500 W electrical power.

Recently, a California based company, Alphabet Energy, introduced a high power, waste heat recovery system that converts the energy in exhaust gas to electrical power. Typical applications are waste heat recovery from high power diesel generators. Alphabet Energy was founded in 2009 and has until 2014 raised more than 30 MUSD in venture capital investment. Currently the company has 23 employees (Source Wikipedia) and one product, the E1. When used together with a 1,000 kWe diesel generator, the E1 is able to produce additionally 25 kWe utilizing the waste heat from the exhaust gas. For applications in the oil and mining industry at remote locations, this 2.5% improvement is considered very valuable. Alphabet Energy claims a payback time of 18 to 36 months for the E1. This is most likely for remote mining locations where the cost of delivered diesel is significantly above the typical price of approx. 1 USD/litre.

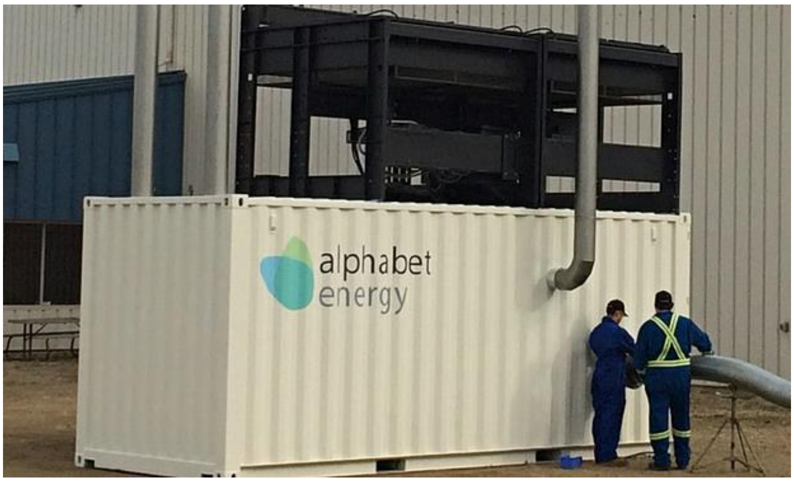


Figure 9 The Alphabet Energy's E1 25kWe thermoelectric generator is housed in a standard shipping container, 16 or 20 feet long.

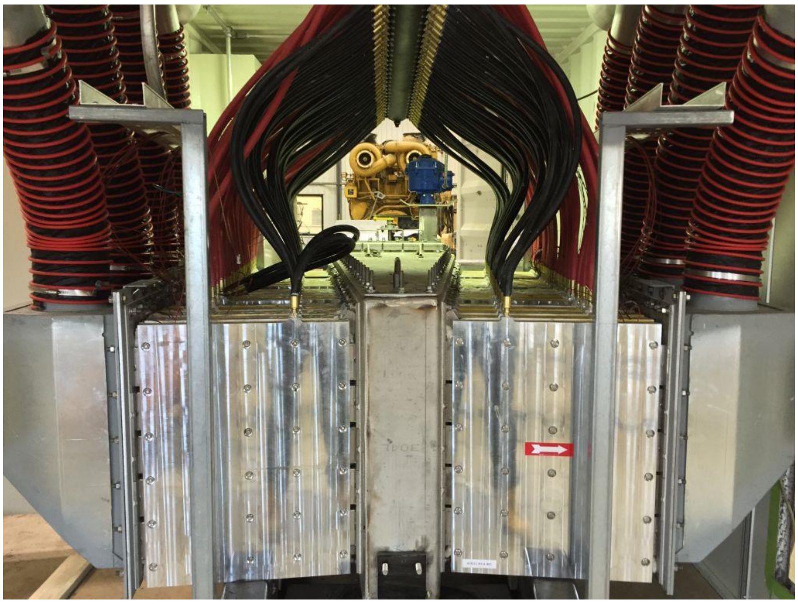


Figure 10 Inside the container, the exhaust gas is lead through an array of so-called Power Modules with thermoelectric generators via the large hoses seen at left and right side of the photo. The Power Modules are cooled by water in the smaller red and black hoses connected to a cooling water manifold centrally in the top of the photo.

Automotive applications

A major future application for TEGs could be waste heat recovery from automotive engine exhaust gasses. Only around 30 % of the energy in the fuel of a car is used to actually move the car. The remaining approx. 70 % is lost primarily in the exhaust gas and in the cooler [7].

Continued efforts to improve fuel efficiency of cars has led to the idea of converting some of the waste heat from the exhaust gas into electrical energy using TEGs. The idea is to let the exhaust gas heat the hot side of a TEG to 300 – 400 ºC and let the existing cooling system in the car keep the cold side at around 90 ºC. Several car manufacturers are currently developing solutions for this, however the technology must be further improved and cost optimized before large-scale deployment takes place. Toyota has estimated that a 2% improvement in fuel efficiency can be achieved when the conversion efficiency of the TEGs reach around 7% compared to today's results of around 2%. [7]

Figure 11 Exhaust gas heat exchanger. The exhaust gas passes through channels in close thermal contact with the TEG's hot side. Cooling water passes through channels in close thermal contact with the TEG's cold side. From [8].

Figure 12 The company GMZ Energy is leading a consortium who has a contract with US Dept. of Energy to develop a 200 W TEG for integration into a Honda Accord (left) and a 1 kW TEG for integration into a so-called Bradley Fighting Vehicle (right) [8].

Hybrid Solar Panel Project

During the first part of this project, a hybrid solar panel was constructed and characterized. The TEGs were mounted directly on the absorber plate in the solar collector in order to obtain a hot side temperature as high as possible – typically 150 – 200 °C. The project faced severe difficulties managing the thermal expansion of the solar collector and at the same time obtaining a good thermal contact to the TEGs.

In order to obtain the maximum electrical output power from each TEG of 5 W, a thermal flow of up to 100 W through each TEG is required. For a solar irradiance of 1,000 W/m^2, each TEG should collect energy from 0.1 m^2 of the absorber. It turned out, that the normal absorber plate in the solar collector was too thin to conduct the heat from this relatively large area without a significant temperature drop due to the thermal resistance in the absorber. For this reason, the absorber plate thickness had to be increased significantly, resulting in a significantly higher cost of the solar collector. One of the assumptions made at the beginning of the project was that a standard commercially available solar collector could be used. This assumption turned out to be wrong.

Theoretical calculations were carried out to compare various types of solar collectors, i.e. traditional flat plate collectors, evacuated tube collectors and more sophisticated concentrated tracking collectors [2]. The calculations illustrated that a flat plate solar collector could not generate sufficient thermal output at temperatures optimal for the TEGs. Flat plate solar collectors are optimal for hot water production at 50-70 °C, but their efficiency degrades rapidly as the operating temperature increases above 100 °C. Commercially available TEGs have maximum efficiency for a hot side temperature around 200 °C. A flat plate solar collector with an outlet temperature of 200 °C will have a very low efficiency.

Other types of solar collectors may be used, see the figure below. The investigation of such collectors in combination with TEGs may be investigated in a future project.

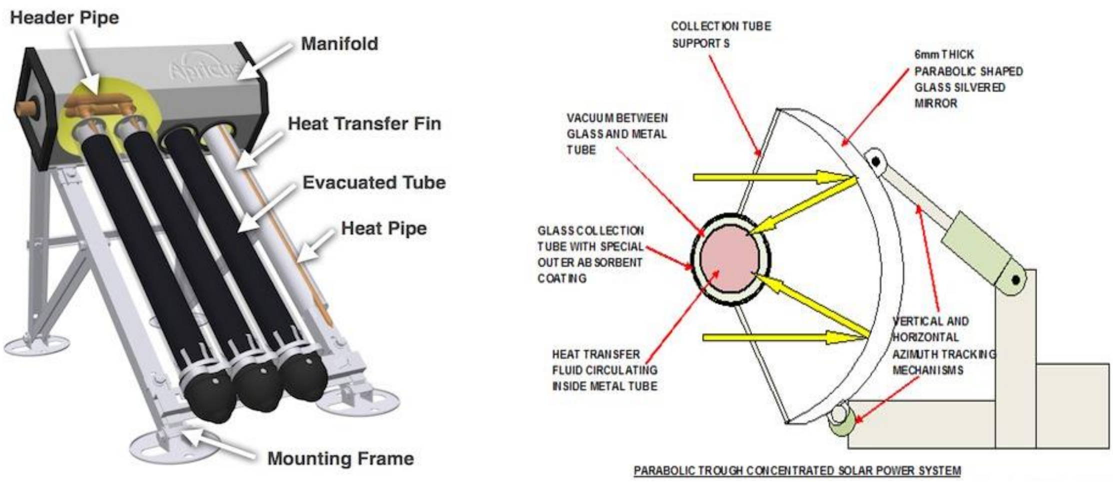


Figure 13 Various types of advanced solar collectors: Evacuated tube and concentrated tracking solar collectors. These collectors typically operates at a much higher temperature than flat plate collectors, making them better suited for combinations with TEGs.

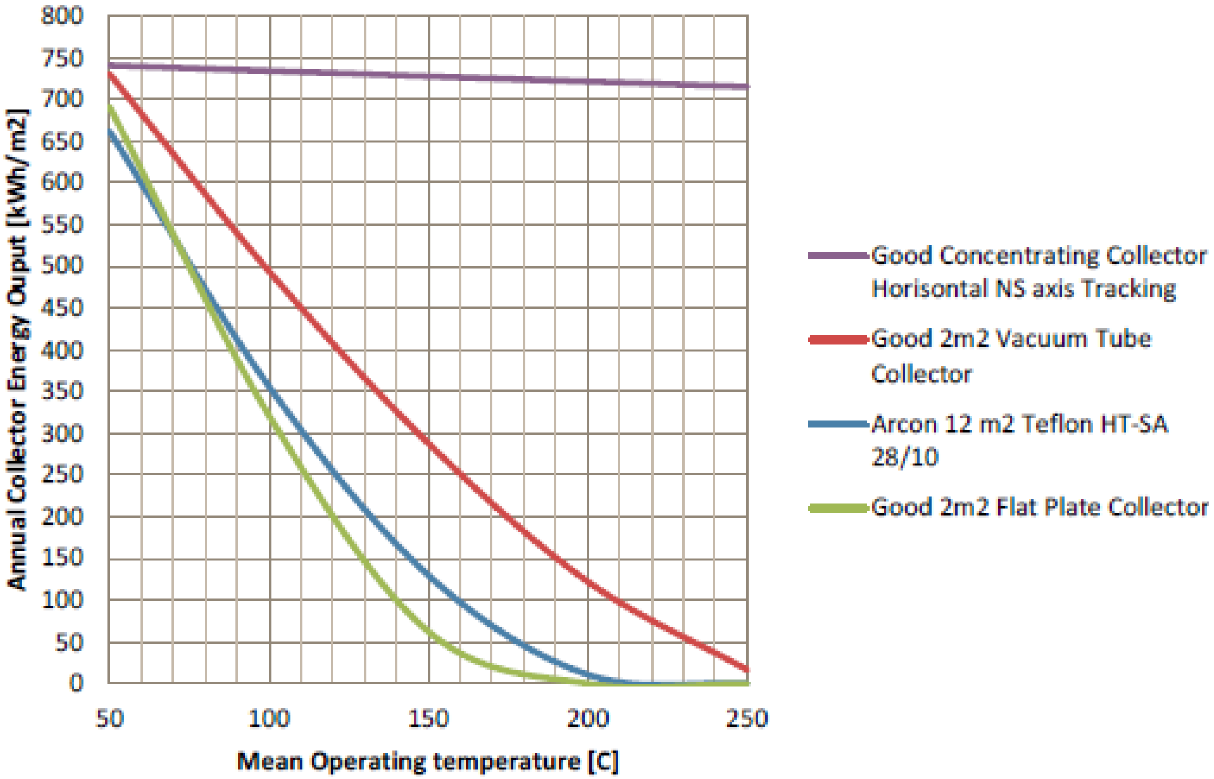


Figure 14 Thermal energy produced by various types of solar collectors as a function of the mean operating temperature, i.e. the average temperature between input and output flow. As seen from the figure, the Tracking Concentrated Collector (purple line) is almost insensitive to the mean operating temperature, making this type of solar collector potentially much better for use in combination with TEGs[2]

The overall result of the theoretical calculations was that the hybrid solar panel based on a flat plate solar collector could not live up to the goals for the project. This was due to several factors, mainly the lack of sufficient thermal energy produced by the flat plate solar collector at temperatures where the TEGs could generate electrical power at a reasonable level.

Alternatively, so-called Evacuated Tube Collectors or even better Concentrated Tracking Collectors may be used. Due to the mechanical construction of these collectors, it will be virtually impossible to mount TEGs directly on the solar collectors to obtain a direct coupling of energy from the solar collector to the TEG. In this case, the TEGs must be separated from the solar collector and heat transferred indirectly e.g. using a heat exchanger with the TEGs placed between the hot and the cold side.

As a consequence of the above results, it was decided to separate the solar collector and the thermoelectric generators in the second part of the project. The project was redefined, and the objectives changed to design and characterization of a so-called hybrid heat exchanger (HHE) with TEGs inserted between the hot and the cold side. The HHE will be able to operate with various heat sources, including solar collectors, but will be a stand-alone physical system.

A small scale HHE was built to test the concept as well as to understand how to optimize a large scale HHE. Following successful demonstration and testing of the small device for a range of different parameters, an optimized large scale HHE was constructed and tested. Testing of this large-scale device demonstrated that that it was possible to generate electrical power of around 200 W from a heat source with a temperature of around 200 ^{o}C with a TEG efficiency of 4 %. Estimated manufacturing cost at today's price level is around 2.0 EUR/W. Since no maintenance is required during the lifetime of the system, this corresponds to a production cost of electricity of around 0.02 EUR/kWh assuming 10 years lifetime.

1.4 Project objectives

It was the overall goal of the Hybrid Solar Panel project to develop and demonstrate a hybrid solar panel that would integrate the properties of solar panels (hot water production) and thermoelectric generators (electrical power production), and thereby be able to supply a household with water for heating as well as consumption and electrical power.

The successful project should deliver a hybrid solar panel on 2,2 m2 that would be able to produce hot water and electrical power. The hybrid solar panel would have with a payback time less than 10 years.

The objective of the Hybrid Solar Panel project is to integrate the thermoelectric generators (TEGs) together with hot water producing solar panels. TEG cells use the excess heat from the solar panels, that otherwise would be wasted, to produce electrical power. In this way, each household will have solar panels on the roof that make hot water for domestic use and heating. When the demand for hot water in the house is met, the TEGs in the same panels will start producing electricity using the solar heat.

As previously discussed in this report, it turned out that the original objectives could not be met, and the project was redefined to design and test a so-called hybrid heat exchanger capable of utilizing excess heat from several sources.

1.5 Project results and dissemination of results

The technical results are presented in five experimental reports, attached as appendices to this report. A summary of these reports are presented here. The first main activity in the project was the building and testing of a solar collector with thermoelectric generators (TEGs) attached directly on the backside of the solar absorber. A major challenge was to obtain a robust mechanical construction, particularly when interfacing the cooling circuit to the cold side of the TEGs using a very efficient Danfoss cooling module called ShowerPower.

Figure 13 Details of the H1 hybrid solar collector. Picture to the left shows TEGs mounted directly on the back-side of the solar absorber using Danfoss ShowerPower modules. Picture to the right shows the interconnection of the cooling circuit to the ShowerPower modules.

Following construction, the prototype, termed the H1, was tested at an in-door solar simulator facility at DTU Byg. The testing took place over three days in January, 2014. The H1 contained numerous different solar collector panels, in order to determine the best design for a collector with TEGs. The H1, mounted on the test rig at DTU Byg is shown in the image to the right. The maximum power generation measured was 0.5 W per TEG, for the best collector material.

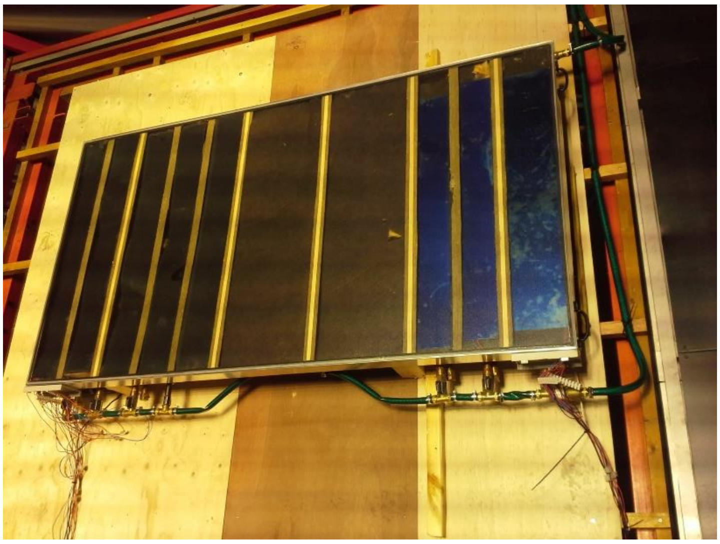


Figure 14 The H1 hybrid solar collector being tested at DTU Byg's solar simulator in January 2014.

Several practical problems and design issues were identified during the H1 test. One of the main results was that it would not be possible to base a hybrid solar panel on a standard solar collector, as the collector plates are too thin to conduct the necessary heat to the TEGs. The large difference in thermal expansion between the hot and the cold sides was another important finding. Due to the thermal expansion, the absorber plate showed significant bending which increased the collector heat losses at high temperatures.

The results of the experiments conducted on the H1 was afterwards discussed and evaluated internally among the project partners. The results showed that substantial power could only be produced if non-standard collector plates, with a much greater thickness than normally used, were used for the construction of the collector. This, combined with the difficult process of constructing the solar collector with TEGs, lead to the idea of directly integrating the TEGs onto the back of the collector plates to be abandoned.
The project chose instead to focus on designing a device that would be able to generate electricity from the hot fluid (typically oil) heated by the solar collector, instead of directly mounting the TEG on the collector plates. This also had the additional benefit that such a device could be adapted to any source of (waste) heat. A small-scale prototype of this device, called the Hybrid Heat Exchanger (HHE), was constructed.

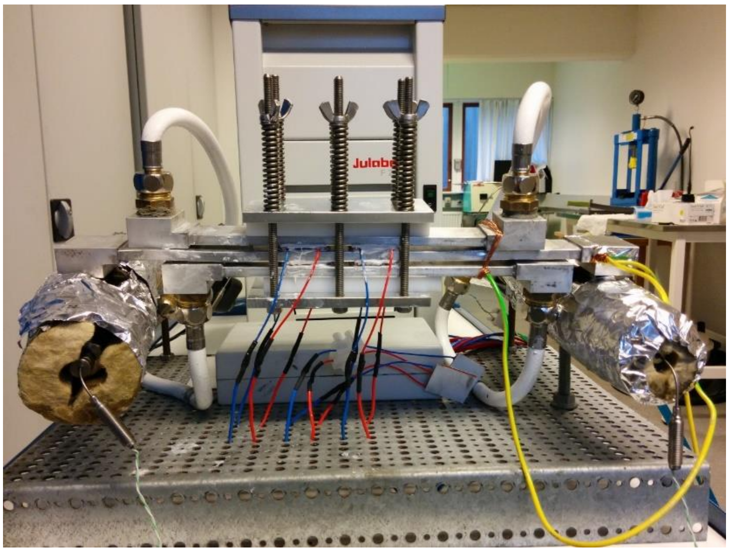


Figure 15 Scale model of HHE during test at DTU Energy, Risø in December 2014. The photo shows the two contra-directional flows with TEGs inserted in the middle.

The design of the HHE was based on a hot and a cold flow in rectangular aluminium tubes with the TEGs placed between the hot tube and the cold tube. Initial testing used contra-directional flows, however the final design was a layered structure with parallel tubes with hot and cold flows perpendicular to each other with TEGs placed at the cross-points.

Following design and construction, the small-scale HHE was tested at DTU Energy. The scientific test determined the power producing capabilities of the device as function of fluid temperature, fluid type and thermal interface material. The device was shown to produce 2 W per TEG at the highest temperature span, i.e. 200 °C hot liquid. A subsequent larger prototype with a total of 100 TEGs was constructed and afterwards tested at DTU Energy and was shown to perform exactly as a scaled version of the smaller HHE. The maximum generated power produced in the large-scale HHE was 130 W, as only a specific type of heat transfer fluid with a lower maximum temperature of 150 °C was used. Had the same fluid been used as in the smaller HHE, 200 W would have been produced,
The full technical details of the performance of the device can be found in the three experimental reports describing the experiments in detail. Additional information can also be found in the scientific articles describing the experiments.

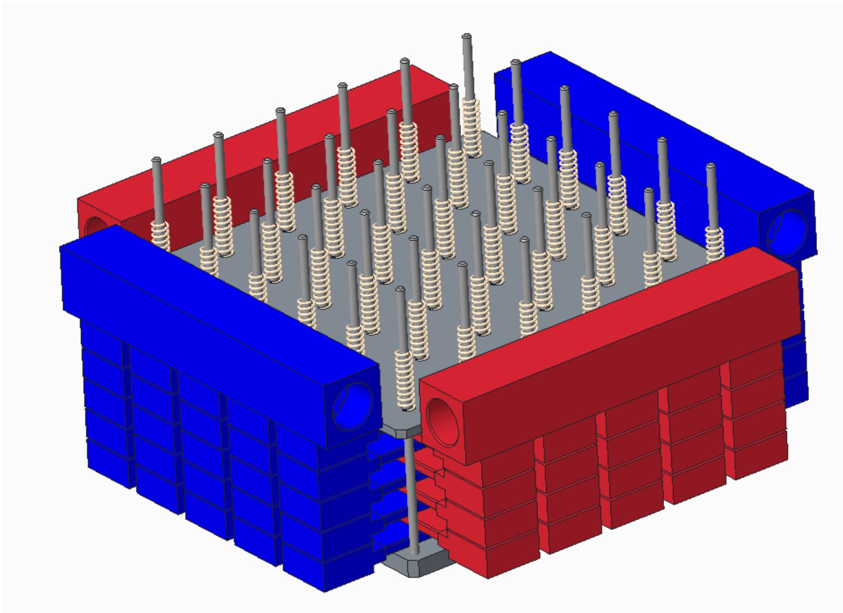


Figure 16 HHE design. Cold side is blue and hot side is red. TEGs are placed at the intersection between the hot side and cold side rectangular tubes. Spring loading secures a good thermal contact between the tubes and the TEGs.

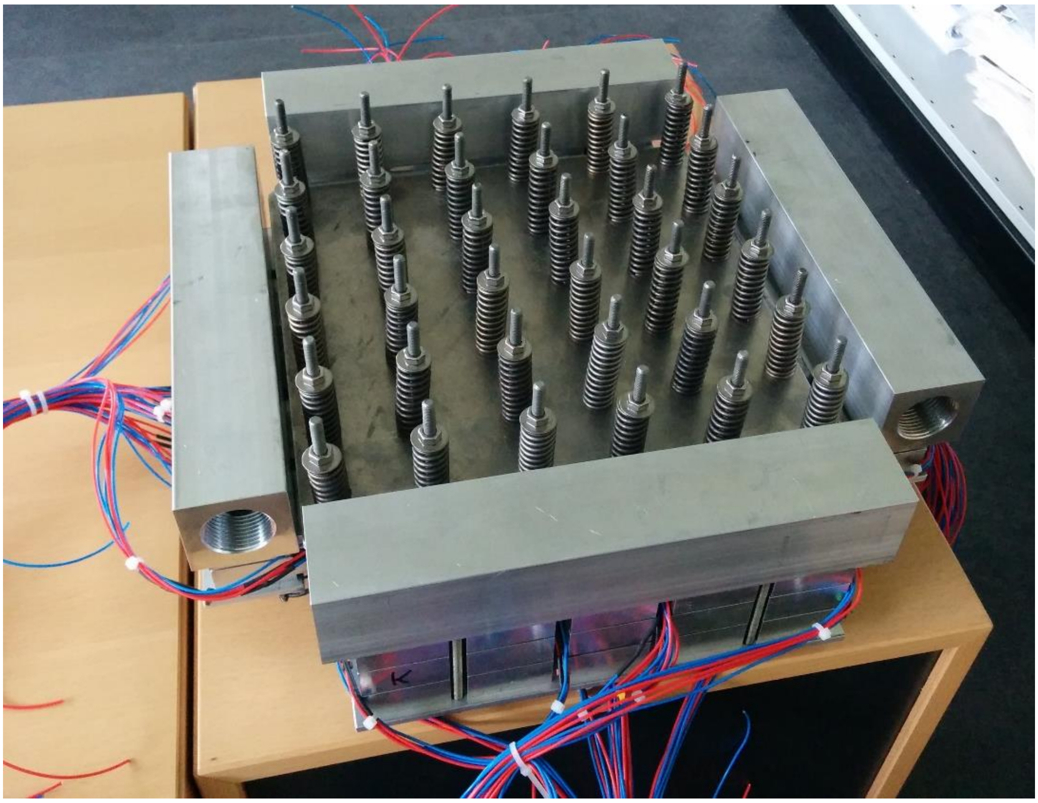


Figure 17 Final HHE mechanical assembly with TEGs mounted. Vertical clamping rods with spring load will maintain a good thermal contact between the aluminum tubes and the TEGs.

Dissemination

The project results has been disseminated through two scientific articles, which are currently being submitted to an international peer-reviewed scientific journal. Once they have gone through the peer-review process, which usually takes over several months, and if they are accepted for publication, the articles will be available to the scientific community. The results have also been presented at the combined International and European Conference on Thermoelectrics 2015 (ICT & ECT 2015) in Dresden, as an oral presentation. Participants to the conference include both members of the scientific community, as well as members from industry.

Specific reports and articles:

- Report: "H1 Experimental Report", DTU Energy, 2014
- Report: "Annual solar collector energy output at TEG high temperature levels", SR 15-01, DTU Byg, 2015
- Report: "HHE Experimental Report – Powerpipe", DTU Energy, 2015
- Report: "HHE Experimental Report 2, DTU Energy", 2015.
- Report: "HHE Experimental Report 3, DTU Energy", 2015.
- Article: "An experimental power generating heat exchanger based on thermoelectric generators", to be submitted to Journal of Power Sources, 2015.

1.6 Utilization of project results

The overall conclusion from the project is that a hybrid solar panel as tested during the first part of the project is currently not economically viable. Nevertheless, PeltPower has filed two patent applications during the project and the company will pursue business opportunities based on the developed hybrid heat exchanger that may be used for a variety of waste heat recovery applications.

PeltPowers improved understanding of TEG-based power supplies has resulted in the development of a power supply for chimney ventilators powered by the thermal energy in the smoke inside the chimney.

Regarding the scientific perspective, the results obtained in this project, could easily be further developed and investigated, with the goal of obtaining a device with increased efficiency. There are numerous aspects of the design of the prototype that would be of interest to investigate further, such as the optimal design of the flow channels, the optimal thermal interface material between the TEGs and the pipes, and the optimal way to design the electrical circuit. It would also be of great interest to investigate the optimal way to cool the TEGs, as this is a problem for almost all applications involving TEGs. Finally, investigating in a more general sense the possibilities and limitations of using TEGs in combination with solar energy systems would also be of great interest. Some of these aspects will be pursued in future applications to e.g. the Danish Council for Independent Research, but the focus of the applications will be the scientific gain of knowledge and not the commercialization of a prototype.

Regarding energy policy, the project focus on converting waste heat directly into electricity will result in a larger energy efficiency and thus be directly in line with current energy policies. Waste heat from various processes, both industrial and automotive, will always be present and is at present in most cases released directly into the atmosphere. While the efficiency of the current prototype produced in this project is not high, even converting just a small percentage of this waste heat into electricity will result in a significant electricity production, and thus a higher overall energy efficiency.

1.7 Project conclusion and perspective

Overall conclusions

- Today thermoelectric generators, TEGs, based on Bi_2Te_3 is a mature technology
- The use of TEG-based power generation has the following advantages:
  - Reasonable first installed cost today, significant cost reductions in future
  - No maintenance required and no noise emitted (acoustic or electrical)
  - Pure solid-state solution – very high reliability, long lifetime
  - Very scalable from kW to mW
- The main disadvantage of using TEGs is the low conversion efficiency in practical systems based on Bi_2Te_3 TEGs, which is typically around 2-3 %.
- New thermoelectric materials becoming commercially available in 3-6 years have the potential to at least double and potentially triple the conversion efficiency.
- Currently TEGs are mostly used for low power applications, e.g. wireless sensors.
- A few high power systems are commercially available. These systems are currently economically viable for remote locations without access to the power grid.
- Current cost for TEGs is around 2 USD/W and 1-2 USD/W for the remaining system.
- A TEG cost of around 1 USD/W is expected in 2020. At this point, the use of TEGs for automotive applications is expected to reach a break-through.
- By 2020, TEG based waste heat recovery systems has the potential to generate electrical power at a very competitive cost of approx. € 2-3 cent/kWh in a situation, where the waste heat is available for free and where there is easy access to cooling, e.g. using sea or ground water or ambient air.

The project has produced the following main results:

1) Participants in the project has gained a solid insight into the state-of-the-art of TEG-based systems including the solution of many practical challenges. This knowledge will be essential in designing next generation of TEG-based systems with new thermoelectric materials such as Skutterutides.
2) It is not optimal to place thermoelectric generators directly on the absorber of a flat plate solar collector. Excess energy should be harvested in a heat exchanger.
3) A general-purpose heat exchanger with thermoelectric power generators placed between a cold flow and a hot flow has been designed, developed and tested. This so-called hybrid heat exchanger is able to generate an electrical net output power of approx. 200 W in the case where the hot flow is 200 ^oC and the cold flow is 20 ^oC.
4) In practical systems with a hot side temperature of less than 200 ^oC, a typical efficiency of TEG-based power generation will be around 2-3 %.
5) During the project period, new technologies have been commercialized, specifically ORC (organic rankine cycle) that currently seems to have a good potential for large scale energy harvesting. ORCs from Viking Development Group are currently tested with indications of a first installed cost of around 2 kEUR/kW and a cost of electricity of 0.04 – 0.14 EUR/kWh. The efficiency of ORC based electricity generation from waste heat at 200 ^oC is around 10 %.
6) During the project period, thermoelectric material performance has been improved to a level where 12 % efficiency can now be obtained in the laboratory.

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Annex

Links and references

Relevant links

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