COMBINED HEAT AND POWER WITH BIOMASS AND SOLAR ENERGY FOR PRIVATE HOUSEHOLDS WITH A HYBRIDSYSTEM CONSISTING OF A PV-GENERATOR LINKED TO A STEAM ENGINE

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 dimensioning criterion of such a system with respect to the data for an average private household in Germany. Special attention in this contribution is given to the steam generator, which has to be able to work with biomass. Important for an effective operation is the capability of the whole system to follow the dynamically characteristics of the energy demand.

1. INTRODUCTION

To build up a completely self-sufficient energy-supply-system for summer/winter or mixed conditions including a photovoltaic (PV) system, an additional equipment for periods with low insolation is necessary, especially also for heating. This could be a piston-type engine with combined heat and power, as shown in figure 1.

To proof this possibility, this hybridsystem has been examined [1], [2] with the help of experimental investigations. Additional theoretical analysis and computational simulations were helpful to build up a process scheme with all necessary components and to determine their sizes [5].

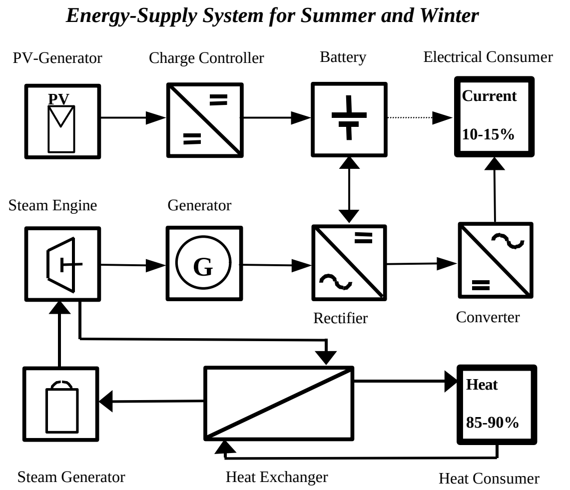

Figure 1: simplified process scheme of the hybridsystem

Maybe 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 heat 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. GENERAL 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 [2],[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:

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

The comparison between these data and the thermodynamically efficiency of a steam engine, as shown in figure 2, supports the decision to investigate the possibility to realise the combined heat and power with the help of a piston-type steam engine [1],[3].

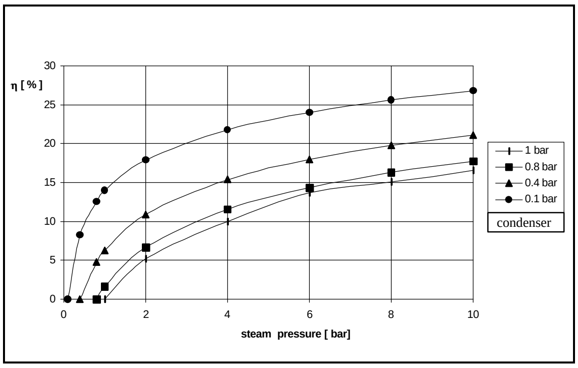

Figure 2: theoretical efficiency of a steam engine

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:

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

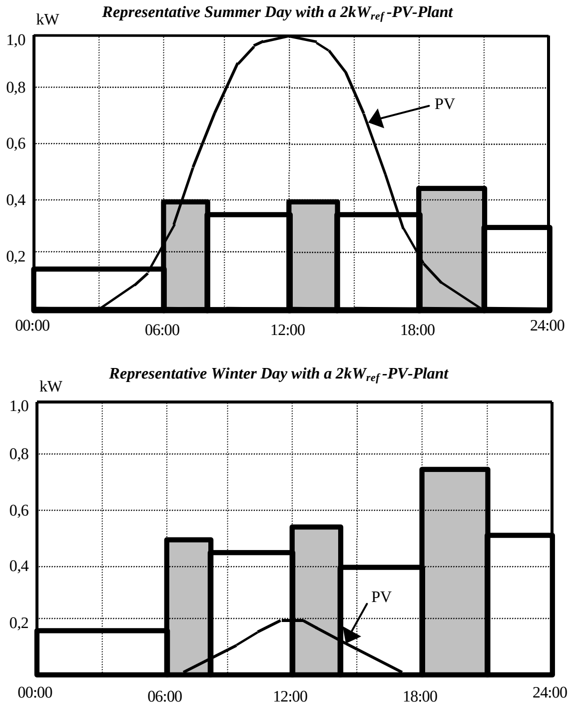

Figure 3: private household with a PV-plant in Germany

The figure 3 above shows typical daily characteristics for the consumption of electrical power of average private households in Germany, in comparison to the energy production of a 2 kW$_{ref}$-PV-plant. Whereas 1 kW$_{ref}$ is equivalent to 1 kW-Peak divided through the so called performance ratio, which regards the individually efficiency conditions of a PV-plant [3].

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:

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

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 'historical' 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.

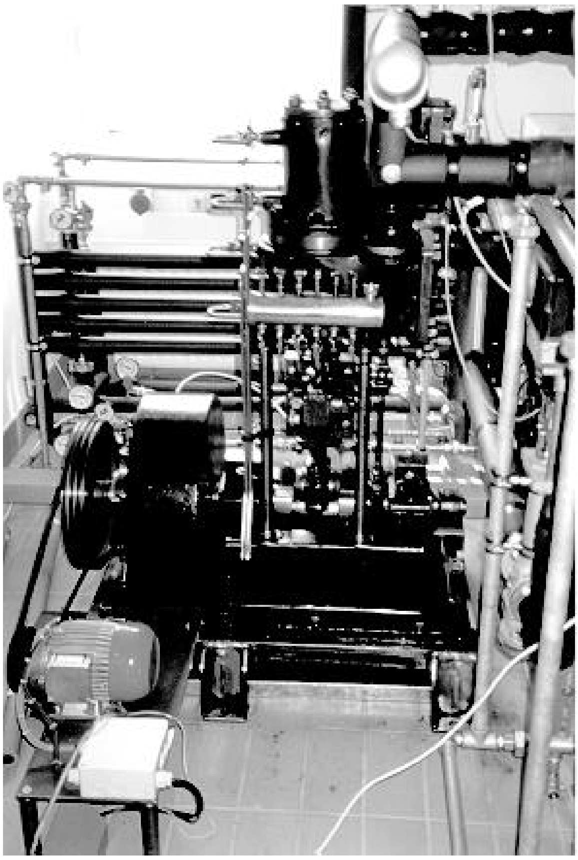

Figure 4: piston-type steam engine test setup

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.

As shown in figure 5, 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 [1],[2],[3].

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.

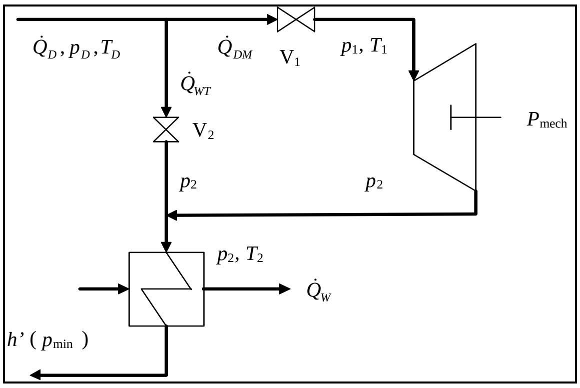

Figure 5: combined heat and power in the test setup

The implemented measuring technique is based on 4-20 mA signals, which are used by a self-made control box with a µ-controller [2],[5].

4. REQUIREMENTS AND DIMENSIONING

The simplified process scheme in figure 1 shows the main parts and functional connections of the above mentioned components.

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

In the middle line, there can be seen the mechanism to produce electrical energy with the help of the steam engine.

The third line symbolises on the left side the steam generation, in the middle the heat exchange circuits and on the right side the heat consumer.

The connecting element in the electrical power production and distribution scheme between the PV-plant and the steam engine, apart from the electrical consumer, is the storage battery. Therefore, the charge-level of the battery is most the important information for the control unit.

kW	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8
%	84	10,9	3,28	1,98	0,54	<0,15	<0,05	< 0,05

Table 1: classification of the electrical power demand

The measured data of a private household, as shown in table 1, demonstrate the necessity for a storage battery as a buffer, but also the dominance of the lower power demand in the region up to 1-2 kW [2].

As it can be seen from the characteristics in figure 3, it is only in summer possible to provide a household self-sufficient with electrical energy, if one excludes the principle possibility of seasonal storage systems.

Such storage systems require a larger capacity as well as a greater area of PV-modules and this means also increasing costs.

If the PV-plant is sufficient dimensioned, the estimated need of the steam engine is in the period form the middle of August to middle of April, as can be seen in figure 6 below.

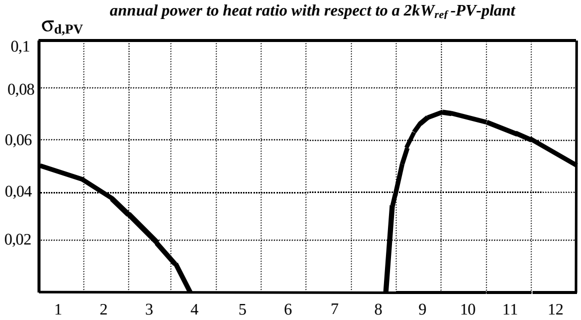

Figure 6: remaining power to heat ratio with a PV-plant

For the residual time period in the summer time, the steam generator is normally only necessary for the production of hot water, which could be done bypassed as shown in figure 5.

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 [2]. 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. 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.

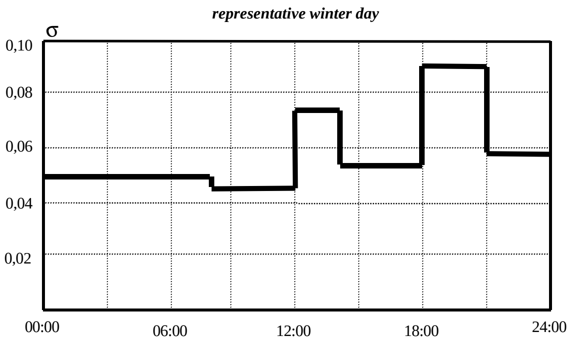

Figure 7: power to heat ratio for private households

The above figure 7 demonstrates as an important result the requirement on the necessary dynamically ability of the biomass driven steam generator, which has to be implemented.

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.

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:

$$PV - plant \cong \frac{z \cdot 2}{PR} kWp \,. \tag{8}$$

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

$$P_{mech} \cong z \cdot 1{,}7 kW \,. \tag{9}$$

Consequently follows for the steam generator with respect to υ:

$$P_{steam} \cong z \cdot 17 kW \,. \tag{10}$$

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

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

$$C_{Battery} \cong z \cdot 52 kWh \,. \tag{11}$$

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, to build up an energy supply based on solar energy and biomass.

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
"Kombinierte Nutzung von Biomasse und Sonnenenergie zum Betrieb eines Hybridsystems bestehend aus Kraftwärmekopplung mit Dampfmaschine und Photovoltaikanlage"
7. Symposium Biobrennstoffe und umweltfreundliche Energietechnik, Deggendorf, November 1998.

[4] K. Brinkmann
"Anforderungen an einen mit Biomasse betriebenen Dampferzeuger für ein Hybridsystem bestehend aus Kraftwärmekopplung mit Dampfmaschine und Photoveltaikanlage"
8. Symposium Festbrennstoffe aus Biomasse und umweltfreundliche Energietechnik,
Staffelstein, November 1999.

[5] K. Brinkmann
"Dimensioning of a Hybridsystem Consisting of a PV-Generator and a Steam Engine with Combined Heat and Power for Private Households"
16th European Photovoltaic Solar Energy Conference Glasgow United Kingdom, May 2000.