DIMENSIONING OF A HYBRIDSYSTEM CONSISTING OF A PV-GENERATOR AND A STEAM ENGINE WITH COMBINED HEAT AND POWER FOR PRIVATE HOUSEHOLDS

K. Brinkmann
FernUniversität Gesamthochschule in Hagen, Germany
Chair of Electrical Power Engineering
Feithstraße 140, Philipp-Reis-Gebäude, D-58084 Hagen, fax: +49/2331/987 357,
e-mail: klaus.brinkmann@fernuni-hagen.de

ABSTRACT: This paper presents the main part of the results of a research project, done at the chair of electrical power engineering of the University of Hagen / Germany. It could be shown, that it is possible to provide private households self-sufficient with heat and power by the help of a hybridsystem, consisting of a PV-plant linked to a steam engine. This builds a special complex combined heat and power system, which enables a maximum exploitation of primary energy with a highest possible portion of renewable energy. This contribution presents the criterion for the dimensioning of such a system and as a concrete example the data for an average private household in Germany.
Keywords: Hybrid - 1: PV System - 2: Off-Grid - 3

1. INTRODUCTION

A major part of the above mentioned research project was the fundamental analysis of a completely self-sufficient energy-supply system for summer/winter or mixed conditions, including a photovoltaic system and a piston-type steam engine with combined heat and power [1], as shown in figure 1.

To reach this aim, this hybridsystem has been examined with the help of experimental investigations [2]. Additional theoretical analysis [3] and computational simulations [4] were helpful to build up a process scheme with all necessary components and to determine their sizes.

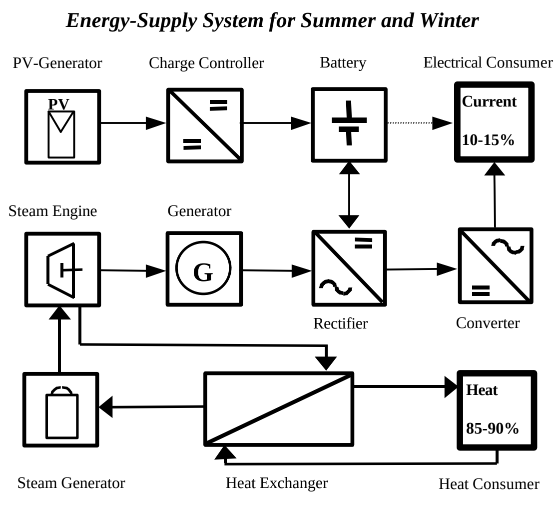

Figure 1: simplified process scheme of the hybridsystem

May be at the first view, the idea to realise the combined heat and power with the help of a piston-type steam engine seems to be curious. This technology has the disadvantage of the missing psychological valuation as a 'high-tech' solution.

But especially technical and scientific developments concerning energy-supply technologies, which are well conditioned to the fundamental rules of the nature and its ecology, ought not to be seen under a pure technical point of view, as it is usual for modern industrial product developments, where the attribute 'high-tech' serves as an important marketing element.

This does not mean, that the technical standard of the beginning of the industrial area has to be taken over. It is self-evident, that the hybridsystem as shown in figure 1 needs a 'modern' steam engine with respect to today's possibilities of the mechanical engineering.

An impressing example for such a development, which encourages to snatch up older technologies, is the success-story of the modern wind energy converter.

The combination of a PV-Plant to a combined power helps primarily to save fuels effectively.

In future, an increasing amount of biomass has to be used, because of its CO_2-neutrality; with respect to efficiency, as far as possible without preceding preparations. This implies shortest possible transportation and in the most cases solid biomass like chopped wood.

These arguments support decentralised energy-supply systems with external combustion. A hybridsystem with a PV-plant linked to a piston-type steam engine with combined head and power could be one possible option.

Additional considerations concerning other important properties like longevity, simple construction, rigidity, low susceptibility to trouble, the remaining necessary degree of efficiency and controllability of the ratio of power to heat, supported the decision to think about a PV-hybridsystem with a steam engine to provide private households.

2. PHYSICAL FOUNDATIONS

The today's annual ratio of electrical to heat energy consumption of average private households in Germany is nearly one to ten.

Essentially for the determination of the dimensioning criterion for the hybridsystem is the correlation of the time dependent consumption functions for electrical power as well as for heat [5].

It is necessary to correlate the effects of the three stochastic parameters current consumption, heat consumption and insolation. Therefore extensive long-term measurements in addition to available publications concerning these parameters for average values, as well as for the dynamic behaviour, were made and systematically examined regarding the seasonal variations.

An average household in Germany for 2,2 persons with 80 m² consumes annually 3146 kWh. The seasonal consumption in winter is greater than in summer. It is possible to approximate the daily consumption as a cosines-function, with the whole year as period.

The daily power consumption in a typical week in summer is 7,439 kWh and for a typical week in winter 10,123 kWh. The following annual ratios are valid:

$$\frac{power}{heating} \approx 0{,}11 \quad and \quad \frac{power}{process - heat} \approx 0{,}56 . \qquad (1)$$

It is also possible to approximate [2],[5] the daily heat-consumption as a cosine-function with sufficient accuracy. For a general private household, the following scaling could be used:

$$P_{general} = z \cdot P_{average} \qquad \text{with} \qquad (2)$$

$$z = \frac{annual \quad power - consumption}{3146 \quad kWh} \qquad (3)$$

With these formulas for power and heat, an approximated daily ratio of power to heat could be given:

$$\sigma(d) = \frac{P_{electrical}(d)}{P_{heat}(d)} \qquad (4)$$

The installation of a PV-Plant for the household results in an additional power supply and reduces the residual ratio of power to heat, which is left for the combined heat and power system:

$$\sigma(d)_{PV} = \frac{P_{electrical}(d) - P_{PV}(d)}{P_{heat}(d)} \qquad (5)$$

With respect to the maximum possible degree of efficiency η_{max} of the combined heat and power, the realisable ratio of power to heat is limited to be smaller than υ:

$$\sigma_{PV} \le \upsilon \quad with \quad \upsilon = \frac{\eta}{1-\eta} . \qquad (6)$$

The usual electrical efficiencies of realised combined heat and power systems for the usage of biomass with piston-type steam engines are today about 16% [2].

These information lead to a formula to determine the PV-plant for the hybridsystem. The following condition allows to adjust the PV-Plant to the steam engine:

$$P_{PV} \ge P_{electrical} - \upsilon \cdot P_{heat} . \qquad (7)$$

This condition has to be fulfilled for every day of the year.

3. TEST SETUP

For experimental investigations a test setup with a real steam engine for approximately 2.5kW from the beginning of this century has been built up and connected to a PV-Generator-Simulator, which could be co-ordinated to the results of the photovoltaic plant of the FernUniversität building.

The installed PV-Generator-Simulator with a power output of maximum 2,5 kW enables an independence of the momentary weather conditions and a time-lapsed investigations.

For the storage of electrical energy, four batteries with a capacitance of 120Ah respectively were implemented in series, with a voltage of 48V totally.

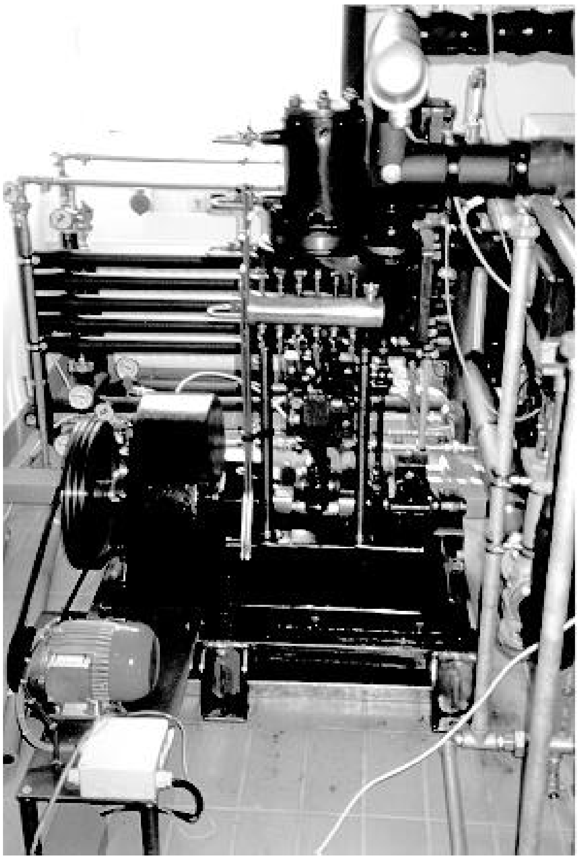

Figure 2: piston-type steam engine test setup

Unfortunately, it seems that nowadays there exists no industrial producer of piston-type steam engines for smaller machines up to 5 kW. So the only way to make progress in this research project was to recourse to a historical model, as shown in figure 2.

For simplicity concerning installation and measurements, the steam generator works with electrical energy and produces maximum 18 kW saturated steam at 6 bar and 159°C.

Two control valves split up the steam flow in two directions, one of them to the steam engine and the other bypassed directly to the condenser. This gives the possibility to regulate the ratio of power to heat and enables to produce only heat without the steam engine, which is necessary if the batteries are sufficiently charged.

The self-made condenser consists of tube heat exchanger, which are implemented in two different heat circuits, one for a radiator and the main part for the production of hot water in a 50 l water vessel.

A pump in the condense water pipe was installed to reduce the back pressure, which results in a greater efficiency of the steam engine [2].

The shaft of the steam engine is coupled to an electrical generator via a cone belt. The nominal power of the generator is 1,3 kW and it is connected to a 3-phase bi-directional converter. This converter allows to switch between motor and generator mode. Because a steam engine with only one piston is in the most cases not able to start by itself, the motor mode can be used to give the first rotations.

The implemented measuring technique is based on 4-20 mA signals, which are used by a self-made control box with a µ-controller.

4. DIMENSIONING OF THE HYBRIDSYSTEM

The process scheme in figure 3 shows the functional connections of the above mentioned components.

In order to determine the dimensioning criterion of the whole system as well as of the single components and their accommodation mutually, a computer program for a system simulation has been developed.

In addition to the experimental experiences with the test setup, this programme is a valuable tool to prove a chosen dimensioning on the basis of mass flow and energy balance calculations.

This simulation was realised with the help of 'LabView', whereas each component can be mathematically described by characteristic curves. The time dependent changes and results of the calculations are readable in a process visualisation [4].

Most important for the determination of the dimensioning was the analysis of the consumption characteristics of private households in Germany as well as for electrical power and for heat [2], which had to be correlated to the expected energy production of the PV-plant. This energy production could be estimated with the help of extensive available meteorological data.

Hybridsystem "Photovoltaic + Combined Heat and Power with Steam Engine"

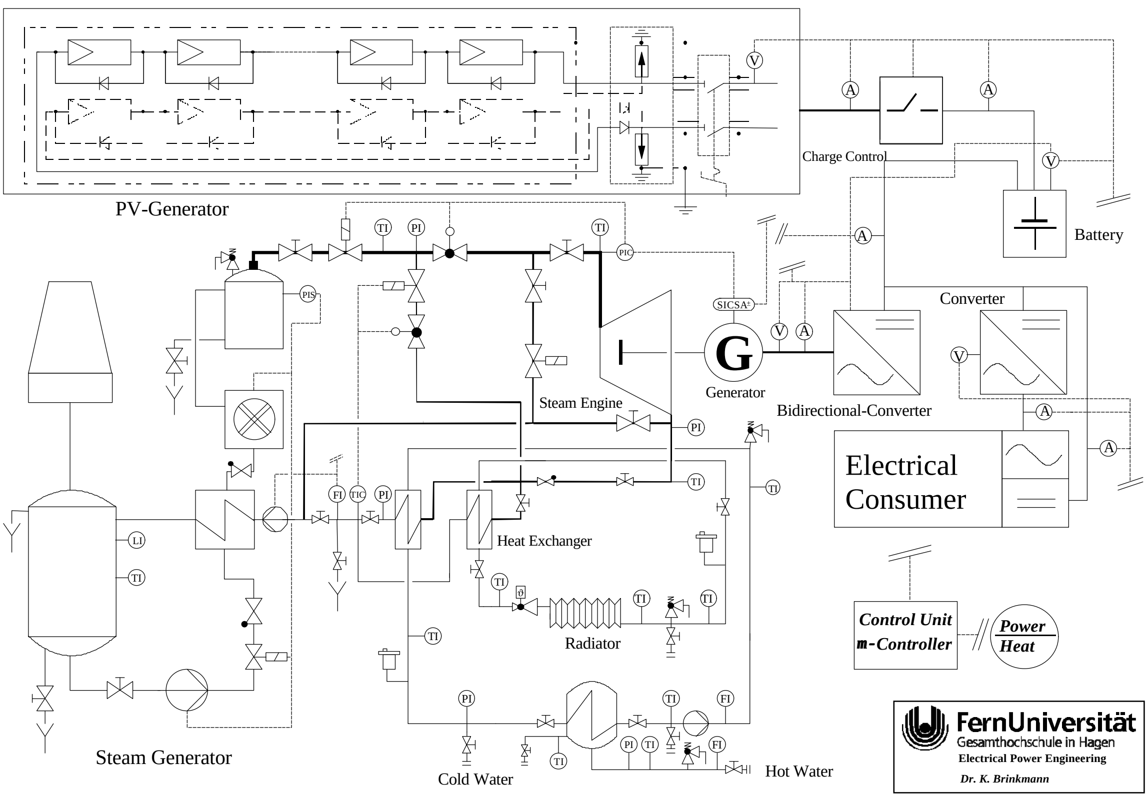

Figure 3: process scheme of the test setup

The upper line in the scheme above symbolises the photovoltaic generator with the charge controller and the connection to the batteries.

Under this, there can be seen three different functional areas, on the left side the steam generation, in the middle the heat exchange circuits and on the right side the electrical components for the power supply and the control unit.

Apart from some details for the heat exchange circuits, one can use this process scheme as basis for a pilot plant.

In order to allow a simple conversion to individually different local conditions, the average time dependent insolation characteristic in Germany has been standardised to an annual total global insolation of 1000 kWh/m².

This characteristic could be described with the help of a numerical approximated function, which can be used in formula (7) for the estimation of P_{PV} and therefore to determine the dimension of the PV-plant [2].

With respect to the piston-type steam engine, the parameter υ was carefully chosen to be 0,1. This value can surely be seen as a lower limit, with respect to the possibilities of modern mechanical engineering.

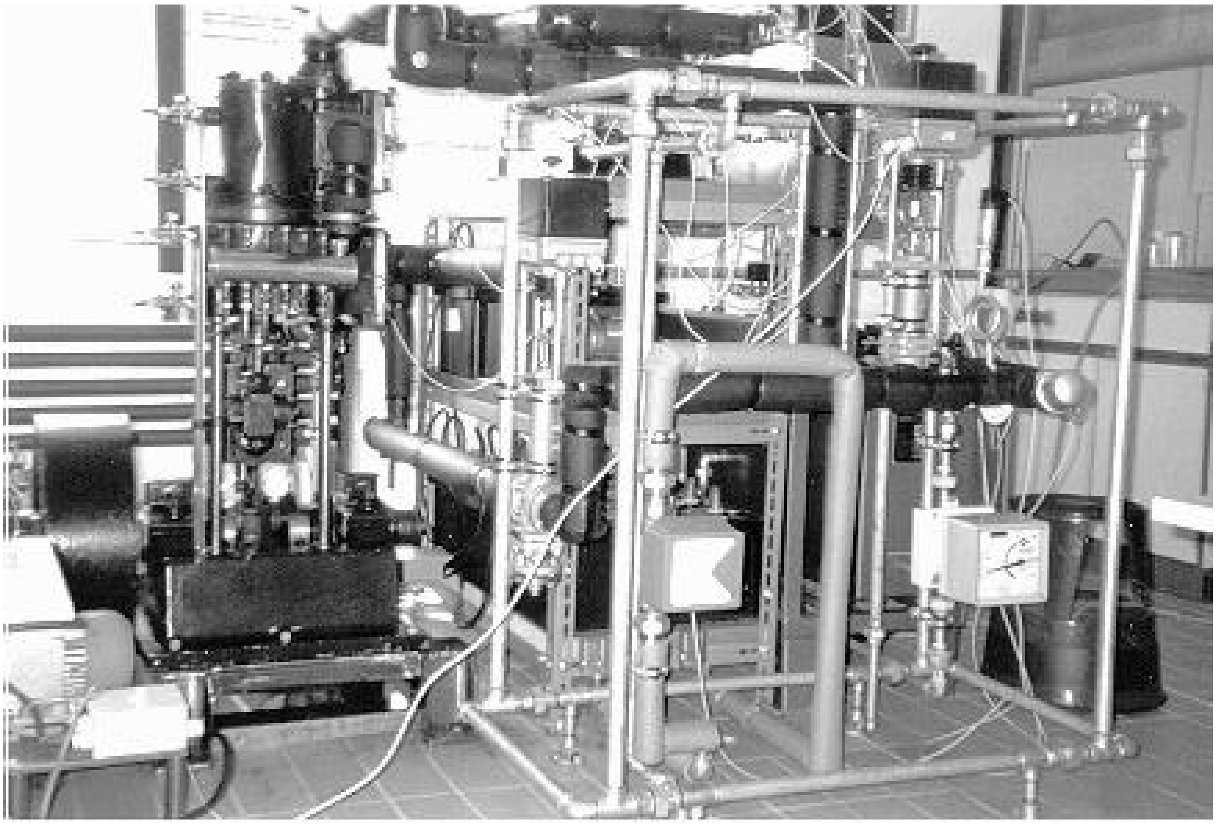

Figure 4: front view of the test setup

Including the influence of the performance ratio PR of a PV-plant, we obtain the following dimensioning for a general average private household in Germany:

$$PV - plant \cong \frac{z \cdot 2}{PR} kWp . \qquad (8)$$

For the steam engine, it could be demonstrated, that the mechanical power has to be about

$$P_{mech} \cong z \cdot 1{,}7 kW . \qquad (9)$$

Consequently follows for the steam generator with respect to υ :

$$P_{steam} \cong z \cdot 17 kW . \qquad (10)$$

This energy flow is a measure for the dimensioning of the condenser and heat exchanger.

These are with sufficient accuracy the main values, which are realised for the dimensioning of the test setup, as shown in figure 4 above. For further details see [2].

With respect to the dimensioning of this hybridsystem as a self-sufficient energy supply the capacity of the storage batteries should be

$$C_{Battery} \cong z \cdot 52 kWh . \qquad (11)$$

5. CONCLUSION

This paper presents the main results of a research project concerning a hybridsystem consisting of a PV-generator linked to a piston-type steam engine, a process scheme and the essential information of dimensioning.

REFERENCES

[1] K. Brinkmann
"PV-Generator linked to a Piston-Type Steam Engine with Combined Heat and Power as a Hybridsystem for a completely self-sufficient Energy-Supply"
2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna Austria, July 1998.

[2] "Systemtechnische Untersuchung eines Hybridsystems bestehend aus Photovoltaikanlage und Dampfmaschine mit Kraft-Wärme-Kopplung"
K.. Brinkmann, Dissertation 1999
FernUniversität Hagen / Fachbereich Elektrotechnik.

[3] K. Brinkmann
"Physical Analysis of a Hybridsystem consisting of a PV-Generator linked to a Piston-Type Steam Engine with Combined Heat and Power for a completely self-sufficient Energy-Supply"
11. Internationales Sonnenforum 1998, July 1998.

[4] K. Brinkmann, R. Taubner
"Simulation eines Hybridsystems bestehend aus Kraftwärmekopplung mit Dampfmaschine und Photovoltaikanlage"
14. Symposium Photovoltaische Solarenergie, Staffelstein 1999.

[5] K. Brinkmann
"Kriterien zur Auslegung von photovoltaischen Hybridsystemen mit Kraftwärmekopplung zur autarken Versorgung privater Haushalte"
15. Symposium Photovoltaische Solarenergie, Staffelstein 2000.