Grid autarchy of automated pellets combustion systems by the means of thermoelectric generators

Ernst HOEFTBERGER

Abstract

Wood pellet combustion units are a comfortable, full automatic and low emission solution for the provision of space heating in small scale applications. The requirement of an auxiliary energy source for the heat supply and distribution however results in a dependence on the electrical grid. The goal of this work is thereby to eliminate this dependence and to meet the auxiliary energy demand through the independent production of electrical energy. The thermoelectric power production method was chosen from a number of technology variations so as to guarantee the silent and maintenance free production of direct current that can be implemented in cellars and space heaters.

A Prototype with thermoelectric generator was characterised with an evaluation method for comparing the electrical performance during practical operation cycles. This standardised method is presented on the bases of experimental results. Furthermore the electricity production costs are calculated.

Keywords: Thermoelectric power generation, pellets combustion, biomass, thermogenerator

Kurzfassung

Holz-Pelletfeuerungen sind für die Raumwärmebereitstellung im kleinen Leistungsbereich eine vollautomatische, komfortable Lösung. Dennoch verursacht der Bedarf an elektrischer Hilfsenergie für die Wärmebereitstellung und –verteilung eine Abhängigkeit vom Stromnetz. Ziel ist es, diese Abhängigkeit auszuschalten und den Bedarf an elektrischer Hilfsenergie durch Eigenerzeugung abzudecken. Aus mehreren Technologievarianten wurde dafür die thermoelektrische Stromerzeugung ausgewählt, da diese Technologie lautlos und wartungsfrei Gleichstrom erzeugt und somit in Keller wie auch in Raumheizgeräten eingesetzt werden kann.

Ein Prototyp mit thermoelektrischem Generator wurde mit einer Methode evaluiert, die die elektrische Performance während eines typischen Betriebszyklus charakterisiert. Diese standardisierte Methode wird anhand von Ergebnissen vorgestellt. Weiters werden die Stromgestehungskosten ermittelt.

1. Introduction and Objective

1.1. Introduction

Pellet combustion systems are the most comfortable form of room heat supply using biomass. They operate fully automated and are very dependable; moreover, these systems are currently the cleanest form of wood combustion for multiple family dwelling units in practical operation.

For the fully automated operation of pellets combustion units, auxiliary electrical power is required for items such as the transportation of the pellets, ignition, combustion regulation and the distribution of the space heating. As such, the following development phase for the pellet combustion units was set to guarantee the independent supply of auxiliary electrical power. Furthermore, it was also defined that this combustion system should be implemented using a technology that is also applicable in the living space. Thermoelectric power generation has the potential to deliver auxiliary power in adequate quantities for the self-sufficient, soundless and maintenance free operation of a biomass fired heating system.
In order to asses the performance of this technology and its place in the future of energy provision, standardised methods [1] are necessary to facilitate the comparison of different system set ups and eventually even technologies. Although a number of methods already exist, they fail to consider non-steady state operation conditions and thus neglect the most important part of micro combined heat and power (micro CHP) systems operation. Due to the complexity of such systems, an experimental evaluation tool is necessary whereby the electrical, thermal and total efficiency at full load and steady state are not sufficient.
If new products with new technologies are introduced into the market, they are compared to already existing technologies in terms of costs and benefits. For pellet combustions with thermoelectric generators the most interesting point are the electricity production costs.

1.2. Objective

Within this paper a new standard analysis method for micro CHP systems with thermoelectric generators is introduced. This method allows for the characterisation of the transient behaviour of thermoelectric generators fuelled with solid biomass by defining standard significant parameters within a standard operation cycle. In order for this standard analysis method to be applied, a suitable operation cycle is chosen for measuring the relevant quantities, which reflects the expected field of applications. The results from this standard analysis method serve to provide feedback for further development and improvements of the investigated system in addition to providing a basis for comparison for diverse thermoelectric generators or even micro-CHP technologies. By applying this standard analysis method, the potential for improvements and further development as well as the associated limitations of the evaluated technologies can be assessed.
The electricity production costs are calculated in the final part of the paper. So the cost efficiency can be estimated.

2. Thermoelectric Power Generation

Micro-CHP technologies in general allow the efficient use of fuels either when the rejected heat from power generation can be utilised or when power production is a by-product of heat generation. In addition, they offer the potential to develop a decentralised energy production system with the advantages of reduced distribution losses as well as the local supply of energy.
This paper focuses on the evaluation of two boilers with integrated thermoelectric power generation with different nominal electrical output. The thermoelectric genera-

tors integrated in biomass combustion units feature two stages of development [2] for this technology. The nominal load is up to 0.4 kW_{el} and the electrical efficiency is up to 4%.
The current research and development on the integration of thermoelectric generators into biomass furnaces has mainly focussed on water cooled pellet furnaces [2] [3]. The two presented prototypes using thermoelectric power generation were also integrated into water cooled pellets combustion units.

2.1 Principle of Thermoelectric Power Generation

The principle of thermoelectric power production is based on the effect of thermo-diffusion. In examining an electrically conductive solid body, the electrical charges shift when exposed to a temperature gradient. If two conductors from two different materials A and B are joined in a loop and the interfaces are placed at different temperatures in an open circuit, a thermal voltage can thus be measured. This effect is known as the Seebeck effect and is shown in Figure 1. The correlation between the thermal voltage U and the temperature difference TH - TK at the interface is described by a material specific parameter called the Seebeck-coefficient α_{AB}.

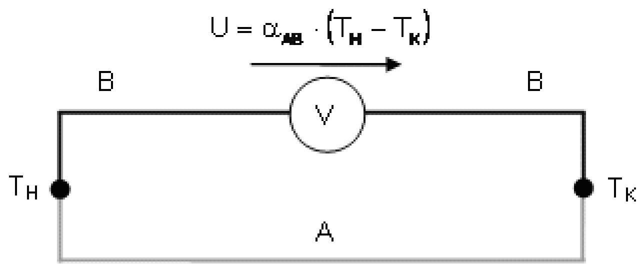

Figure 1: Sketch describing the Seebeck effect

During the generation of thermoelectric power, the circuit is closed by the electrical load whereby a direct current is manifested when heat flows in parallel across a semiconductor pair from the hot to the cold side of the thermo-generator. P- and N-doped semiconductor materials are used for the semiconductor pair and the amount of power produced is proportional to the temperature difference between the hot and cold side (TH TK), see Figure 2.

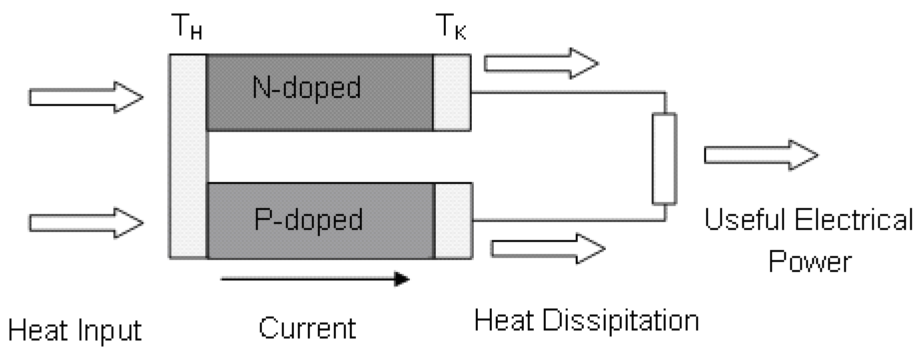

Figure 2: Principle of Thermoelectric Power Generation [2]

2.2 Design and Technical Specifications of a Prototype with Integrated TEG 250

The prototype presented in Figure 3 and Table I is constructed with industrial available thermoelectric material consisting of bismuth telluride which allows operating temperatures of up to 250 °C. The thermoelectric ge nerator is named according to the allowed operating temperature and is thus called the TEG 250.

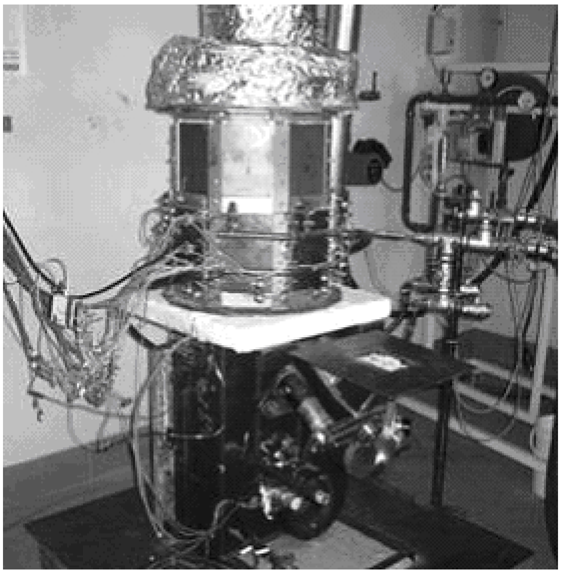

Figure 3: Micro-CHP Prototype: water-cooled biomass boiler with integrated TEG 250

Table I: Design specifications of the prototype with integrated TEG 250

Parameter	Value
Nominal Fuel Heat Input	10 kW
Fuel Heat Input Range	3-10 kW
Hot Surface Temperature of the TEG	250 °C
Nominal Electrical Power Output	200 W_{el}
Electrical Efficiency	2%
Fuel	wood pellets

2.3 Design and Technical Specifications of a Prototype with Integrated TEG 400

The prototype shown in Figure 4 is designed to have a two-stage TEG allowing operating temperatures of up to 400 °C, thereby facil itating higher efficiencies at half the production costs. The lower temperature stage is designed to consist of the same material as that of the TEG 250 and the upper temperature stage is planned to consist mainly of lead telluride. As the upper and lower stages are thermally connected in series, the same amount of heat would flow through both stages, thus resulting in almost the same amount of thermoelectric power generation.

As thermoelectric materials for the upper temperature stage have not been commercially available at the time of the performed experimental, the prototype is erected with a TEG 250 in combination with materials having similar thermal properties to the material of the proposed upper temperature stage. This upper temperature stage serves as a thermal model and does not deliver any electricity yet. The advantage of using such a model for the TEG 400 is that both the development of thermoelectric materials and the R&D on the thermal integration could be done simultaneously. The design point of the prototype with the model of a TEG 400 is shown in Table II.

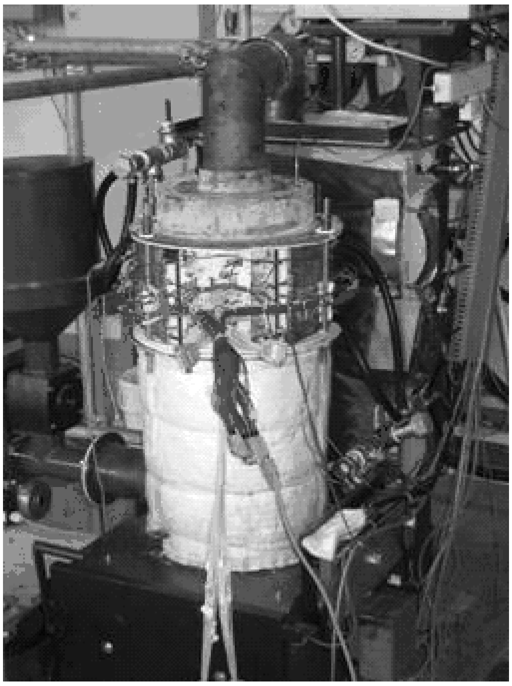

Figure 4: Micro-CHP Prototype: water-cooled biomass boiler with integrated model of a TEG 400

Table II: Design specifications of the prototype with integrated model of a TEG 400

Parameter	Value
Nominal Fuel Heat Input	11 kW
Fuel Heat Input range	3,3-11 kW
Hot surface Temperature of the TEG	400 °C
Nominal Electrical Power Output, lower stage	200 Wel
Estimated Nominal Electrical Power Output*	400 Wel
Electrical Efficiency*	3,6%
Fuel	wood pellets

* including projected power production from upper stage thermal model (thermoelectric material not yet available)

3. Test Methodology

3.1 General Description

The standard analysis method serves to characterise the transient behaviour of micro-CHP systems with thermoelectric generators over the course of a practical operation cycle. For the standard evaluation, a typical but simplified operation cycle is chosen which consists of starting the micro-CHP system, operation until steady state is reached followed by the system shut down.
In order to describe the entire operation cycle, standard parameters are defined in order to characterise the energy production and consumption patterns of combustion units, thereby providing a basis with which various micro-CHP units can be compared.
Of interest for this standard method are the power production ($P_{produced}$) and power consumption ($P_{consumed}$) curves, which can be integrated to yield the energy production ($E_{produced}$) and energy consumption curves ($E_{consumed}$):

$$E = \int P \cdot dt \tag{1}$$

This standard method is of particular significance when examining the possibility of attaining grid independent operation with thermoelectric generator system.

3.2 Description of Phases

In this analysis method, a standard operation cycle is broken down into 3 distinct and successive phases:

- Start Up Phase
- Energy Surplus Phase
- Shut Down Phase

Figure 5 shows the three phases in a standard operation cycle. The four curves in the diagram represent the produced power (dark thick line), the produced energy (thick grey line), the power consumed by the system (thin dark line) and the energy consumed by the system (thin grey line). The boundary conditions for these phases will be defined in the following sections.

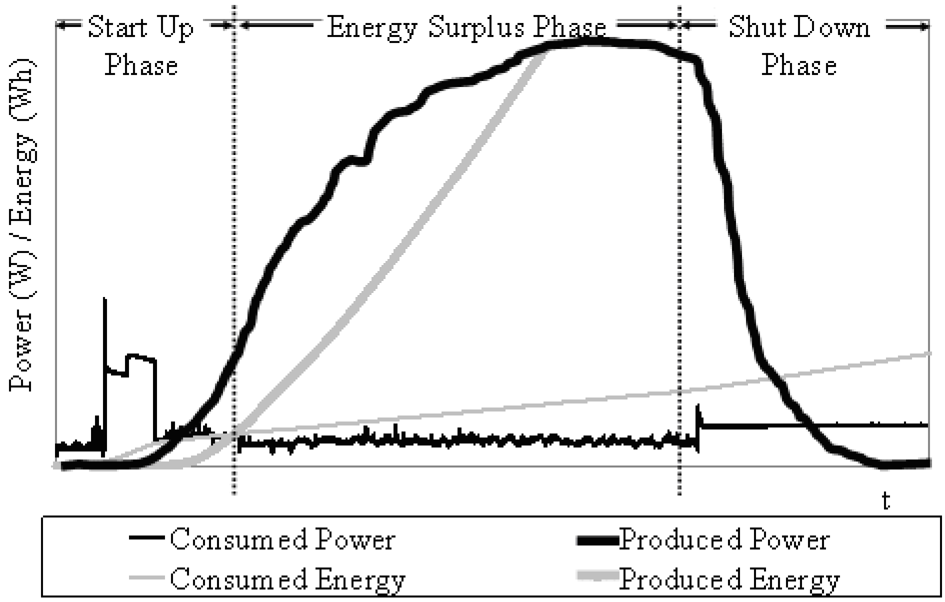

Figure 5: Phases in standard operation cycle

In order to define the phases, the change in system energy is examined:

$$\Delta E_{System} = E_{produced} - E_{consumed} \qquad (2)$$

Within each phase, standard parameters are defined to characterise the key stages of the standard operation.

3.2.1 Start Up Phase

The Start Up Phase is defined by the period of time at the beginning of the operation in which there is a net energy deficit in the system:

$$\Delta E_{System} < 0 \qquad (3)$$

This phase begins as soon as the fuel delivery is started and ends once the energy produced exceeds the energy required by the system for operation ($E_{produced} > E_{consumed}$).

To further characterise this phase, two standard parameters are defined: the Start Up Energy (E_{SU}) and the Minimum Operation Time ($t_{min,op}$). The ladder standard parameter ($t_{min,op}$) is synonymous with the point when $E_{produced} > E_{consumed}$ and thus marks the end of the Start Up Phase. This phase is of special importance when considering grid independent operation of heating systems with thermoelectric generators.

3.2.2 Energy Surplus Phase

The Energy Surplus Phase is the period in the operation during which there is a net energy surplus:

$$\Delta E_{system} > 0 \tag{4}$$

The period starts once the energy produced exceeds the energy required by the system for operation ($E_{produced}$ > $E_{consumed}$) and ends at the point in time when the fuel input to the system is stopped. This point during the operation is denoted as the fuel stop time ($t_{fuel,off}$).

During the Energy Surplus Phase, an important sub-phase known as the Steady State Phase is also defined. Steady state is defined by the phase in which the power produced by the thermoelectric generator is relatively constant. During this period of consistent power production it is thus easily possible to calculate the average amount of power produced as well as the average amount of power consumed. In order to facilitate the application of these calculations to different types of micro-CHP systems, a standardised procedure is created in order to identify the start of the Steady State Phase.

The instantaneous power produced at the time when the fuel input is stopped is used as a reference point as it is a clearly identifiable point in the operation cycle. Furthermore, based on the defined test operation that is chosen for the evaluation purposes of this standard analysis method, the fuel stop time ($t_{fuel,off}$) is known to be in the Steady State Phase. The instantaneous power produced at this time is denoted as $P_{fuel,off}$.

The system is said to have reached steady state when the produced power ($P_{produced}$) is within 5% of $P_{fuel,off}$, i.e., when the following condition is met:

$$0{,}95 \cdot P_{fuel,off} \leq P_{produced} \leq 1{,}05 \cdot P_{fuel,off} \tag{5}$$

Once the Steady State Phase in the operation cycle is determined, average values can be calculated from within this time period. A value of great importance is the average power production (P_{avg}), which is the average amount of power produced by the system during the Steady State Phase. Likewise, the average consumed power ($P_{cons,avg}$) can be calculated, which is the average amount of power consumed by the system during the Steady State Phase.

3.2.3 Shut Down Phase

The Shut Down Phase begins as soon as the fuel delivery into the system is stopped ($t_{fuel,off}$). The end of the Shut Down Phase (and also the end of the standardised operation) occurs when the system can be safely shut off, ensuring that no water in the system will boil. This end point is defined as the end of operation time ($t_{op,end}$). In a system with an automatic control system, the end of operation time is predefined and the system will automatically operate to this point when shutting down or changing to standby mode. In a system with a manual control system, this point must be determined based on the aforementioned criterion. In order to characterise the Shut Down Phase, two standard parameters are defined: the Energy Storage (E_{ES}) and the Shut Down Energy (E_{SD}).

During the Shut Down Phase there is both a power surplus and a power deficit. The point in time at which the produced power sinks below the consumed power is defined as the power deficit time (t_{pd}). In terms of the net energy balance during the shut down phase, it can be described with the following equations:

$$\Delta E_{System} > 0 \ : t_{fuel,off} < t < t_{pd} \tag{6}$$

$$\Delta E_{System} < 0 : t_{fuel,off} < t \leq t_{op,end} \tag{7}$$

Based on the two defined standard parameters, important information can be deduced regarding the energy storage capacity of the system as well as the potential for grid independent operation.

3.3 Parameters in Start Up Phase

3.3.1 Start Up Energy

The Start Up Energy (E_{SU}) is the energy required by the system until the point in time where $P_{produced} > P_{consumed}$. This point in time is defined as the power surplus time (t_{ps}). The Start Up Energy can be calculated using the following formula:

$$E_{SU} = \int_0^{t_{ps}} P_{consumed} \cdot dt \tag{8}$$

The Start Up Energy is the amount of energy required by the system for operation during the period of energy deficit during the start up phase. During this time ($t < t_{ps}$), the thermoelectric generator is thus not able to produce enough power to operate its auxiliary devices. As such, the start up energy represents the amount of energy that would be required by an external source for start up, in the event that the combustion unit were to be operated independently from the grid. Figure 6 provides a graphical representation of this parameter.

3.3.2 Minimum Operation Time

The Minimum Operation Time ($t_{min,op}$) is the point in time at which the energy produced by the system exceeds the energy consumed by the system ($E_{produced} > E_{consumed}$). As the name suggests, this is the minimum operation time for the combustion unit. Should a battery be used in conjunction with the system to store energy during the operation, this point in time represents the point at which the storage conditions in the battery would be the same as the conditions upon start up.

$$t_{min,op} = \text{time at which } E_{produced} > E_{consumed} \tag{9}$$

The Minimum Operation Time also marks the end of the Start Up Phase and subsequently, the beginning of the Energy Surplus Phase. Figure 6 graphically depicts the start up energy as well as the minimum operation time in a standard operation cycle.

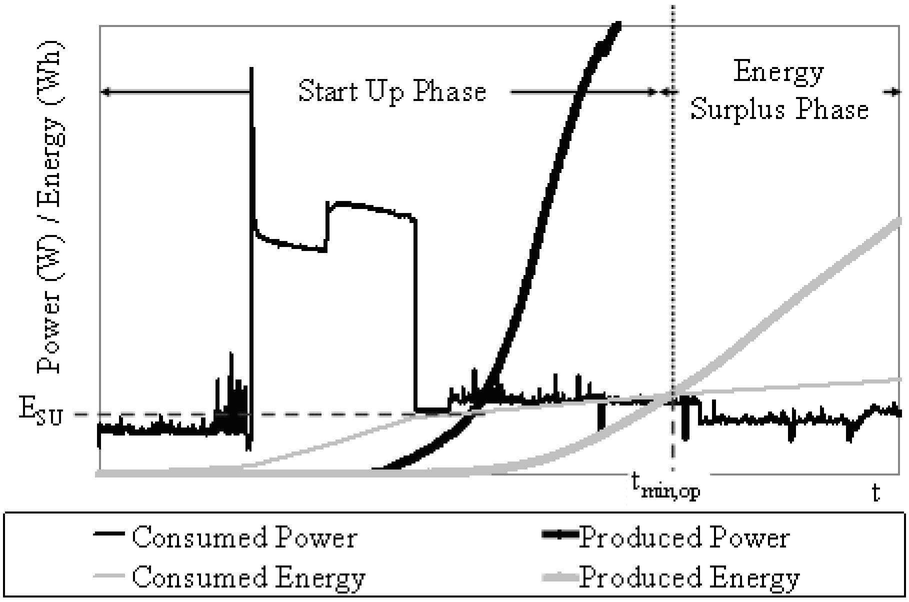

Figure 6: Start Up Phase with standard parameters: Start Up Energy (E_{SU}) and Minimum Operation Time ($t_{min,op}$)

3.4 Parameters in Energy Surplus Phase

3.4.1 Average Power Surplus

The average power surplus is the excess power that is available during steady state operation. This parameter represents the amount of energy that is available to be stored during this period of time and is calculated using the following equation (see Figure 7 for graphical support):

$$P_{avg,surp} = P_{avg} - P_{cons,avg} \tag{10}$$

Two subsequent standard parameters can then be calculated based on the Average Power Surplus: the 50% Power Time and the 90% Power Time.

3.4.2 50% Power Time and 90% Power Time

Both the 50% Power Time ($t_{50\%}$) and the 90% Power Time ($t_{90\%}$) serve to provide an indication of the speed at which the system reaches steady state conditions. The parameters denote the time it takes to achieve 50% and 90% of the Average Power Surplus ($P_{avg,surp}$) respectively.

$$P(t_{50\%}) = 0{,}5 \cdot P_{avg,surp} \tag{11}$$
$$P(t_{90\%}) = 0{,}9 \cdot P_{avg,surp} \tag{12}$$

These two numbers provide information relevant to the characterisation of the system's power production behaviour over time as well as information regarding the energy storage capacity of the system. For example, a system that has a high energy storage capacity would have longer 50% and 90% power times as more energy would be stored in the system upon start up, resulting in less power produced. *Figure 7* graphically depicts the standard parameters in the Energy Surplus Phase.

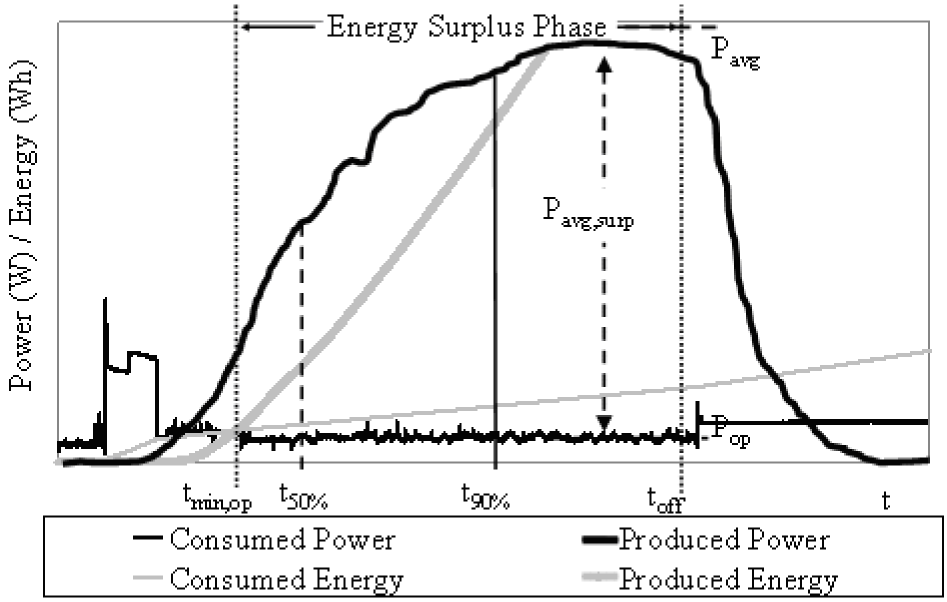

Figure 7: Standard Parameters during the Energy Surplus Phase: Average Power Surplus ($P_{avg,surp}$) 50% Power Time ($t_{50\%}$) and 90% Power Time ($t_{90\%}$).

Based on preliminary research of heating systems with thermoelectric generators, the 50% Power Time and 90% Power Time were found to fall in the Energy Surplus Phase and have thus been described as such in the standard methodology. This however may not hold true for all systems, particularly systems which exhibit very steep power production curves. In such cases, the 50% Power Time may in fact be found in the Start Up Phase and not the Energy Surplus Phase.

3.5 Parameters in Shut Down Phase

3.5.1 Energy Storage

After the fuel input into the system is stopped, it can be observed that power continues to be produced (i.e. there is still a power surplus), meaning that energy stored in the system during operation is being released. This period of stored energy release begins at the fuel stop time ($t_{fuel,off}$) and ends as soon as there is a net power deficit ($P_{consumed} > P_{produced}$). The time at which the power deficit occurs is defined as the power deficit time (t_{pd}). This point is defined as it marks the end of the power surplus in the Shut Down Phase and thus the end of useful energy production.

The Energy Storage (E_{ES}) is the electric energy produced after the fuel input has been stopped and is due to the energy that was stored in the system during operation. This parameter can be calculated from the energy produced minus the energy consumed during the time interval of power surplus in the Shut Down Phase:

$$E_{ES} = \int_{t_{fuel,off}}^{t_{pd}} P_{produced} \cdot dt - \int_{t_{fuel,off}}^{t_{pd}} P_{consumed} \cdot dt \qquad (13)$$

The Energy Storage parameter thus provides information regarding the energy storage characteristics of the micro-CHP system. In Figure 8 the Energy Storage is represented by the shaded area between the power production curve and consumed power curve, as defined by the formula above.

3.5.2 Shut Down Energy

The Shut Down Energy is defined as the amount of energy required by the system to operate during the period of energy deficit ($\Delta E_{system} < 0$) in the Shut Down Phase. The beginning of this period is marked by the energy deficit time (t_{pd}) and ends at the point when the system can be safely shut off, ensuring that no water in the system will boil ($t_{op,end}$). In a system with an automatic control system, this point is automatically defined by the control system and the required safety conditions for a successful shut down. In a system with a manual control system, this point must be determined based on the aforementioned criterion.
The Shut Down Energy (E_{SD}) is thus defined by the energy deficit left at the end of the operation on the consumed energy curve:

$$E_{SD} = \int_{t_{pd}}^{t_{op,end}} P_{produced} \cdot dt - \int_{t_{pd}}^{t_{op,end}} P_{consumed} \cdot dt \qquad (14)$$

The shut down energy is of significant importance in terms of achieving grid independent operation because it represents the energy demand that would be required from an external energy storage device (such as a battery) for a safe shut down if the system were to be operated independently from the grid. In this case, the consequent energy deficit resulting in the external energy storage device at the end of the operation represents the energy deficit that would be present in the device upon entering a subsequent operation. Figure 8 shows the shut down parameters.

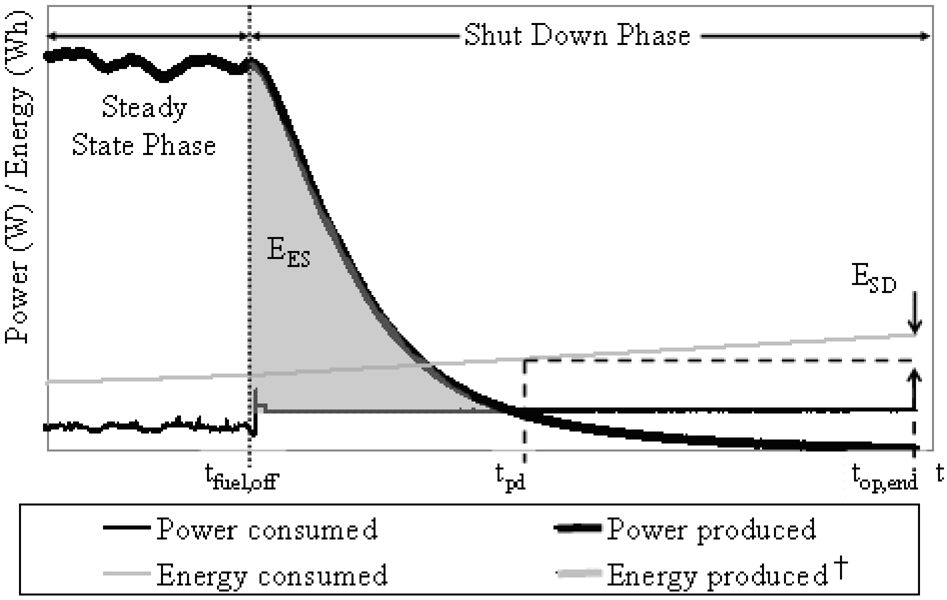

Figure 8: Standard Parameters during the Shut Down Phase: Energy Storage (E_{ES}, shaded area between produced and consumed power) and Shut Down Energy (E_{SD})
† The produced energy is not shown as it is out of the chosen scale range in the figure

3.6 System Parameters

In order to analyse the entire system performance, three standard parameters were defined: the Electrical Efficiency, Thermal Efficiency and Total Efficiency. Of great importance for these standard parameters are the fuel heat input, the useful heat and the electric power produced. The fuel heat input is defined as the amount of heat available in the fuel based on the heat value (NCV).
The useful heat attained from the system is defined by the amount of heat that can be readily used. In the case of systems with thermoelectric generators, the useful heat is the amount of heat delivered to the cooling water that can be used for domestic heating. The electric power is likewise the power that is delivered from the thermoelectric generator that can be readily used either by the combustion unit itself or by a storage device.

3.6.1 Electrical Efficiency

The Electrical Efficiency is defined by the ratio of the average power produced (P_{avg}) and the average fuel heat input (both in kW) during the steady state phase:

$$\eta_{el} = \frac{P_{avg}}{\dot{Q}_{FuelHeatInput}} \tag{15}$$

3.6.2 Thermal Efficiency

The Thermal Efficiency is defined by the ratio of the average amount of useful heat energy and the average fuel heat input (both in kW) during the steady state phase:

$$\eta_{th} = \frac{\dot{Q}_{UsefulHeat}}{\dot{Q}_{FuelHeatInput}} \tag{16}$$

3.6.3 Total Efficiency

The Total Efficiency is defined by the ratio of the average amount of power produced plus the average amount of useful heat energy and the average fuel heat input (all in kW) during the steady state phase:

$$\eta_{tot} = \frac{\dot{Q}_{UsefulHeat} + P_{avg}}{\dot{Q}_{FuelHeatInput}} \tag{17}$$

3.7 Summary of Parameters

Table III provides a summary of the characteristic parameters defined by the standard analysis method with the corresponding units.

Table III: Characteristic parameters

Parameter		
Electrical Efficiency	η_{el}	%
Thermal Efficiency	η_{th}	%
Total Efficiency	η_{tot}	%
Start Up Energy	E_{SU}	Wh
Minimum Operation Time	$t_{min,op}$	s
Average Power Surplus	$P_{avg,surp}$	W
50% Power Time	$t_{50\%}$	s
90% Power Time	$t_{90\%}$	s
Energy Storage	E_{ES}	Wh
Shut Down Energy	E_{SD}	Wh

3.8 Implications for Grid Independent Operation

In analysing the potential of a system with thermoelectric generators for achieving grid independent operation, two steps are required. The first is analysing the net energy balance of a single, isolated operation. The second is carrying over the net energy balance of the aforementioned isolated operation to a subsequent operation.
In performing this assessment using the presented standard analysis method, two parameters are of great importance: the Shut Down Energy and the Start Up Energy. The Shut Down Energy plus the Start Up Energy is thus equal to the minimum amount of energy required by an external energy storage device so that the micro-CHP system may operate independently from the grid. This also corresponds to the

minimum amount of energy that is required to be produced by the thermoelectric generator system during operation to recharge the external energy storage device.

4. Results

4.1 Test Procedures

The test procedures for each system are performed so as to constitute a Start Up Phase, Steady State Phase and Shut Down Phase. For all three systems, it is endeavoured to achieve consistent test procedures. Due to the diverse nature of the technologies and their respective control systems however, inevitable variations in the test procedures occur. The test procedures are thus described, identifying any variations between the test processes.

4.1.1 Test Procedure for TEG 250

The test procedure for the prototype with the TEG 250 is defined to begin as soon as the initial fuel delivery is started. During the system start-up, a manual control sequence for the ignition, fuel screw and flue gas fan is used. Directly following the successful ignition, the fan is set to maximum speed in order to deliver a maximum amount of oxygen into the combustion chamber and the nominal load of pellets is fed into the combustion chamber. During the system start up, the excess air ratio is very low and monitored as all the pellets in the combustion chamber are ignited. As soon as the residual oxygen content in the flue gas exceeds 6%, the flue gas fan control is switched from manual mode to control mode, whereby the fan adjusts its speed based on the excess air ratio, so as to maintain a residual oxygen content in the flue gas between 6% and 8%. This automatic excess air ratio control of the flue gas fan is maintained throughout the Steady State Phase along with maintaining a constant fuel heat input at nominal load. The system shut down is manually initiated upon which time the fuel screw is turned off and the flue gas fan is switched back to manual mode at 100% power to cool the combustion chamber as quickly as possible. As the TEG 250 requires a manual control sequence, the end of operation point ($t_{op,end}$) is selected to be when the temperature in the combustion chamber is less than 100℃. This temperature is selected so as to ensure that the water in the system would not boil and that no damage to the thermoelectric material would occur.

4.1.2 Test Procedure for TEG 400

The test procedure for the prototype with the TEG 400 is defined to begin as soon as the initial fuel delivery was started. A standard control system (provided by the manufacturer) is used to control the system parameters. The control system features a standard automatic start-up programme, whereby the pellets input is increased stepwise after the ignition until reaching the nominal fuel heat input. The Steady State Phase is operated with a constant fuel heat input at nominal load. In both these phases the fan speed is controlled using a lambda probe to adjust the desired excess air ratio as set by the standard control system. The system shut down is manually initiated upon which time the standard control-system stops fuel input and increases the flue gas fan speed to cool the system. As with the TEG 250, the end of operation point ($t_{op,end}$) is chosen to be when the temperature in the combustion chamber falls below 100℃.

4.2 System Boundaries

In terms of system boundaries, the prototype with the TEG 250 and the prototype with the TEG 400 effectively exhibit the same system. In both systems, the electric power consumption of the water circulation pump was not measured and as such, a 10 W pump (high efficiency pump for a well dimensioned heat supply system) was assumed and added to the measured electric power consumption. The lambda probe of the integrated TEG 250 system was not measured, therefore a lambda probe sensor of 15 W was assumed. Table IV and Table V provide a list of the components considered in the system energy balance for the prototype with the TEG 250 and the TEG 400 respectively. Figure 9 provides a graphical representation of the system boundaries used in performing the system energy balance for both systems.

Table IV: Electrical components considered in the evaluation of the electric power consumption of the boiler with integrated TEG 250

Component	Consumption
Fuel Screw	12 VDC, measured
Flue Gas Fan	12 VDC, measured
Ignition	12 VDC, measured
Manual Control System	12 VDC, measured
Lambda Probe	12 VDC assumed 15 W
Pump for Water Circulation	12 VDC assumed 10 W

Table V: Electrical components considered in the evaluation of the electric power consumption of the boiler with integrated model of a TEG 400

Component	Consumption
Fuel Screw	230 VAC, measured
Flue Gas Fan	230 VAC, measured
Ignition	230 VAC, measured
Lambda Probe	230 VAC, measured
Auxiliary Drives for Air Control	230 VAC, measured
Automatic Control System	230 VAC, measured
Pump for Water Circulation	230 VAC, assumed 10 W

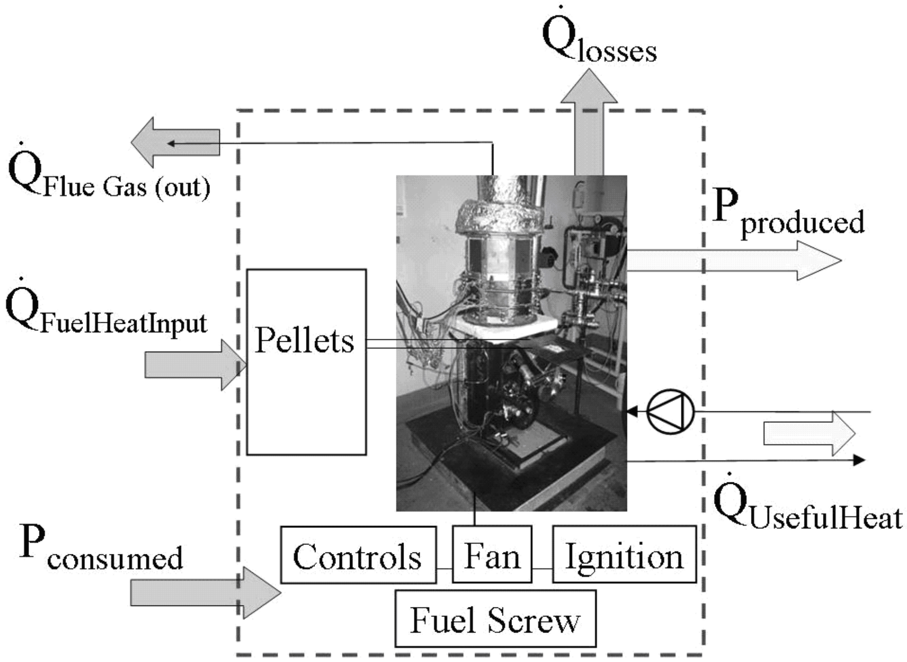

Figure 9: System boundaries for the prototypes with the integrated TEG 250 and TEG 400

4.3 Experimental Results for the Prototypes with Integrated Thermoelectric Power Generation

The standard analysis method presented in chapter 3 has been applied to both the prototype with the integrated TEG 250 and the prototype with the model of a TEG 400. The calculated standard parameters based on the measurements performed during the experimental trials are listed in Table VI for the TEG 250 and in Table VII for the TEG 400. For the TEG 400, the standard parameters based on both the measured electrical power consumption with the 230 VAC standard components and the estimated power consumption with the assumption of using high efficiency 12 VDC components are provided. This is done in order to show the effect that using efficient 12 VDC electrical components would have on the calculated standard parameters. Furthermore, Figure 9 to Figure 11 show the trends of produced and consumed power and energy over a standard operation cycle for the prototype with the TEG 250. The calculated parameters from *Table V* are also shown in Figure 9, Figure 10 and Figure 11.

The results show that of the two investigated prototypes, the prototype with the integrated TEG 250 requires less energy for start up and less time to reach steady state. This is shown as the Start Up Energy for the TEG 250 prototype is found to be one fourth of the Start Up Energy for the TEG 400 prototype. The Minimum Operation time of the TEG 250 prototype is lower, equal to half that of the TEG 400 prototype. Moreover, the TEG 250 prototype requires almost half the time to reach both the 50% and 90% Average Power Times.

On the other hand, the Average Power Surplus of the prototype with TEG 400 is found to be approximately double that of the TEG 250 prototype. The average power consumption of the TEG 400 prototype is approximately double that of the TEG 250 prototype.

Both prototypes are found to have approximately the same energy storage and shut down energy.
In examining the provided data in Table VI, the estimated effect of using efficient 12 VDC electrical components on the calculated standard parameters is shown. The most notable difference is seen in the average power consumption and the Shut Down Energy (see notes under the table for a full description).
For both prototypes, the average achieved electrical power production is lower than expected. The deviations from the design point concerning the thermal system integration and the operation of the TEGs have been investigated and discussed in [2], but are not a subject of this paper. The Average Power Surplus also depends on the electrical consumption of the prototypes. For the prototype with TEG 250, very efficient electrical components based on 12 VDC are used. The prototype with the TEG 400 on the other hand is designed with standard electrical components based on 230 VAC. As a result, the average power consumption of the prototype with the TEG 250 is half that of the prototype with the prototype of the TEG 400.

Table VI: Test results for the prototype with the integrated TEG 250

Parameter	Value
Electrical Efficiency	1,5%
Thermal Efficiency	not measured
Total Efficiency	not measured
Energy (E_{SU})	24 Wh
Minimum Op. Time ($t_{min,op}$)	57 min
50% Power Time ($t_{50\%}$)	37 min
90% Power Time ($t_{90\%}$)	74 min
Avg. Power Production	149 W
Avg. Power Consumption	34 W
Avg. Power Surplus ($P_{avg,surp}$)	115 W
Energy Storage (E_{ES})	12 Wh
Shut Down Energy (E_{SD})	31 Wh

TableVII: Test results for the prototype with the integrated model of a TEG 400 (power output from the TEG 400 is based on the extrapolated power output from the upper stage – material not yet available)

	Electric Components	
Parameter	230 VAC	12 VDC*
Electrical Efficiency	1,5%	unchanged
Thermal Efficiency	not measured	
Total Efficiency	not measured	
Start Up Energy (E_{SU})	104 Wh	~ 100 Wh**
Minimum Op. Time ($t_{min,op}$)	96 min	~ 90 min**
50% Power Time ($t_{50\%}$)	58 min	unchanged
90% Power Time ($t_{90\%}$)	126 min	unchanged
Avg. Power Production	345 W	unchanged
Avg. Power Consumption	69 W	44 W**
Avg. P. Surplus ($P_{avg,surp}$)	276 W	301 W
Energy Storage (E_{ES})	12 Wh	~ 13 Wh**
Shut Down Energy (E_{SD})	26 Wh	~ 13 Wh**

* High efficient components

** The Start Up Energy and the Minimum Operation Time would be reduced by only approximately 5% as these values are largely based on the power production curve, which is not effected by the selected electrical components. The Average Power Consumption and thus the Average Power Surplus would benefit from savings in using high efficiency drives for the flue gas fan and fuel screw. Furthermore the Energy Storage (E_{ES}) would be approximately 10 % higher and the Shut Down Energy (E_{SD}) would be approximately halved.

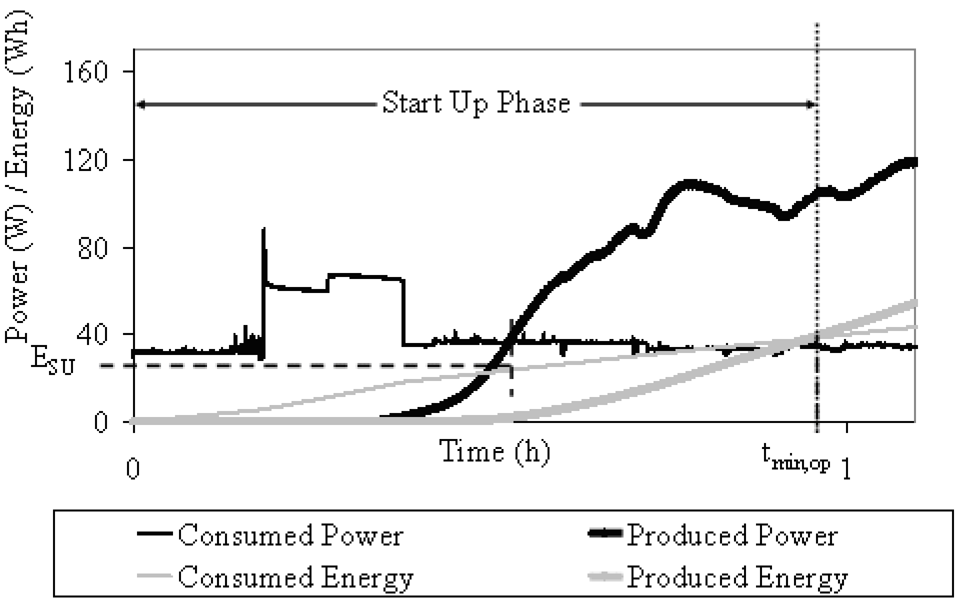

Figure 10: Results for the standard parameters during the Start Up Phase for the prototype with integrated TEG 250: Start Up Energy (E_{SU}), Minimum Operation Time ($t_{min,op}$)

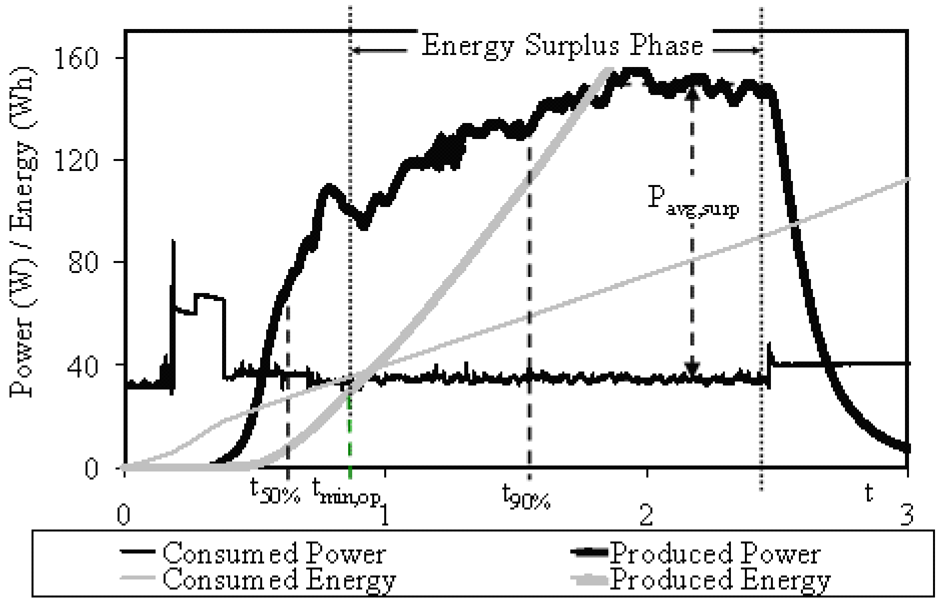

Figure 11: Results for the standard parameters during the Energy Surplus Phase for the prototype with integrated TEG 250: 50% Power Time ($t_{50\%}$) and 90% Power Time ($P_{90\%}$), Average Power Surplus (P_{avg})

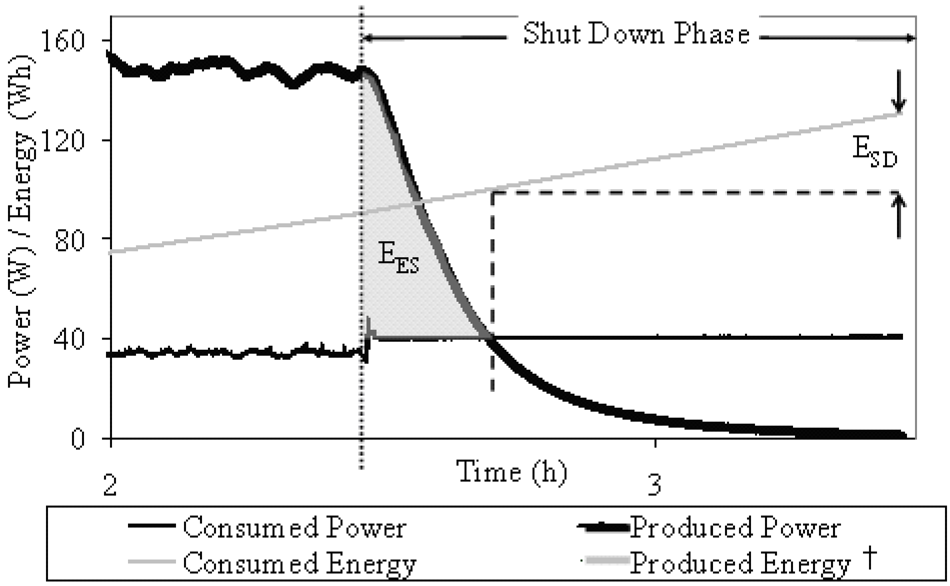

Figure 12: Results for the standard parameters during the Shut Down Phase for the prototype with integrated TEG 250: Energy Storage (E_{ES}, shaded area between produced and consumed power) and Shut Down Energy (E_{SD})

†The produced energy is not shown as it is out of the chosen scale range in the figure.

5. Electricity Production Costs

It is the main goal of pellets combustion with thermoelectric power production to produce enough electrical energy for the heating and heat distribution. Hence the nominal electrical output of the prototype is not defined by economic needs (maximum possible!!). It is set to 200/400!! W_{el}. To be able to make a common cost comparison of electricity production costs [4] are calculated by the annuity method.

5.1 Assumptions

The basis for the calculation of the electricity production costs of a pellet combustion system with thermoelectric electricity production are the additional costs in comparison to a standard pellet combustion system for room heating.

For the calculation of costs for the production of electrical energy the following assumptions are met:

- The assumed calculation rate per cent for capital costs is 5%
- The life cycle for a pellet combustion with thermoelectric power production is 20 years
- It is referred to a fuel heat output of 9 kW and 2000 full load hours. The number of full load hours is varied.
- The annual use efficiency of the micro CHP system is 80%, including the amount of electrical net energy, which is estimated by an assumed practical annual load distribution.
- The reference price for wood pellets is the averaged value, ascertained by ProPellets Austria for July 2008. The price corresponds to a delivery of 6 tons according to ÖNORM M 7135. Referring to the energy contents this is 0,0366 €/kWh. The fuel costs are varying (www.propellets.at)
- The costs of operation are composed of maintenance cost for the thermoelectric generator and the upkeep costs. For the annual maintenance costs of 1% of the investment costs are assumed, for the upkeeping additional costs of 10 €/year compared to conventional pellet combustion systems are assumed.

5.2 Break of Costs

The investment costs for the thermoelectric power generation include the thermoelectric generator, the heat transferring system, additional costs for electrical power treatment and storage as well as additional costs for firing and the heat distribution system. Table VIII gives an overview of the investment costs for all variations.

Table VIII: Investment costs for thermoelectric power generation

Generator model[1]	Investment costs for thermoelectric power generation
TEG 250/200	2700 €
TEG 400/200	2100 €
TEG 400/300	2625 €
TEG 400/400	3150 €

A comparison of the two thermoelectric generators with 200W nominal electrical output shows significant higher costs for the single-step generator with a hot side tem-

[1] TEG xxx/yyy: xxx ist he nominal surface temperature of the hot side of the thermoelectric generator; yyy is the nominal electrical output of the thermoelectric generator in [W[. The model TEG 250/200 was already used successfully as a one step thermoelectric generator. The models TEG 400/yyy are actually under development as multi-step thermoelectric generators.

perature of 250℃. This is because a main part of t he costs is caused by the thermoelectric material. More of this material is needed for the TEG 250/200 because the electrical efficiency is lower.

TableIX: fuel costs and operational costs for maintenance and upkeeping

Generator model[2]	Annual electr. efficiency	Electrical output	Fuel costs	Operational costs
TEG 250/200	1,5 %	344 kWh/year	16 €/year	37 €/year
TEG 400/200	2,6 %	605 kWh/year	26 €/year	31 €/year
TEG 400/300	2,8 %	653 kWh/year	30 €/year	36 €/year
TEG 400/400	3,0 %	701 kWh/year	32 €/year	41 €/year

The annual use efficiency for electrical power generation is estimated for a typical load distribution for room heating. The thermoelectric models TEG 250/200 and TEG 400/400 focus on the maximum possible electrical output. Hence the electrical use efficiency is maximised at nominal load. The other models (TEG 400/200 and TEG 400/300) are optimised for partial load. Hence the maximum electrical output is at partial load. These values are used to calculate the amount of annual produced electrical energy and the fuel costs.
Figure 13 shows a comparison of the specific energy production costs for the 4 different models. The costs are divided in capital costs, fuel costs and operational costs. A comparison of the two thermoelectric generators with a nominal electrical output of 200 W shows that there are significant cost advantages for the TEG 400/200 due to a higher electrical efficiency. The increase of the specific electricity production costs with increasing nominal electric output is caused by the fixed nominal heat output of 9kW.

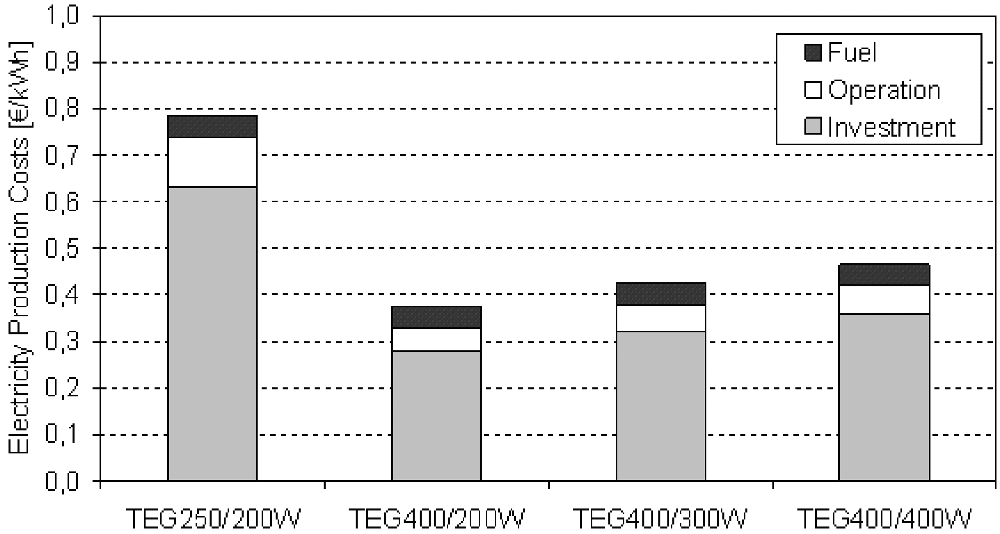

Figure 13: Comparison of the specific power production costs for different thermoelectric generator models with a nominal heat output of the pellet combustion of 9 kW

[2] TEG xxx/yyy: xxx ist he nominal surface temperature of the hot side of the thermoelectric generator; yyy is the nominal electrical output of the thermoelectric generator in [W[. The model TEG 250/200 was already used successfully as a one step thermoelectric generator. The models TEG 400/yyy are actually under development as multi-step thermoelectric generators.

If the relation of heat output and nominal electrical output is kept constant and the heat output is increased, the power production costs only sink marginally. This is due to the fact that thermoelectric material is with 43 % one of the main cost factors for the thermoelectric generators and the needed amount of this material is increasing linear with the nominal electrical output. The minimal cost reduction is caused by the better cost relation of the components for preparation and storage of the direct current.

In *Figure 14* the sensitivity of some parameters is shown starting with the TEG 250/200. The amount of full load hours is the most important parameter. The material used for the thermoelectric generators is shown because it is not negligible with a cost fraction of 43 % for the basis case. On the other side there are cost uncertainties for the acquisition of qualified material. The effects of price variations are comparable with those for fuel and operational costs.

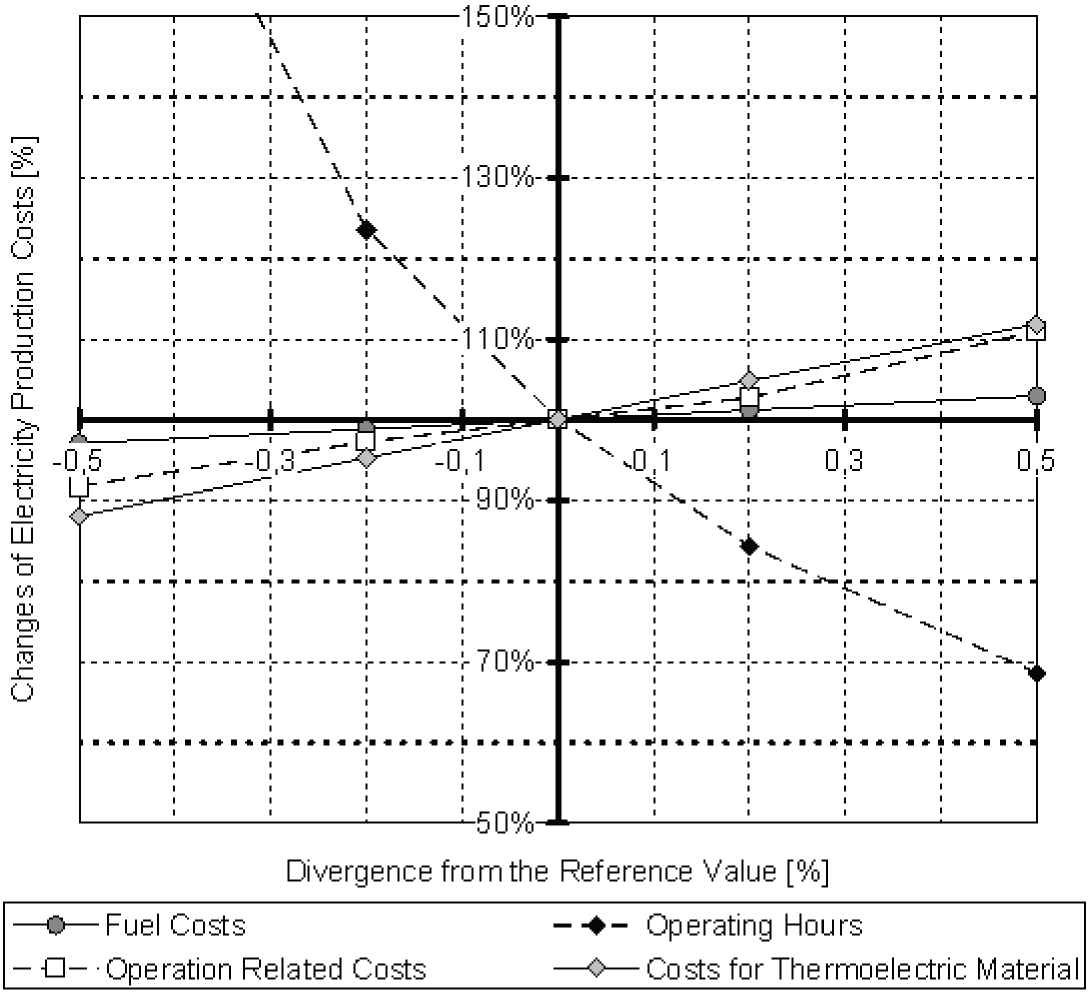

Figure 14: Effects of changes of essential parameters on the power generation costs

6. Summary and Outlook

The development of the pellets combustion focuses on a fully automated room heating production by biomass, which is independent from an electrical grid. The technology for power production should be used in central heating devices as well as in room heating devices. Hence thermoelectric is the chosen system.
In a first development step a pellets combustion with 10 kW fuel input is designed, in which a thermoelectric generator with a nominal output of 200 W is integrated. The thermoelectric generator is a single-step model and transfers in the design point the heat from the combustion gas with 250 ℃ into the b oiler water with 60 ℃. The resulting electric efficiency is 4 %. The electric system efficiency referred to the fuel heat output is 2 %, if 50 % of the fuel heat output is transferred over the thermoelectric generator.
The experimental result of the first prototype of the pellets combustion with thermoelectric generator shows that the aimed system efficiency is realisable. In case of standard operation, which is the basis for the variation of single parameters, the electrical efficiency of the thermoelectric generator is 3,3 %, the electrical system efficiency is 1,5 % and the electrical output is 150 W. These values are reproducible. By the means of optimisation at the heat insulation and the operation parameters the efficiency of the thermoelectric generator was improved to 3,6 %, the electrical system efficiency reached up to 1,7 % and the maximum electrical output was 220 W.
The calculated effective temperature difference over the thermoelectric generator was not reached. By the means of adoption of the heat resistance of the thermoelectric generator this circumstance can be corrected. Furthermore 4 of the 16 thermoelectric modules do not perform at the optimum due to minor defects at the thermal contacting. If these circumstances are part of the calculation the theoretical electrical efficiency of the thermoelectric generator is nearly 4 %, the system efficiency is 2 % and the electrical output is 200 W. The aimed values can be reached and the self sufficiency is possible.
The next development step is the increase of the hot side temperature to 400 ℃ by the means of a multi-step thermoelectric generator. By this the electrical efficiency is increased to 8-9 % and the electrical system efficiency is 4 %. In addition the production costs of electricity are reduced to 0,38 €/kWh.
This generation of thermoelectric generators will be integrated into a 12 kW pellet combustion boiler and an 8 kW pellet furnace. So the self sufficiency will be demonstrated.
Furthermore the existing prototypes can be used to test thermoelectric generators, which can be operated at temperatures from 200 to 400 ℃ and which provide enough electricity for a grid independent operation. With some additional adaptations thermoelectric generators could be used at temperatures up to 600℃.

7. Acknowledgements

The shown results have been produced within the Kplus and comet program and have been funded by the Austrian federation, Styria, Lower Austria and Graz. Many thanks also to the involved companies

- HET – Heiz- und Energietechnik Entwicklungs GmbH
- KWB biomass heating systems

- RIKA – Innoivative Ofentechnik GmbH
- Brigitte Schrödl
- SHT – heating technology from Salzburg
- Viessmann Werke GmbH & Co KG

The scientific partner

- Vienna University of Technology – Institute of chemical engineering
- FJ-BLT – Biomass Logistics Technology at Francisco Josephinum

And our development partners

- TEC COM GmbH
- DLR – German Aerospace Center

References

[1] G. Friedl, A. McCarry, S. Aigenbauer, W. Moser, E. Höftberger, W. Haslinger, Evaluating the Transient Behaviour of Biomass Based Micro-CHP Systems - Steam Piston Engine and Integrated Thermoelectric Power Generation. 18th European Biomass Conference, Lyon, France, 2010

[2] G. Friedl, W. Moser, A. McCarry, K. Berndt, R. Schöpke: Micro-CHP – Experiences with thermoelectric generators integrated in a wood pellet combustion unit, 28th International and 7th European Conference on Thermoelectrics, Freiburg, Germany, July (2009)

[3] W. Moser, S. Aigenbauer, M. Heckmann, G. Friedl, H. Hofbauer: Micro-scale CHP based on biomass – intelligent heat transfer with thermoelectric generators. Bioenergy 2007, Jyväskylä, Sweden, September 2007

[4] G.Friedl, W. Moser, S. Griesmayr, Pelletfeuerung m it thermoelektrischer Stromerzeugung, 10. Holzenergiesyposium, Zürich, Switzerland, 2008

The Authors

DI Dr.techn. Ernst HOEFTBERGER, Bioenergy 2020+, Wieselburg-Land
DI Dr.techn. Wilhelm MOSER, Bioenergy 2020+, Wieselburg-Land
DI Stefan AIGENBAUER, Bioenergy 2020+, Wieselburg-Land
DI Dr.techn. Guenther FRIEDL, Bioenergy 2020+, Wieselburg-Land
DI Dr.techn. Walter HASLINGER, Bioenergy 2020+, Wieselburg-Land