A Biomass-Fuel based Micro-Scale CHP System with Thermoelectric Generators

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ABSTRACT: Pellet burners need auxiliary electrical power to provide CO_2-balanced heat in a comfortable and environment-friendly way. The idea is to produce this and some extra electricity within the device in order to save resources and to gain operation reliability and independency. An option for micro-scale CHP is the usage of thermoelectric generators (TEGs). They allow direct conversion of heat into electrical power. They have the advantage of a long maintenance-free durability and noiseless operation without moving parts or any working fluid. The useful heat remains almost unaffected and can still be used for heating. Therefore TEGs are predestined for the use in micro-scale CHP based on solid biomass. In this paper the first results from a fully integrated prototype are presented. The performance of the TEG was observed for different loads and operating conditions in order to realise an optimised micro-scale CHP based on solid biomass.
Key Words: combined heat and power generation (CHP), stand-alone systems, solid biofuels

1 INTRODUCTION

1.1 Background

In the last years small-scale pellet boilers and pellet stoves had their breakthrough in many European countries. They provide CO_2-balanced heat in a comfortable and environment-friendly way [1], [2]. The European Union demands an increased utilisation of biomass as energy source in order to reduce the emission of green house gases and the import of non-renewable energy sources [3]. Combined heat and power generation has the advantage of avoiding waste heat from electricity production. For Austria there is the greatest potential for new CHP systems at small and micro scale plants [4]. A tremendous amount of heat capacity is nowadays used for room heating or supply of hot water in small scale systems, e.g. in Austria about 50-70 PJ firewood and wood chips for private consumers each year [5]. A high potential for saving resources can be realised if a part of this heat could be refined into electricity. Therefore, there are intensive activities going on in order to develop small- and micro-scale combined heat and power generation plants, e.g. using the Stirling technology [6] or externally heated micro-turbines [7]. Thermoelectric Generators are an alternative for special applications.

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1.2 Aims and Scope

Automatically running biomass furnaces need for operation some auxiliary electrical power. The idea is to produce this and some extra electricity within the system in order to gain operation reliability and independency and to save resources. For small-scale applications based on solid biomass we identified thermoelectric power generation as a promising technology because it allows a very simple assembly.

Our Investigations about the basics of thermoelectric power generation and the combination with biomass furnaces were followed by first experiments with TEGs in biomass furnaces to validate theoretical considerations [8]. Based on this work the next step was the construction, erection and start-up of a fully integrated prototype of a biomass furnace with TEG. The prototype should allow both state-of-the art combustion with low emissions and a maximum of thermoelectric power production. The performance of the prototype during the first experiments is reported in this paper.

Two main types of products are possible with this technology: The basic system will allow grid-independent operation of automatically running biomass furnaces including fuel delivery from storage and circulation of the heating water. The advanced system will also provide electricity for network supply or other electrical devices as an additional benefit. For grid independent operation not only the production of electricity but also self consumption of the furnace – especially at start-up – is important. Therefore we performed analyses and optimisation of the electrical components and balanced production and consumption of the furnace during operation. For network supply we were searching for operating points with maximum power production.

1.3 Thermoelectric Power Generation

Thermoelectric generators (TEGs) allow the direct conversion of heat into electrical power [9] (principle see figure 1). The TEG receives heat at high temperature and delivers heat at a lower temperature while generating electricity. TEGs can be interpreted as intelligent heat exchangers which refine some of the exchanged heat into electricity. No working fluids or moving parts are necessary, therefore TEGs operate even soundlessly. One can expect maintenance-free long life durability. State of the art materials can convert a maximum of 5-6% of the useful heat into electricity, new materials promise 10% and more [10]. Until now TEGs were only used for certain niche applications especially due to their relatively high price. New applications with higher lot size will result in lower costs.

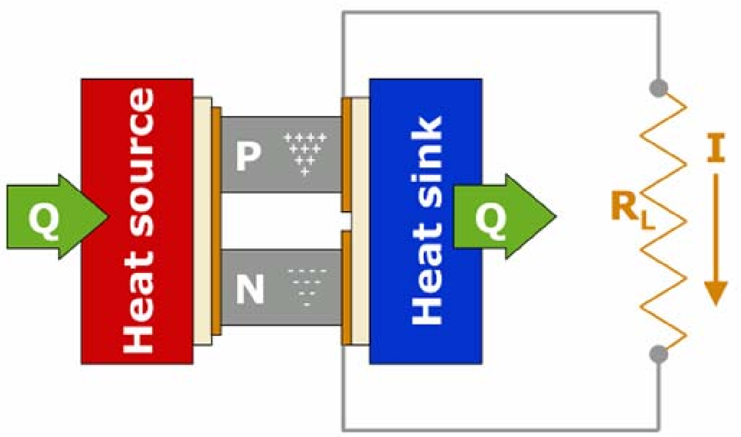

Figure 1. Principle of Thermoelectric Generation (Q..heat flux, R_L..electrical load, I..current, P/N..p-/n-doped semiconductor)

1.4 System integration

The electrical performance of a biomass-fuel based micro-scale CHP system with thermoelectric generators depends on two main factors: On the one hand the efficiency of the TEGs – hence the efficiency of thermoelectric materials – is important. On the other hand the amount and the temperature level of heat which can be transferred to the TEG determine the possible electrical power output. Pellet burners reach combustion temperatures up to 1200°C. The heat exchanger for the TEG has to be constructed properly in order to reach very high heat transfer rates and high as well as constant surface temperatures without disturbing combustion. The total efficiency of the micro-scale CHP is the same with or without TEG (energy balance see figure 2). The difference is that a part of the provided energy is converted into electricity. The remaining heat can still be used for heating. The user of such a system will notice only increased comfort and security of supply.

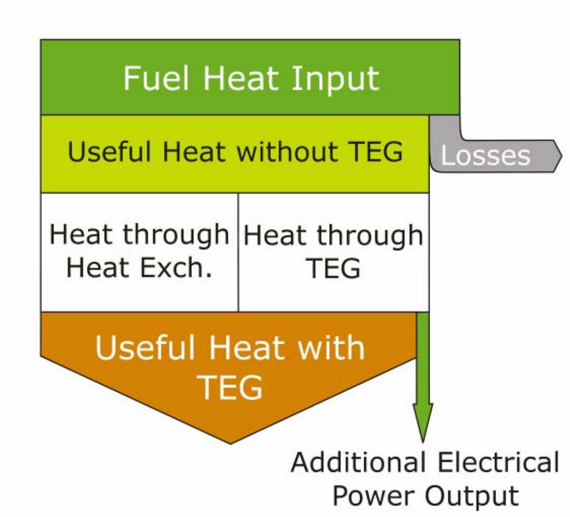

Figure 2. Energy Balance of a Pellet Boiler with TEG

2 EXPERIMENTAL

2.1 Construction of the Prototype

The prototype had to meet many demands; certain specifications determined the possible performance. The main aim was to realise a micro-CHP system with a TEG fired with biomass in order to prove the theoretically calculated potential for this technology. For this purpose TEG and furnace had to be fully integrated. We calculated and balanced the expected heat flows from the furnace through the heat exchanger to the TEG in order to optimise the total heat transfer.

The prototype was designed to reach the theoretically possible electrical efficiency of 2%. This efficiency can be reached if about 50% of the available heat streams through the TEG and the efficiency of the TEG is 4%. This value is lower than the 5-6% from paragraph 1.2 due to the operating conditions of the TEG in the system: The hot side temperature cannot be held constant at the allowed maximum of 250°C because of temperature fluctuations. Overheating would destroy the thermoelectric material has to be avoided strictly. The cold side temperature is higher than best for the TEG in order to reach more than 50°C in the cooling water of the TEG which will be heating water in commercialised systems.

To save costs and time we used basic components from an existing furnace, the SHT Vision Comfort EKA 12. The furnace was cut horizontally in order to integrate burner and TEG with short distances (furnace see figure 3). In the prototype the flame is not visible any more. We only used wooden pellets for combustion. The fuel heat input is possible in the range from 4 to 13kW; the nominal power of the prototype is 10kW. With regard to grid independent operation we changed the electrical components from 230V alternating current to 12V direct current.

Figure 3. SHT Vision Comfort EKA 12 – commercially available (left) and cut for the prototype (right)

The provided TEG has a nominal power of 200W. It consists of 16 thermoelectric modules (see figure 4, left) which are connected electrically in series and are arranged in two rings situated one on top of the other. So the TEG forms an octagonal (almost round) tube which is heated by the flame and hot gas from the inside and cooled from the outside (see figure 4, right). The thermoelectric modules consist of Bismuth-Telluride which is commercially available and usually used for thermoelectric cooling at ambient temperatures.

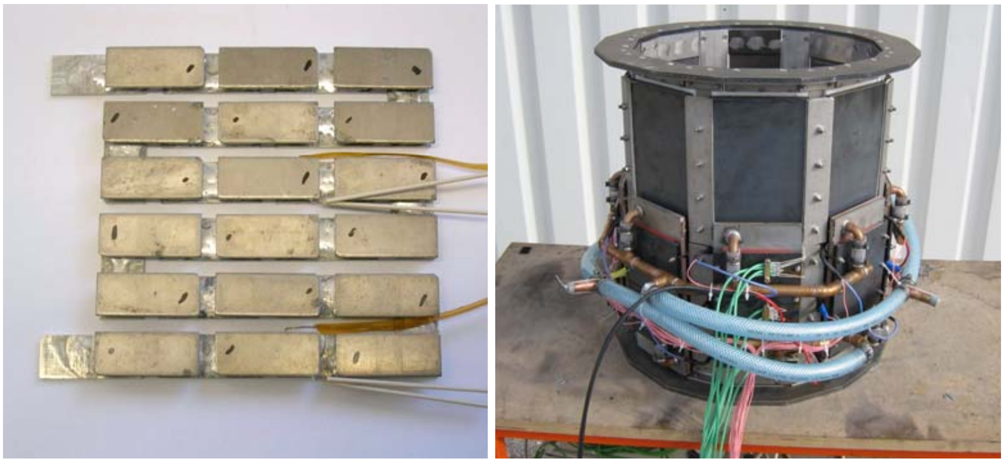

Figure 4. TE-Module and TEG of the prototype

The flue gas leaving the TEG is not used for heating any more in the prototype. It is a basic task to design a heat exchanger to reach a high thermal efficiency of the system. In commercial systems this heat will also be used.

2.2 Operation of the Prototype

In the first 10 days of operation the prototype was running for almost 50 hours. We measured several important heat streams, currents and voltages, temperatures of the flue gas, heat exchanger and the TEG as well as the excess air and CO-emissions in the flue gas. After successful start up we varied some parameters in order to optimise the systems performance. The main variations concerned the fuel heat input, the temperature and flow rate of the cooling water, operation at different electrical loads, power supply (by batteries or a laboratory power supply unit), the insulation and modifications of the heat exchanger and the combustion chamber.

3 RESULTS AND DISCUSSION

3.1 Combustion

Complete combustion is a basic requirement of a state of the art micro-scale CHP. The prototype has a modified combustion chamber compared to the commercialised furnace. It is smaller but not water cooled any more. The combustion temperature is higher and the excess air is lower (see table 1). The CO-emissions still can be low (see figure 5). The average of the CO-emissions of the diagrammed data was 110 mg/Nm3 relating to 13% O_2.

Table 1. Technical data of the combustion chamber in the prototype compared to the commercialised one

	Prototype	Vision Comfort EKA 12
Volume of the combustion chamber	10dm³	17dm³
Combustion temperature	up to 1200°C	600°C
Excess air	1,3-2	2-2,5
Maximum fuel heat input	13kW	13kW

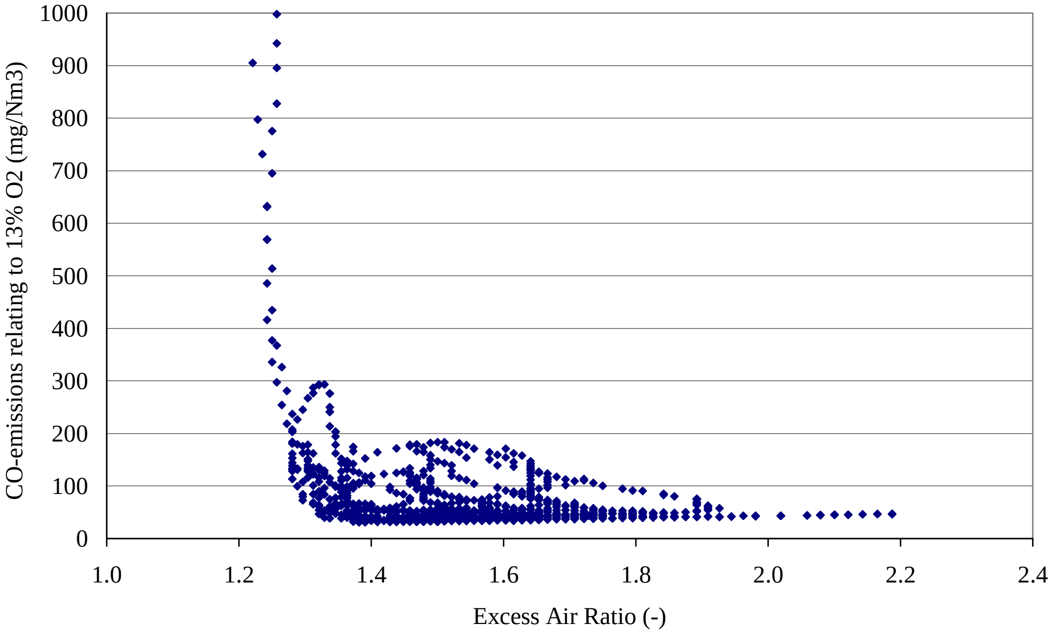

Figure 5. CO-emissions of the prototype versus excess air ratio

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3.2 Heat Transfer

With our special concept for the heat transfer we realised both a high amount of heat transferred to the TEG as well as the required high and constant heat flows on the small surfaces of the TEG (see table 2 and figure 6).

Table 2. Heat transfer within the prototype

Characteristic for heat transfer	Realised values
Logarithmic mean temperature difference	550-600K
Heat-transfer coefficient	55-64W/m²K
Specific heat flow	29-39kW/m²
Surface Temperature TEG	200-230°C

The voltages of the 16 thermoelectric modules of the generator diagrammed in figure 6 indicate qualitatively the heat flow through each module. The same heat flow causes the same voltage. The voltages and therefore the heat flows were almost constant.

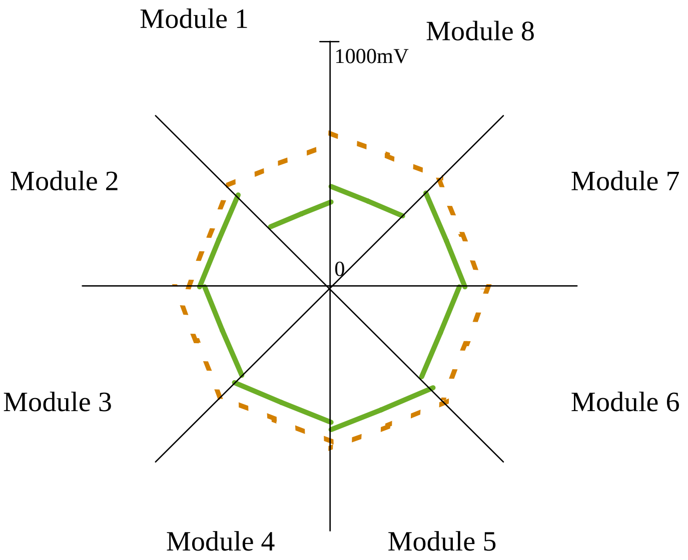

Figure 6. Voltages of the 16 modules of the generator indicate qualitatively the local heat flow (radar diagram according to the construction of the TEG, continuous lines: modules on the lower ring, dashed lines: modules on the upper ring)

3.3 Thermoelectric Power Generation

The higher the temperature difference across the TEG, the higher is the electrical output. The second main influence is the load resistance (see figure 7). To validate the operation of the TEG we measured voltage and current depending on the load resistance at a constant operating point of the furnace. The measurements show a very good consistency with theoretical calculations. For the calculation of the current I, voltage U and electrical power P the following formulas were used (ULL means the open circuit voltage, R the load and RI the internal resistance of the TEG):

$$I = ULL / (R + RI)$$
$$U = R*I$$
$$P = U*I$$

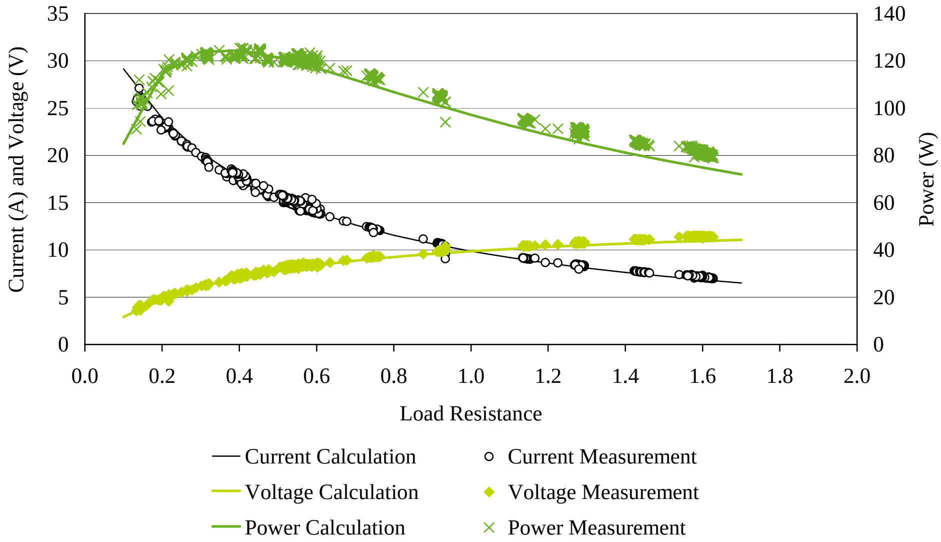

Figure 7. Voltage, current and electrical power of the TEG versus the load resistance

At steady operation the prototype achieved the values summarised in table 3. Figure 8 shows the electrical power output of the system versus the total fuel heat input. Most of the experiments were carried out with about 10kW fuel heat input. The performance varied according to the differences in experimental setup. The higher the fuel heat input, the higher is the electrical output.

Table 3. Performance of the whole system

Parameter	Prototype operation	Calculated Values
Electrical power	168W	200W
Electrical efficiency	1,5%	2,0%
Efficiency TEG	3,5%	4%
Heat through TEG	45%	50%

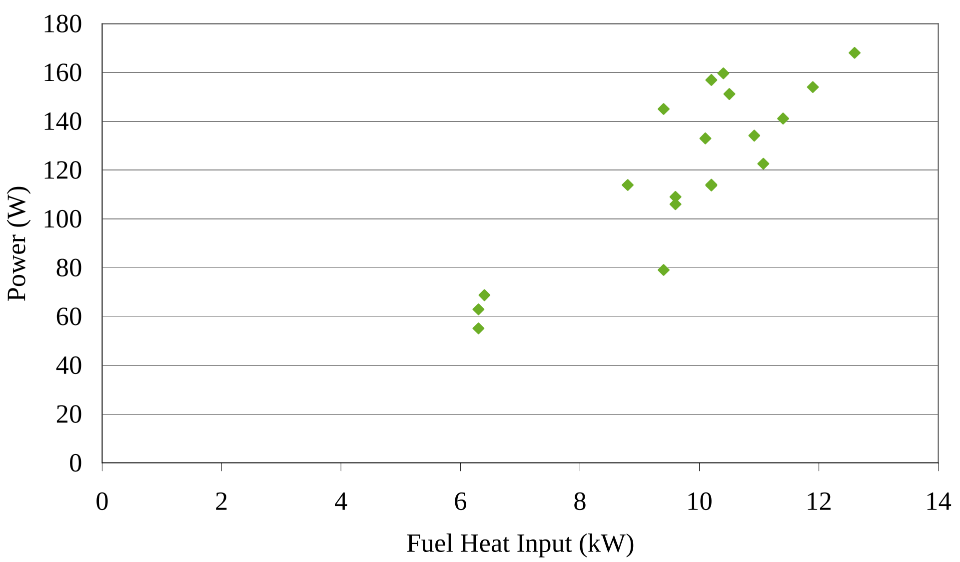

Figure 8. Electrical power versus fuel heat input

4 CONCLUSIONS

The first results with the fully integrated prototype are encouraging. The theoretical potential is confirmed, the ambitious aims could be reached up to a high degree. The requirements for grid independent operation can be fulfilled and network supply is possible. In the following project we will develop optimised micro-scale CHP-systems with advanced thermoelectric materials which promise better performance at lower costs. For both materials long-time operation has to be observed due to the high requirements on the materials of furnace, heat exchanger and TEG.

The idea to produce at least some electricity with the available heat is charming. As it is technically feasible, there should be intensive research and development on this promising future technology. The potential of this technology depends mainly on the efficiency and costs of thermoelectric materials. Therefore we are collaborating not only with leading producers of pellet boilers but also experienced producers of TEGs (TEC COM GmbH, Halle, Germany) and thermoelectric materials (DLR German Aerospace Center, Institute of Materials Research, Köln, Germany).

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Content

- Micro-Scale CHP
  - Basic Idea
  - Thermoelectric Power Generation
  - Combination of Technologies

- Prototype
  - Integration of Furnace and Thermoelectric Generator (TEG)
  - Performance in Experiments

- **Conclusions**

Micro-Scale CHP

Automatically running Biomass Furnace

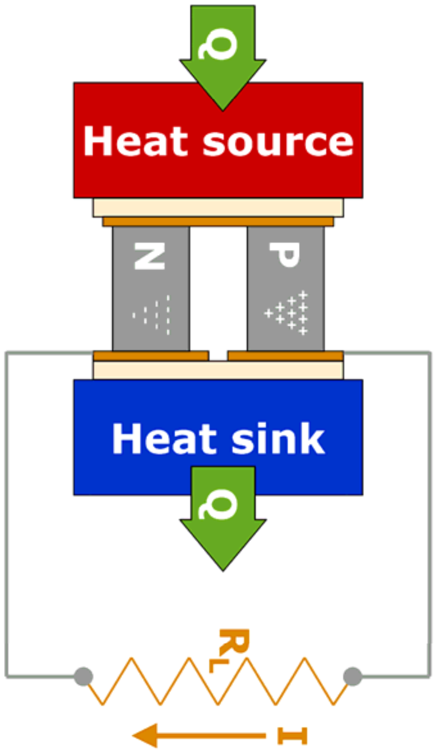
with Thermoelectric Generator

⇨ **Grid-Independent Operation**

⇨ **Production of Electricity**

Without losing Convenience

Thermoelectric Power Generation



Principle of TE
Power Generation

- **Direct Energy Conversion**
- **Maintenance-free Durability**
- **Noiseless Operation**
- **No moving Parts**
- **No Working Fluids**

Predestined for
Micro-Scale CHP
Based on Biomass

System Integration

Energy Balance

- **Maximising Heat Flow through TEG**
- **High Temperatures on Small Surfaces**
- **Maximum Efficiency of the TEG**

Objectives

Prototype Micro-CHP:

Biomass Furnace with TEG

- Construction
- Build-Up
- Start-Up

Prototype – Adapted Furnace

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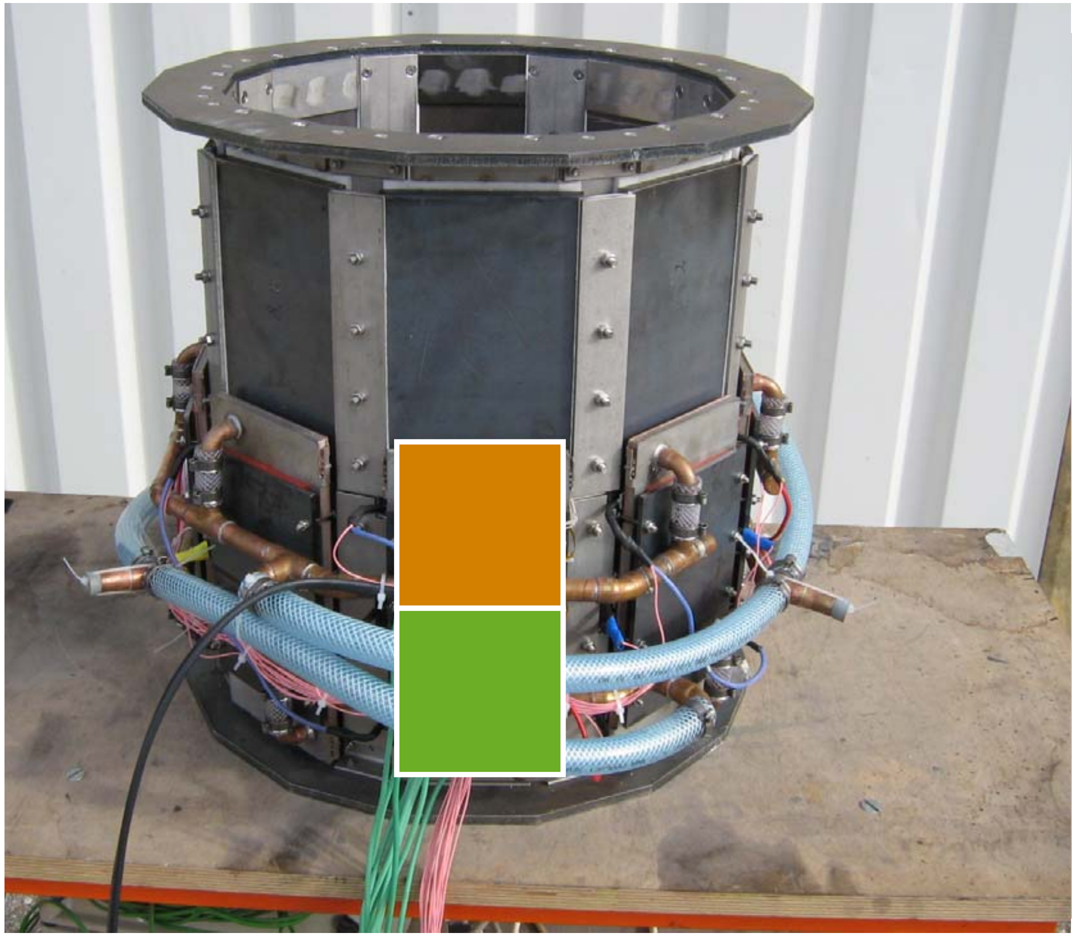
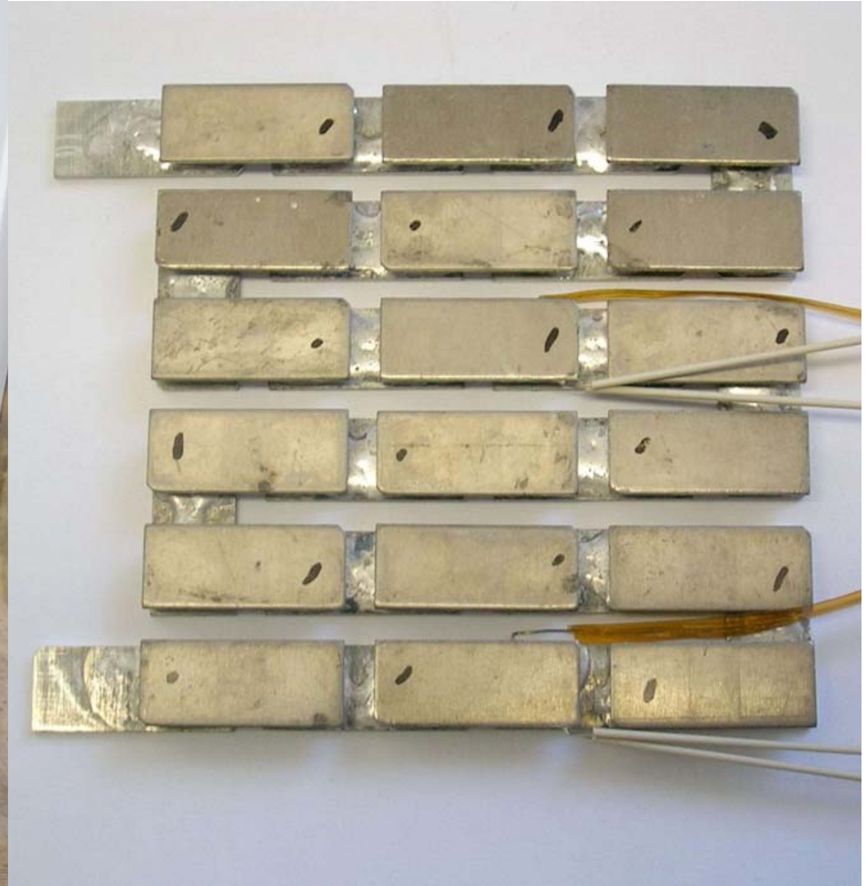
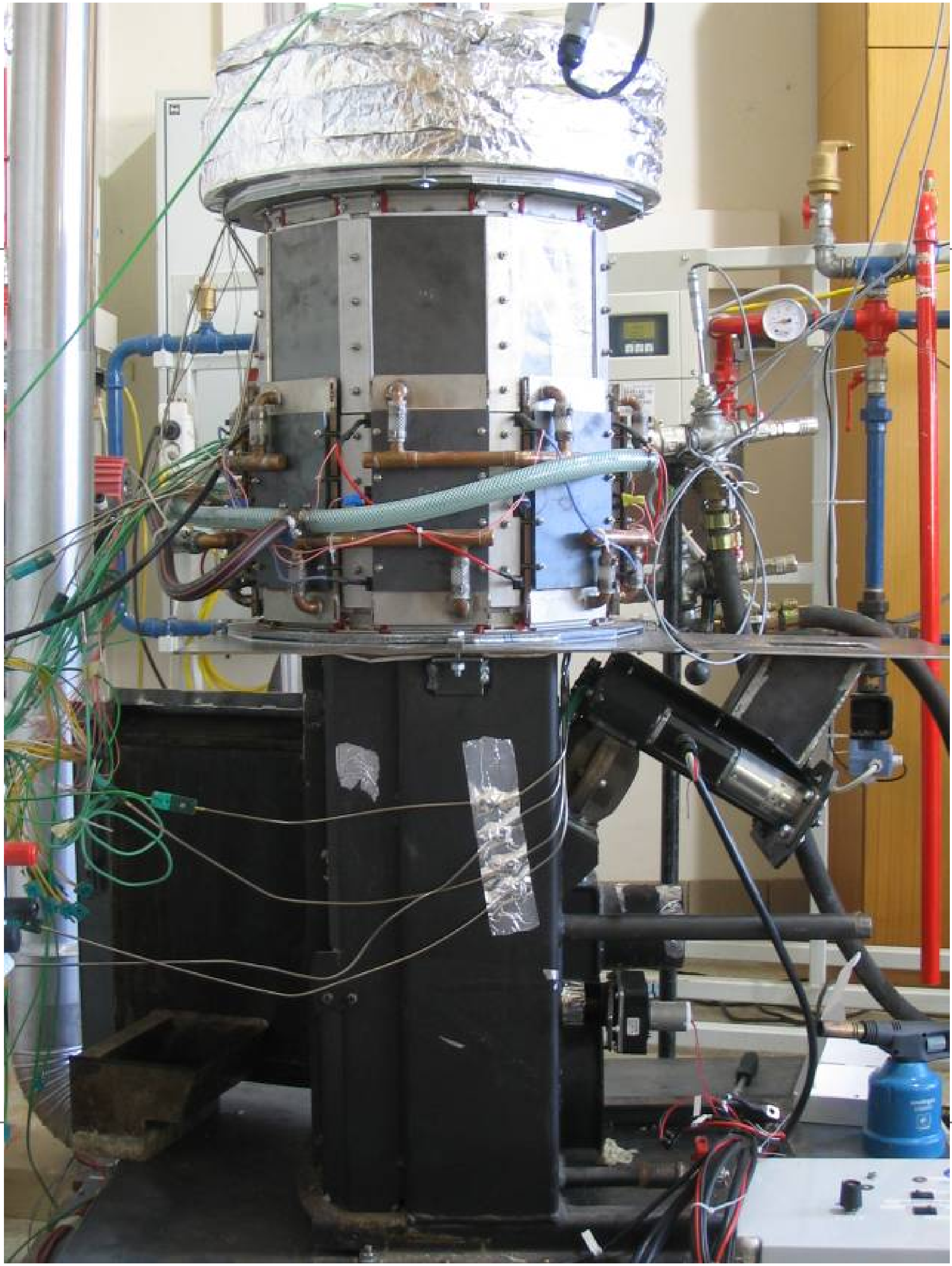
Prototype – Constructed TEG







Experiments with the Prototype

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- **Combustion**
- **Heat Transfer**
- **Thermoelectric Power Generation**

Combustion

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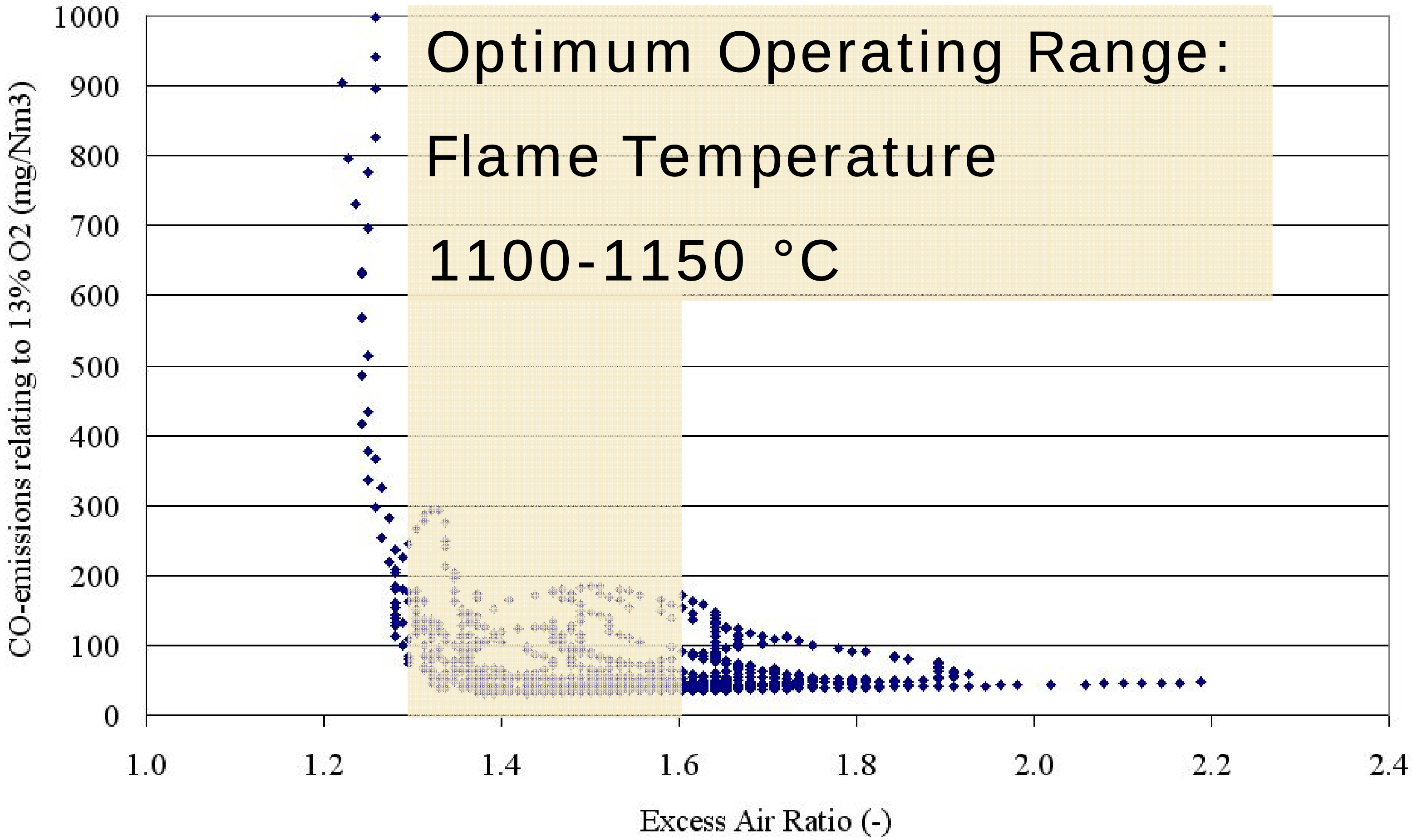

Heat Transfer

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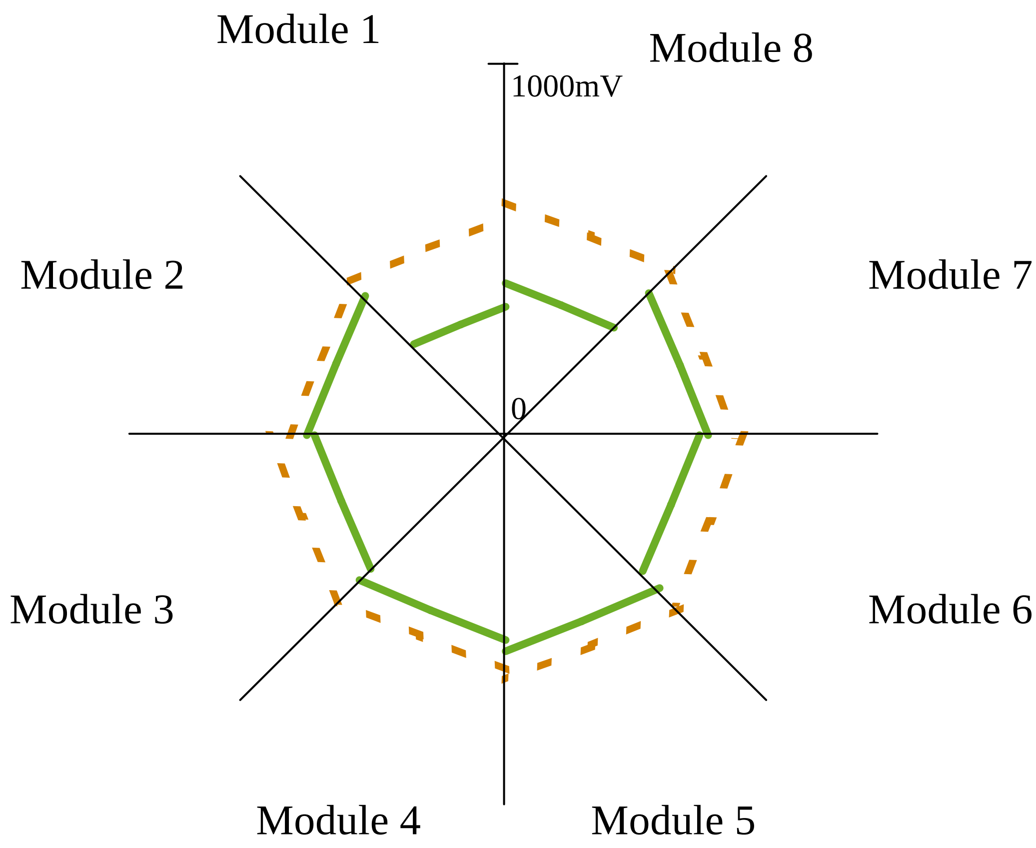
Voltage (mV) of
TE-Modules
Indicate
Local Heat Flow:
Radar Diagramm

Continuous Lines:
Lower Ring
Dashed Lines:
Upper Ring



Thermoelectric Power Generation

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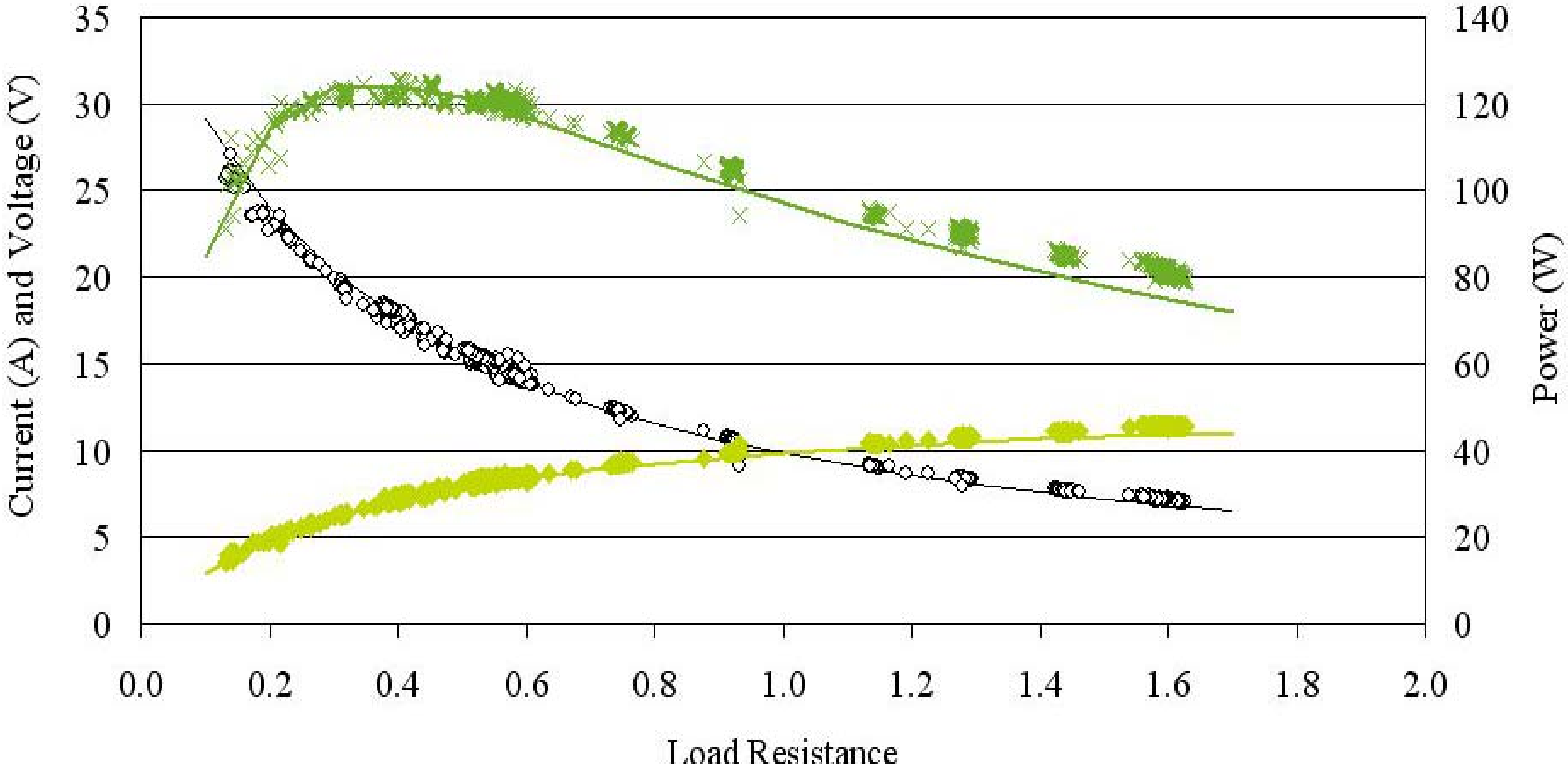

System Performance

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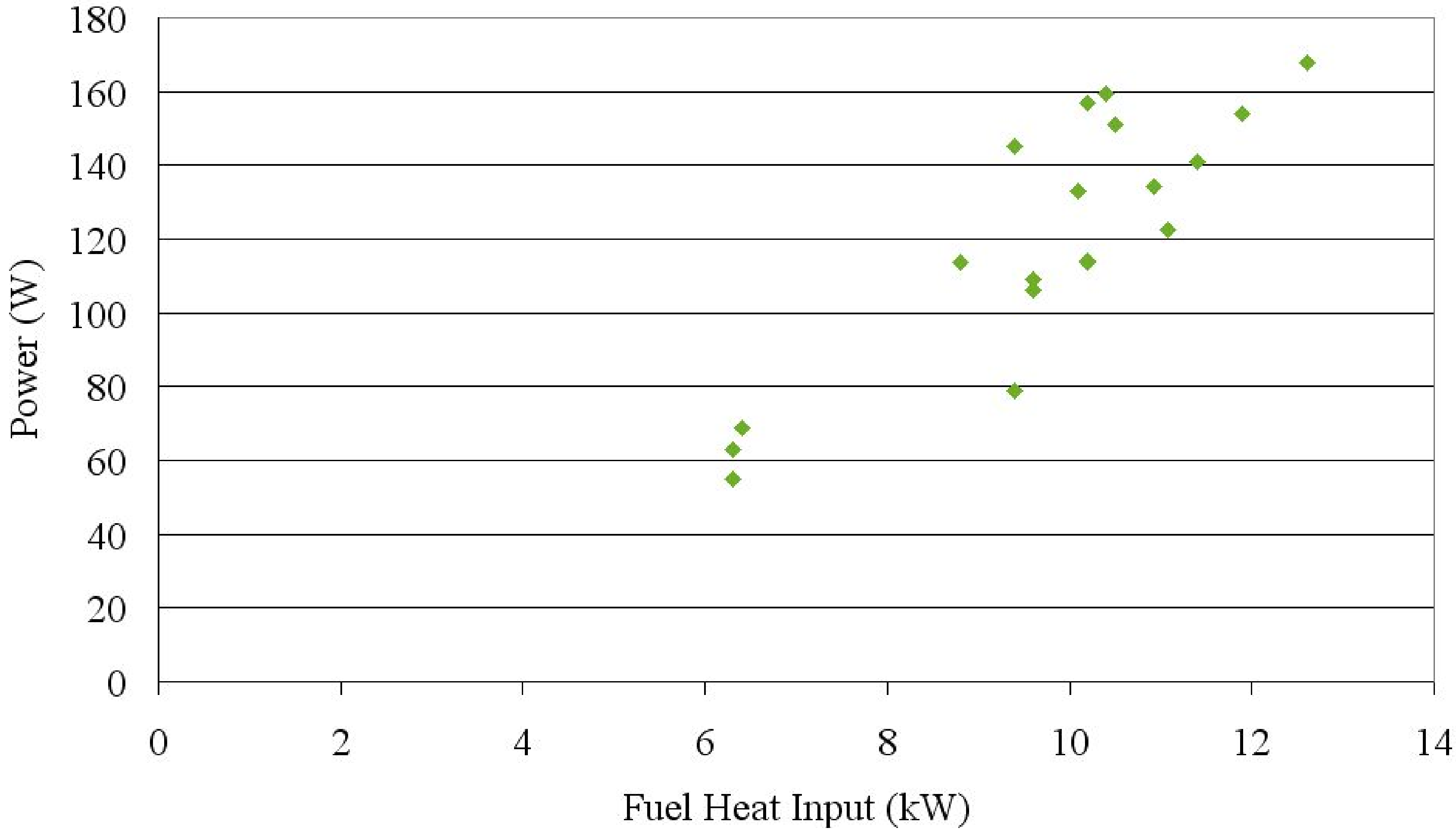

Conclusions

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- Successful Combination of Technologies
- Grid-Independent Operation
- Power Generation
- Cooperation with TEC COM GmbH and the German Aerospace Centre (DLR)

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KWB Biomasseheizungen

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