Combined Heat and Power System for Stoves with Thermoelectric Generators

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Abstract

Solid-fuel stoves are used in developing countries, remote locations, and in general more commonly due to convenient fuel cost for space heating. The possibility of also using the stove heat to heat water and produce electricity represents an added benefit.
This work presents an application of thermoelectric generators to a solid-fuel stove to concurrently charge a lead-acid battery and transfer heat to water for heating or household use. The feasibility of the proposed CHP system is demonstrated for a common solid-fuel stove.
This system produces an average of $600W_{th}$ and $27W_{el}$ ($42W_{el}$ peak) during a 2-h long experiment in which the TEG efficiency is around 5% and the MPPT efficiency of the power converters used is demonstrated.

Keywords: thermoelectric, TEG, heat transfer, CHP, stove, MPPT

1. Introduction

A thermoelectric generator (TEG) is a robust and reliable solid-state device that converts part of the heat flowing through it into dc current when a temperature difference is maintained across it. The most commonly used commercial TEG devices use Bismuth Telluride (Bi_2Te_3) as the thermoelectric material, and they can work up to a maximum of 300°C.
Bass and Killander [1] presented a prototype thermoelectric generator for a wood-burning stove, simply placed on the top of it. This produced up to $10\,W$ from a $75x75\,mm^2$ TEG with cooling provided by a $2\,W$ fan blowing air over the heat sink. Nuwayhid [2] proposed a similar system cooled by air convection, producing up to $4.2\,W$ from a single $56x56\,mm^2$ TEG. Rinalde *et al.* [3] developed a prototype TEG system for firewood stoves, producing $12.3\,W$ from a temperature difference of 200°C with two TEGs, but they reported problems of non-uniform contact pressure. Champier [4] presented a TEG system for stoves that was tested in the lab with a gas heater and produced a maximum of $9.5\,W$ from a $56x56\,mm^2$ device. The authors highlighted the influence made on heat transfer by mechanical pressure and thermal contact resistances. O'Shaughnessy [5], Kinsella *et al.* [6] proposed a TEG system for portable biomass cook-stoves that uses commercially-available parts to produce up to $5.9\,W$ from a $40x40\,mm^2$ TEG and an average of $3\,Wh$ of energy stored in a $3.3\,V$ *lithium-iron phosphate* battery.
The main aim of all the aforementioned systems applying TEGs to stoves is to produce electrical power and they rely on inefficient natural or forced air convection for the cooling of the TEG's cold side. Min and Rowe [7] provided an alternative solution to overcome the low efficiency drawback: combining generation

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of heat and power into a "symbiotic" system, in which the heat released to the cold side is used to pre-heat water, thus effectively creating a combined heat and power (CHP) system. The overall efficiency of the symbiotic system is equal to that of a conventional heating system, but with the advantage that both electricity and heat are produced. A similar symbiotic system was developed by Vieira and Mota [8]. Chen *et al.* [9] examined the feasible deployment of TEGs in various CHP plants, analyzing efficiency improvements, technical drawbacks and economic benefits. Alanne *et al.* analysed the integration of thermoelectric modules in the combustion chamber of a wooden-pellet fueled boiler ($20\,kW_{th}$).

This work presents a TEG system comprising of a heat exchanger that fits into a solid-fuel stove, four $40x40\,mm^2$ TEGs with individual water-cooling blocks and a circulating water infrastructure to and from a 60-L water tank. This system is designed to absorb part of the heat produced by a common stove, burning coal, wood or charcoal and to direct it through the TEGs to circulating household water in such a way that the water is heated up while the TEGs produce electrical energy. This is effectively a CHP system and the basic system diagram is shown in Fig. 1. It is important to note that despite the low efficiency of thermoelectric generators all the heat flowing through them is used for household purposes, *e.g.,* heating, shower, etc. Hence, this TEG CHP system for stoves can be considered being $\sim$100% efficient.

The following section presents the proposed system, Section 3 shows the performance of this system during a typical two-hour burning time, Section 4 analyses the economics of this system and Section 5 contains a discussion before the Conclusions.

2. Description of the CHP System

The block diagram of the complete experimental rig is shown in Fig. 2. The TEG heat exchanger system was added to the stove where the top flue outlet was available. This has no impact on the stove in terms of mechanical machining work nor it interferes with the combustion efficiency. This makes a TEG based solution suitable for a wide range of current stove products and can be retro-fitted easily to existing installations.

Four TEG devices are positioned on top of an Aluminium heat exchanger, milled from a single block, that covers the top opening of the stove and has fins protruding inside it to improve the transfer of heat. The TEGs are retained in place by four slots milled (1mm) on the top surface of the hot-side heat exchanger, as shown on the left side of Fig. 3. Four individual water-cooled Aluminium blocks are placed on top of the TEGs, as shown on the right image of Fig. 3. The whole system is mechanically clamped by a single M20 nut acting via a thrust bearing, and one $500\,lb/inch$ spring per TEG ensures even distribution of the force onto each fixture and mechanical compliance during thermal expansions. A 24-V dc pump circulates water from a 60-L water tank (with header tank on top) to the flow and return manifolds distributing water to the cold blocks. The water tank is insulated, while all the piping connections are not. The product code of the TEGs used is GM250-241-10-12 sold by *European Thermodynamics Ltd*[1]. Graphite-based thermal grease is used on both sides of the TEGs to minimise thermal contact resistance. Fig. 4 shows the complete CHP system (on the left) and a close-up of the TEG rig positioned on top of the stove (on the right).

The pump consumes $8\,W_{el}$ when set at a flow rate of $4.5\,L/min$ (measured by a Hall-effect in-line flow sensor). As detailed in Fig. 2, thermocouples are used to measure the temperatures on the cold sides of the TEGs, on the TEG side of the hot-side heat exchanger, and at the top and bottom of the fins inside the stove. The temperatures of the water inside the tank and at the inlet and outlet manifolds are also measured.

Two synchronous Buck-Boost converters, described in [10] and sold by *Thermoelectric Conversion Systems*[2], are used to maximise the power produced by the TEGs and to interface them to a 12-V 12-Ah lead-acid battery. The converters are necessary to continuously ensure that for any given thermal condition the power output is maximised; the Maximum Power Point Tracking (MPPT) efficiency exceeds 99% and the

[1]http://www.europeanthermodynamics.com/products/thermoelectric-modules/peltier-generator/power-generation-module-40-x-40mm-11-3w-gm250-241-10-12

[2]KM2-30V - http://www.teconversion.com/?p=11

converters' electrical efficiency is up to 97%. Each converter is connected to two TEGs in parallel, and the converters' outputs are connected in parallel to the battery, as shown in the connections diagram of Fig. 5. The voltage at the input of the MPPT converters, *i.e.* the TEGs output, the battery voltage and the battery current are measured. All sensors are connected to an Agilent datalogger to record the data through a program composed in Agilent VEE Pro (see Fig. 2).

3. Experimental Results

The stove was initially loaded with 4kg of charcoal and fired. The results presented in this paper are obtained during two hours of consecutive burning, however the initial 16 minutes of testing are omitted due to experiment setup. During this experiment approximately 0.5kg of solid fuel has been added approximately after 83 min, 107 min and 120 min to maintain high temperature.

Fig. 6 shows the temperatures established at the bottom (T_{Fins}) and top (T_{HX}) of the fins (inside the stove) of the hot-side heat exchanger, on the hot (T_{HOT}) and cold ($T_{COLD\,avg}$) side of the TEGs, inside the water tank ($T_{Water\,tank}$), and the temperature difference across the TEGs, ΔT. The four thermocouples directly in contact with the TEGs cold sides measured almost identical values. Only one thermocouple was used to measure T_{HOT}, hence a direct measurement of the TEGs hot-side temperatures is not available. Nevertheless, the thickness of the heat exchanger and its high thermal conductivity provide good temperature uniformity, hence T_{HOT} approximates the values of the temperatures on the hot sides of the TEGs.

T_{HOT} reaches almost 300℃ after 40 min. To prevent excessive temperature on the TEG hot side the window of the stove has been seldom opened, easily noticeable by sudden drops of T_{Fins}. Despite this, the large thermal mass of the stove heat exchanger limits this temperature swing on the TEG side.

The temperature difference across the TEGs varies considerably during the experiment. For this reason MPPT converters are used to continuously ensure operation at the maximum power point, regardless of temperature variations [11]. The TEG operating voltages, $V_{TEG\,1}$ and $V_{TEG\,2}$ of Fig. 5, are reported in Fig. 7, together with the battery voltage and current. $V_{battery}$ varies because some power resistors are periodically connected to prevent over-charging of the battery.

The thermal power transferred to the water, P_{Water}, can be calculated from the temperature difference between the water in the outlet manifold, $T_{Water\,Out}$, and that in the inlet manifold, $T_{Water\,In}$, as shown in Eq. 1:

$$P_{Water} = \dot{m} C_{P,v} \left(T_{Water\,Out} - T_{Water\,In} \right) \tag{1}$$

where $\dot{m}$ is the flow rate in [L/s] and $C_{P,v}$ is the isobaric volumetric heat capacity in [J/LK]. P_{Water} and the electrical power generated by the TEGs ($P_{OUT} = V_B I_B$) allow calculating the thermal-to-electrical efficiency, η, of the TEG system as shown in Eq. 2:

$$\eta = \frac{P_{OUT}}{P_{Water} + P_{OUT}} \tag{2}$$

Fig. 8 plots P_{OUT}, P_{Water} and η.

4. Discussion of Results

This work proposes a CHP system that offers superior performance compared to other similar systems for stoves presented in literature and described in the Introduction. As shown in Fig. 8 P_{OUT}, the total electrical power produced by four $40x40\,mm^2$ TEGs and transferred to the battery (therefore including losses in the MPPT electronics), exceeds $42\,W$ at the maximum temperature difference of 250℃. This agrees with the performance listed in the TEG datasheet[3], thereby also validating the MPPT efficiency of the power converters used [10]. The average electrical power output during the considered period of time is $27\,W$,

[3]http://www.europeanthermodynamics.com/products/thermoelectric-modules/peltier-generator/power-generation-module-40-x-40mm-11-3w-gm250-241-10-12

which is more than enough to drive the dc pump ($8\,W$) and two high-power USB devices ($2\,A$ each). The two MPPT converters were working at almost identical operating points (purple and orange lines in the plot on the right of Fig. 3), demonstrating similar performance from TEGs and MPPT converters. The negligible difference could be due to small effects of thermal mismatch due to uneven mechanical conditions or to temperature variability [12] on the four TEGs due to their position on the stove, *e.g.*, the TEG closer to the stove door could sit at lower temperature.

The obtained thermal-to-electrical efficiency is between 4 and 5 %, which is in line with the performance of commercial Bi_2Te_3 devices. The main concern is the potential issue of excessive temperature on the TEG hot side that could occur if the stove was loaded with a significant quantity of fuel or if the bottom door of the stove was left open. A possible solution is represented by cascading two TEGs, one for high temperatures and one for low temperatures [13]. Future work will address this issue.

Fig. 6 shows that the temperature of the water in the tank (orange line) was raised by 20℃ by an average thermal power of $582\,W$ transferred through the TEGs. This is a convenient outcome because it can be used for heating or other household use, thus off-loading fuel consumption in the boiler. Further, the heat produced by the stove can be transferred to other parts of the house, passing through radiators or the under-floor heating system.

5. Economics of this stove CHP system

This section studies the economics of the TEG CHP system for stoves presented in this paper. This system captures part of the heat generated burning solid fuels (*e.g.,* coal, wood or charcoal) in the stove, using a heat exchanger, and it transfers it to recirculating water from a water tank through four TEGs which convert part of the thermal energy into electricity. If the water tank was to be placed at a higher location compared to the TEG system no circulating pump would be needed due to gravity circulation; in any case, such a system could be integrated in an already-present water and/or heating system at minimal extra cost. In Sections 3 and 4 it was shown that the four TEGs produced up to $42\,W_{el}$ and transferred an average $582\,W_{th}$ to the water tank during the normal use of the stove. *Cernunnus*[4] suggests that the average consumption of hot water per person per day is around $40\,L$. UK mains water is provided at 10℃ and the water ought to be heated up to at least 60℃ (this is a requirement by UK Health and Safety to kill off any *Legionella* bacteria). Thus the water temperature needs to be raised by at least 50℃ in the tank. It must be noted that rarely is water needed at 60℃, therefore hot water is mixed with cold water, hence the volume of hot water required is less. However, for the sake of this analysis and to take into account possible losses in the pipes and tank, $40\,L$ remains a reasonable requirement.

The thermal power (in Wh) required to increase the temperature of one litre of water by 1℃ is $1.16\,Wh$. Therefore the total quantity of power needed is

$$P_{water} = 40\,L \cdot 1.16\,Wh/℃L \cdot 50℃ = 2.3\,kWh \tag{3}$$

This corresponds to leaving the stove heated up for around 4 hours, which is a reasonable expectation when using the stove for heating and cooking, especially during colder months. The cost of $1\,kWh$ of electricity in the UK is around £0.15, therefore using an electric boiler this heating task costs £0.35; assuming such daily saving for every day of the year, this equates to £126 per year. However, the cost of coal, which stands at around £$0.036/kWh$ must be taken into consideration, so that the yearly saving decreases to £96. This figure does not take into consideration the production of electricity which could be stored in a battery for use with low-power electronics (smart-phones, computers) and energy-saving lighting; furthermore such features would be of great benefit in rural households not connected to -or interrupted from- mains power, especially in developing countries.

[4]http://www.cernunnos-homes.co.uk/technology/boilers-explained/sizing-a-hot-water-tank/

6. Conclusions

This experiment demonstrated the technical feasibility of the proposed CHP system for a common solid-fuel stove. This system both exchanges heat from the stove to circulating water for heating or normal household use, and it provides electrical power for the required pump and additional electrical equipment. Almost $600\,W_{th}$ and $27\,W_{el}$ are produced on average during a 2-h long burning experiment. The TEG efficiency is around 5% and the MPPT converters prove to constantly set the correct maximum power point at the TEGs' output.
Future work will focus on the simulation of this experiment with the dynamic model presented in [14], on the optimisation of the TEG pellets [15] and on the improvement of this technology with the aim to lower its cost.

Acknowledgements

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References

[1] J. C. Bass, A. Killander, A Stove-Top Generator for Cold Areas, in: 14th International Conference on Thermoelectrics, pp. 390–393.

[2] R. Nuwayhid, A. Shihadeh, N. Ghaddar, Development and testing of a domestic woodstove thermoelectric generator with natural convection cooling, Energy Conversion and Management 46 (2005) 1631–1643.

[3] G. Rinalde, L. Juanicó, E. Taglialavore, S. Gortari, M. Molina, Development of thermoelectric generators for electrification of isolated rural homes, International Journal of Hydrogen Energy 35 (2010) 5818–5822.

[4] D. Champier, J. P. Bedecarrats, T. Kousksou, M. Rivaletto, F. Strub, P. Pignolet, Study of a TE (thermoelectric) generator incorporated in a multifunction wood stove, Energy 36 (2011) 1518–1526.

[5] S. OShaughnessy, M. Deasy, C. Kinsella, J. Doyle, A. Robinson, Small scale electricity generation from a portable biomass cookstove: Prototype design and preliminary results, Applied Energy 102 (2013) 374–385.

[6] C. Kinsella, S. OShaughnessy, M. Deasy, M. Duffy, a.J. Robinson, Battery charging considerations in small scale electricity generation from a thermoelectric module, Applied Energy 114 (2014) 80–90.

[7] G. Min, D. Rowe, Symbiotic application of thermoelectric conversion for fluid preheating/power generation, Energy Conversion and Management 43 (2002) 221–228.

[8] J. A. B. Vieira, A. M. Mota, Thermoelectric generator using water gas heater energy for battery charging, 2009 IEEE International Conference on Control Applications (2009) 1477–1482.

[9] M. Chen, H. Lund, L. a. Rosendahl, T. J. Condra, Energy efficiency analysis and impact evaluation of the application of thermoelectric power cycle to todays CHP systems, Applied Energy 87 (2010) 1231–1238.

[10] A. Montecucco, A. R. Knox, Maximum Power Point Tracking Converter Based on the Open-Circuit Voltage Method for Thermoelectric Generators, IEEE Transactions on Power Electronics 30 (2015) 828–839.

[11] I. Laird, H. Lovatt, N. Savvides, D. Lu, V. G. Agelidis, Comparative Study of Maximum Power Point Tracking Algorithms for Thermoelectric Generators, in: Australasian Universities Power Engineering Conference (AUPEC'08).

[12] A. Montecucco, J. Siviter, A. R. Knox, The effect of temperature mismatch on thermoelectric generators electrically connected in series and parallel, Applied Energy 123 (2014) 47–54.

[13] K. Simpson, A. R. Knox, A. Montecucco, Thermoelectric generators, 2014.

[14] A. Montecucco, A. R. Knox, Accurate simulation of thermoelectric power generating systems, Applied Energy 118 (2014) 166–172.

[15] A. Montecucco, J. Siviter, A. R. Knox, Constant Heat Characterisation of Thermoelectric Generators and Optimisation of Pellets Packing Factor, Applied Energy 149 (2015) 248–258.

Figure 1: Power balance diagram for the proposed CHP system for solid-fuel stoves.

Figure 2: Diagram of the stove CHP system detailing connections and measurements.

Figure 3: Mechanical fixtures to host four $40x40\,mm^2$ TEG devices on the stove.

Figure 4: Picture of the complete CHP system (left) and close-up image of the stove and the mechanical fixtures (right).

Figure 5: Electrical connections diagram with pictures of the MPPT converters used (KM2-30V - http://www.teconversion.com/?p=11).

Figure 6: Temperature distributions versus time of experiment. From top to bottom, temperatures on: bottom of fins, heat exchanger, TEG hot side, temperature difference across the TEGs, TEGs' average cold side, water tank.

Figure 7: Electrical measurements versus time of experiment: battery voltage (red), MPPT converters, battery current (green).

Figure 8: P_{OUT} and η (left y-axis) and P_{Water} (right y-axis) versus time of experiment.

Figure 1

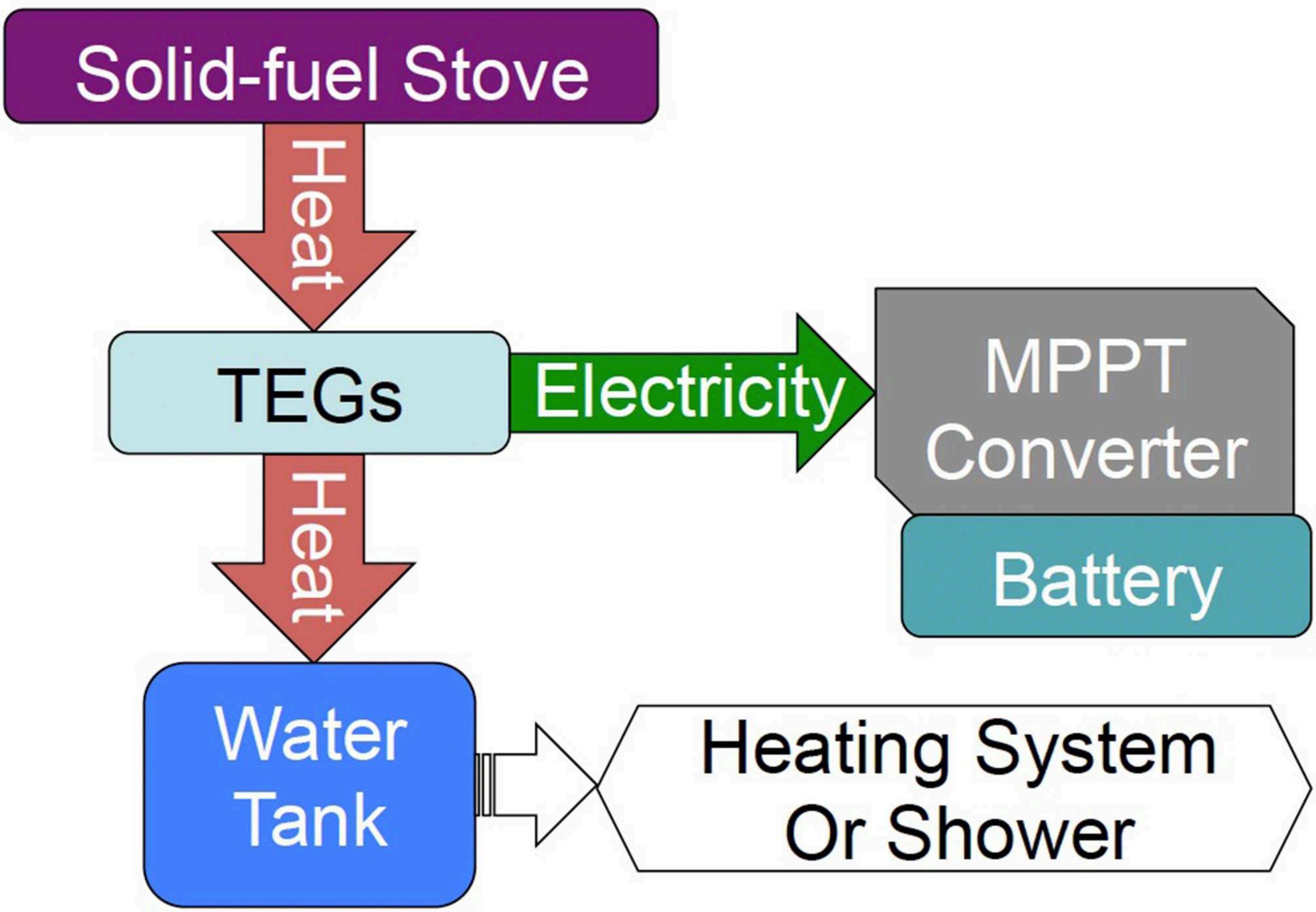
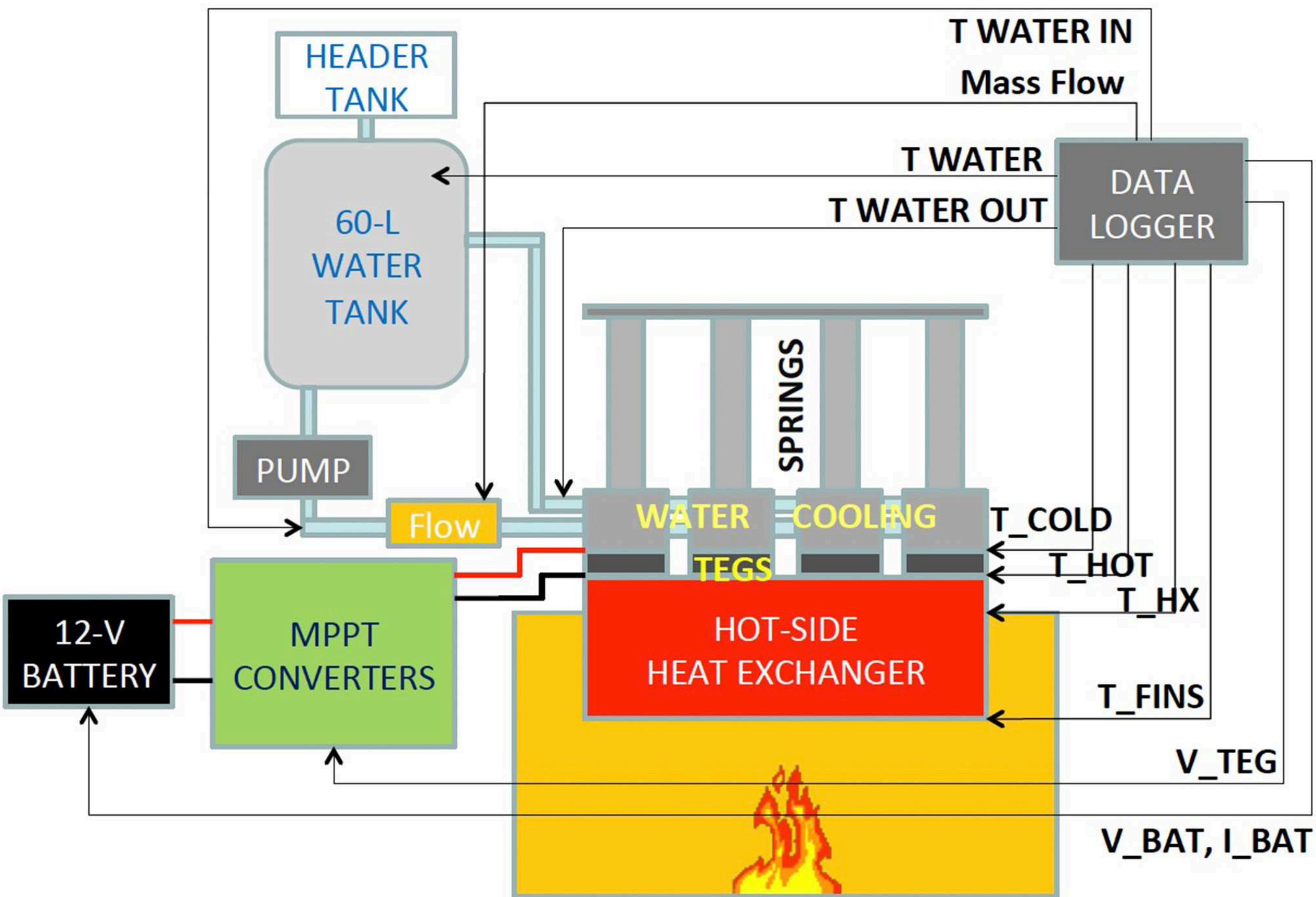
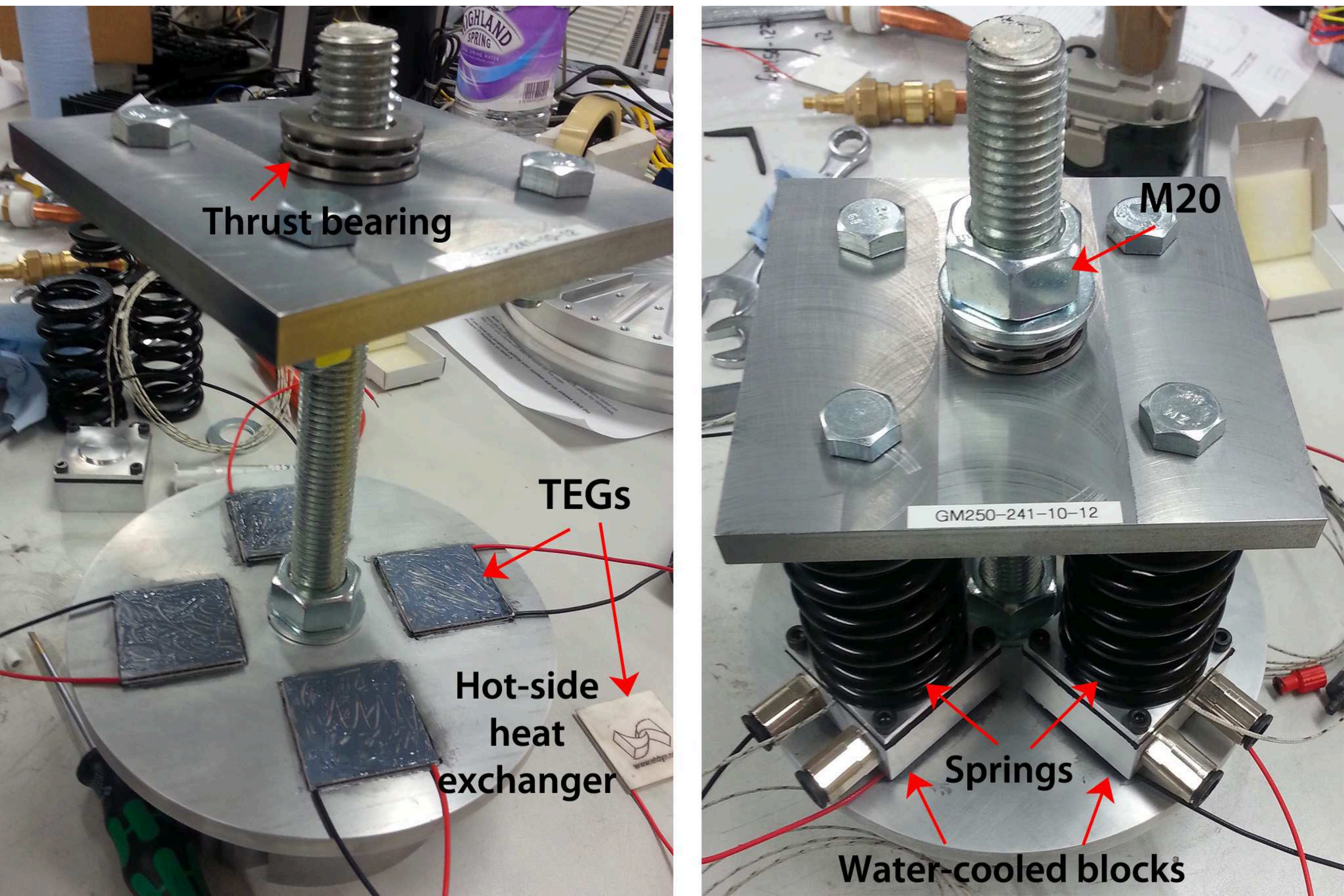

Solid-fuel Stove
Heat
TEGs
Electricity
MPPT
Converter
Battery
Heat
Water
Tank
Heating System
Or Shower

Figure 2



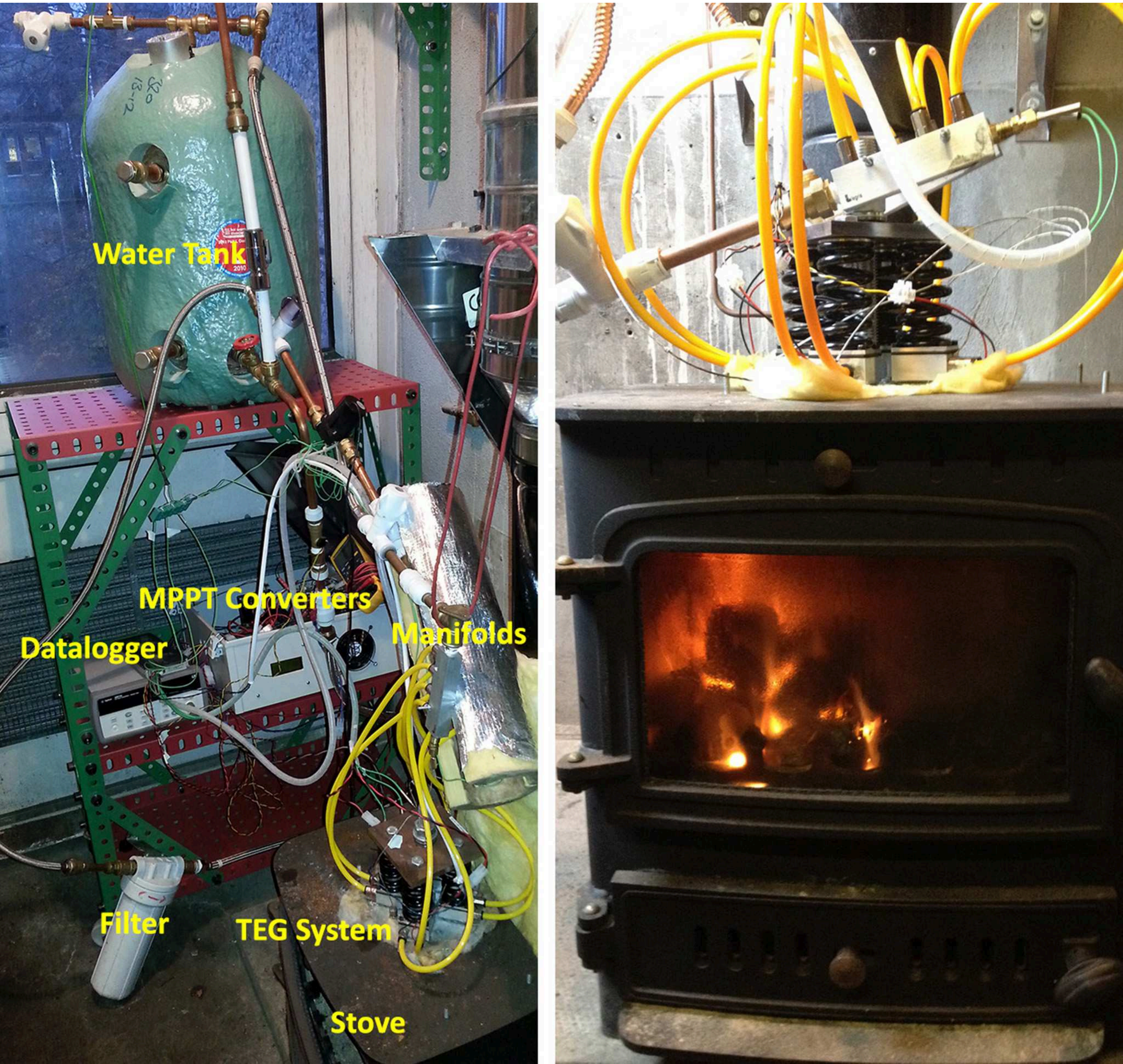
T WATER IN
Mass Flow
HEADER TANK
T WATER
DATA LOGGER
T WATER OUT
60-L WATER TANK
SPRINGS
PUMP
Flow
WATER COOLING
TEGS
T_COLD
T_HOT
T_HX
12-V BATTERY
MPPT CONVERTERS
HOT-SIDE HEAT EXCHANGER
T_FINS
V_TEG
V_BAT, I_BAT

Figure 3



Thrust bearing
TEGs
Hot-side heat exchanger
M20
GM250-241-10-12
Springs
Water-cooled blocks

Figure 4



Water Tank
MPPT Converters
Datalogger
Manifolds
Filter
TEG System
Stove

Figure 5

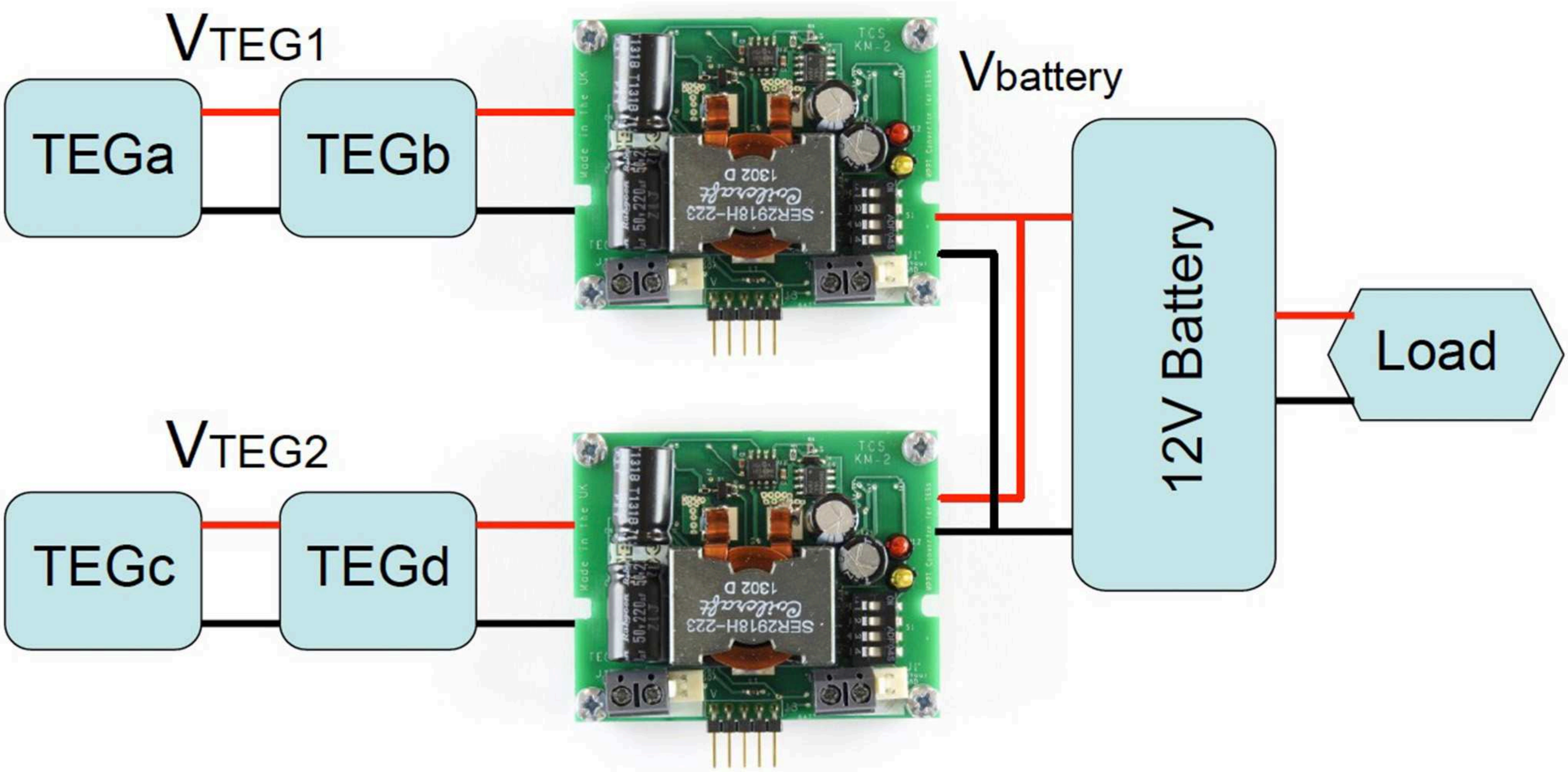
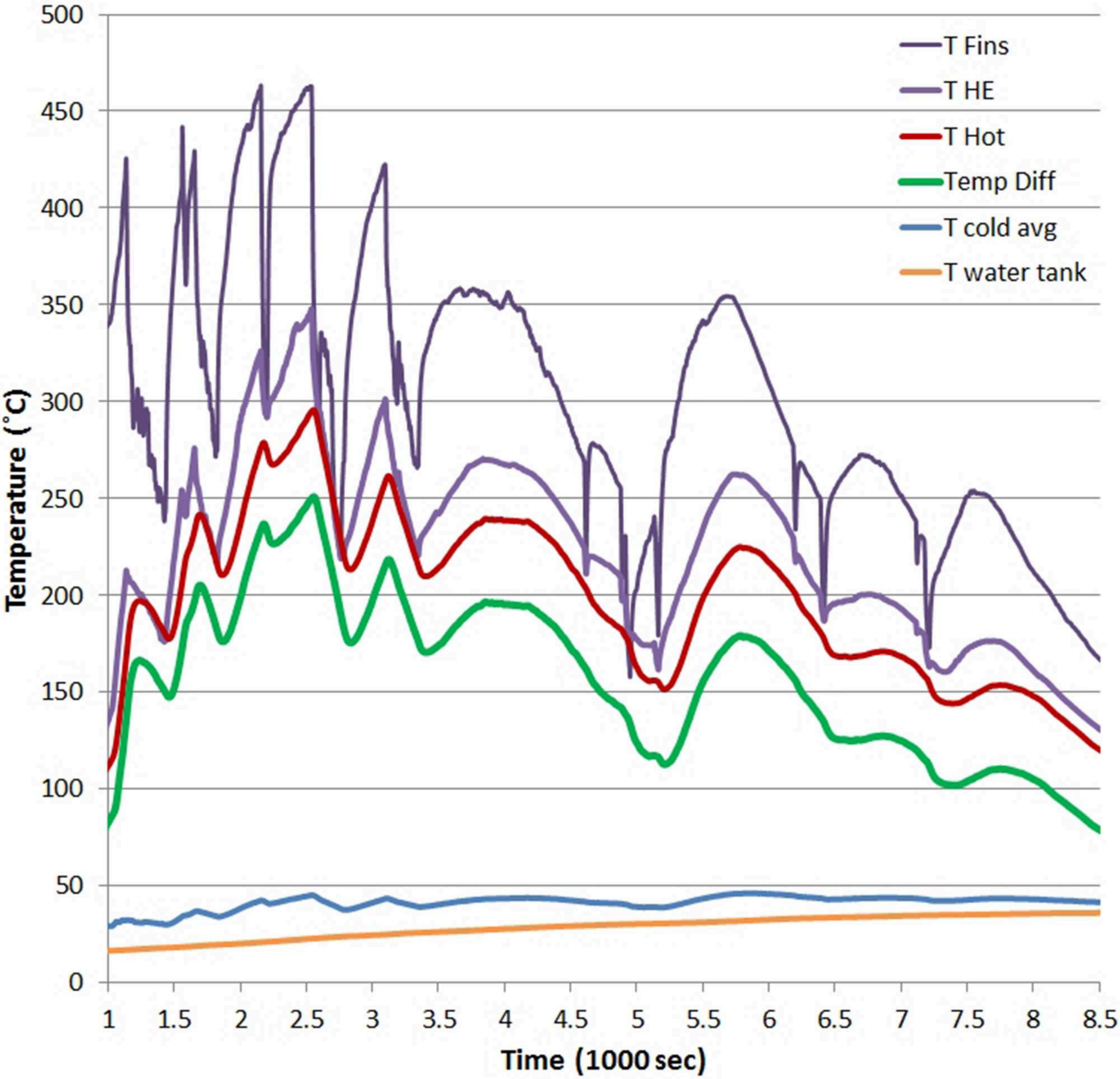
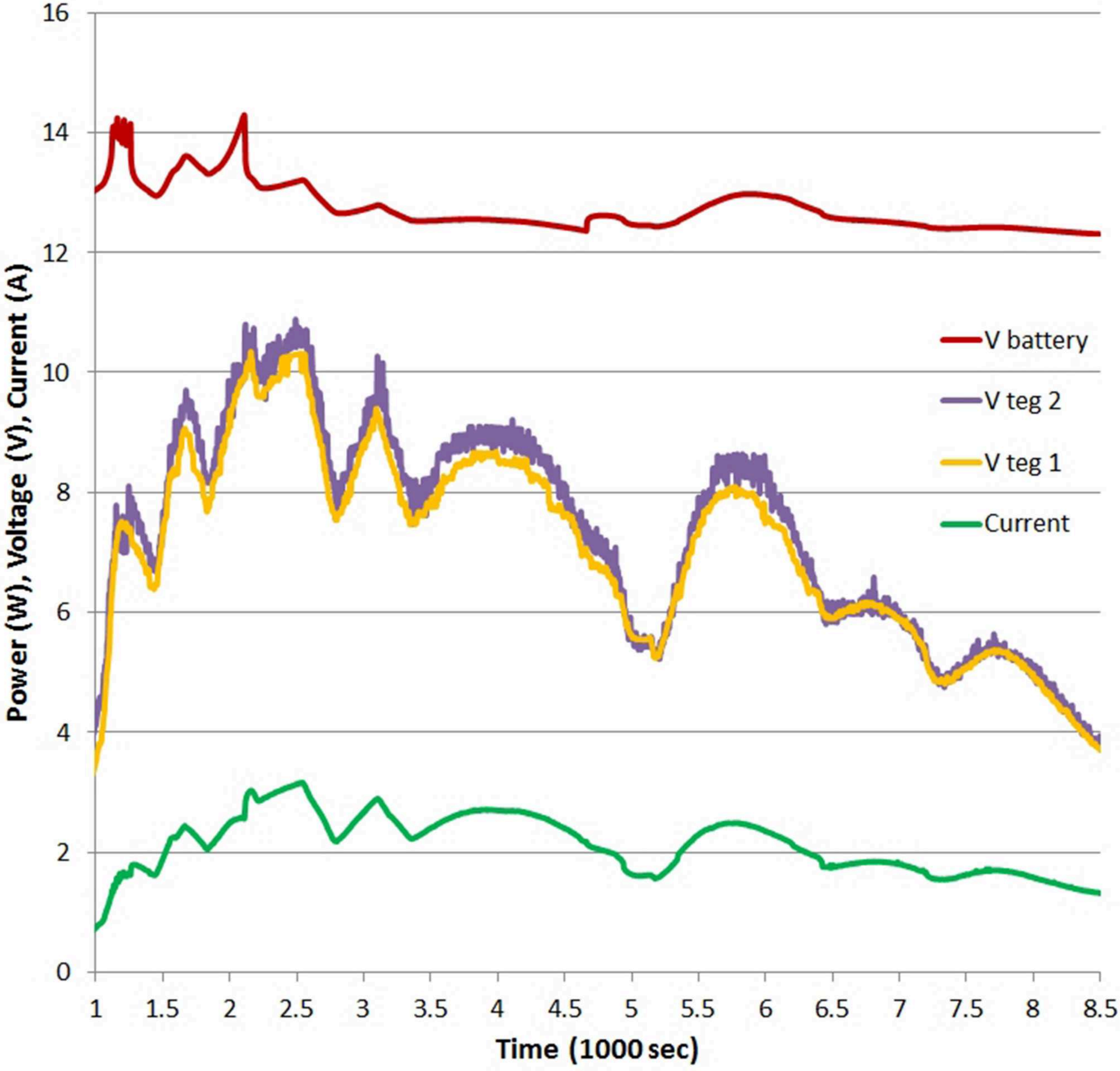


Figure 6



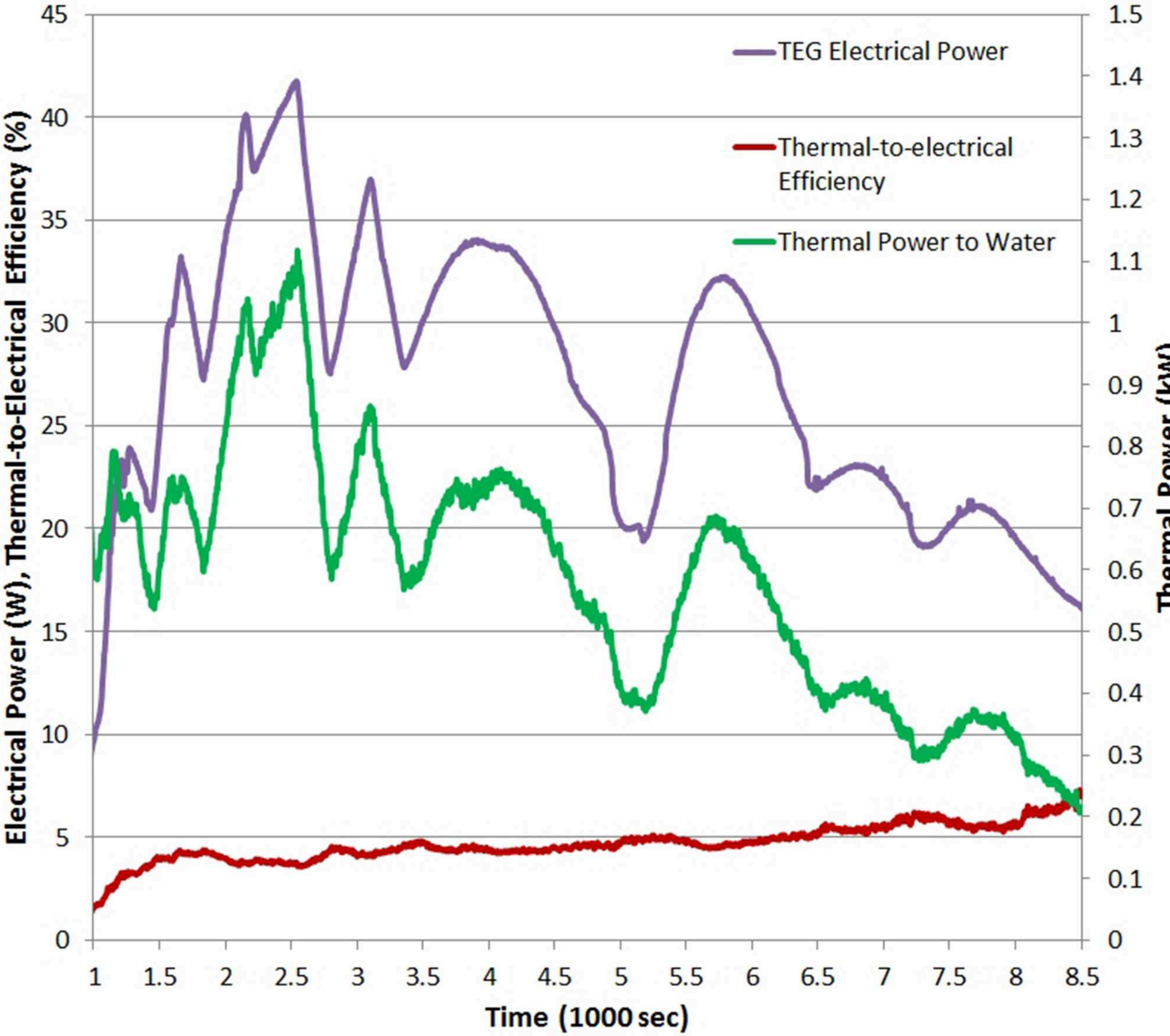
T Fins
T HE
T Hot
Temp Diff
T cold avg
T water tank
Temperature (˚C)
Time (1000 sec)
0
50
100
150
200
250
300
350
400
450
500
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5

Figure 7



16
14
12
10
8
6
4
2
0
Power (W), Voltage (V), Current (A)
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
Time (1000 sec)
V battery
V teg 2
V teg 1
Current

Figure 8


TEG Electrical Power
Thermal-to-electrical Efficiency
Thermal Power to Water
Electrical Power (W), Thermal-to-Electrical Efficiency (%)
Thermal Power (kW)
Time (1000 sec)
0
5
10
15
20
25
30
35
40
45
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5