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

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Abstract:

To build up a completely self-sufficient energy-supply-system for summer/winter or mixed conditions including a photovoltaic system, an additional equipment for periods with low insolation is necessary, especially also for heating.
Aim of this paper is to work out the physical properties of a Power-Supply-System which enables a maximum exploitation of available primary energy with a highest possible portion of renewable energy. It is shown, that it is possible to provide private households or interdepartmental industrial consumers with heat and electrical energy with a hybridsystem consisting of a photovoltaic with combined heat and power. Inherent to these applications is an annual average ratio of electrical and heat energy of nearly one to ten. Therefore the combined heat and power can be implemented by a piston-type steam engine with respect to its mechanical efficiency of 10-15%.
This method combines the advantages of the PV to produce electric energy without CO_2-production with the well known principle of combined heat and power with its high possible total efficiency. So it may be possible to achieve minimum CO_2-emissions.
One of the most important advantages of the piston-type steam engine is the highest possible degree of individual freedom for the choice of the fuel for the separated steam generator.

Introduction:

To reach these aims, all necessary components of this system were defined and coordinated to each other to build up a process scheme. In advance of this, it was 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 seasonal variations.
The physical properties of these components were worked out and formed to a mathematical description as well as for their interaction with respect to the influencing stochastic parameters. Regarding this it was possible to build up a mathematical model for the necessary control system to guarantee a gap free energy supply with the actually required ratio of electrical energy and heat with respect to the insolation.
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 coordinated with the results of the photovoltaic plant of the FernUniversität building.

Hybridsystem:

With a 3-5kWp photovoltaic linked to a piston-type steam engine up to 5kW electrical energy for combined heat and power it is possible to provide an average private household completely self-sufficient with energy. The schematic diagram in figure 1 shows the necessary essential components for the Hybridsystem and their interrelations.

These components have to be dimensioned with respect to the stochastic behaviour of the insolation and the energy consumption. To equalise temporary deviations between energy production and consumption, storage batteries for electrical current as well as for heat are implemented.

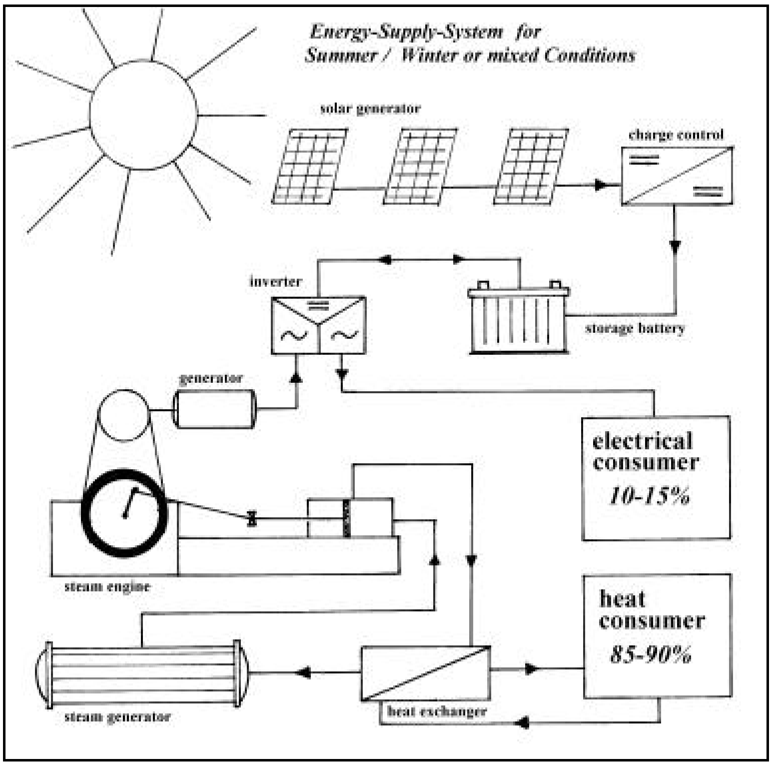

Figure 1: Simplified schematic diagram of the Hybridsystem

With an average ratio of electrical and heat energy for the summer of nearly 1:3 and for the winter of nearly 1:17 we obtain the aforementioned annual ratio of 1:10. Regarding this, it is possible to choose for the combined power and heat a piston type steam engine with a mechanical efficiency of 10-15%. The theoretical thermodynamic efficiency for saturated steam is sufficient and includes also enough reserves, as shown in figure 2.

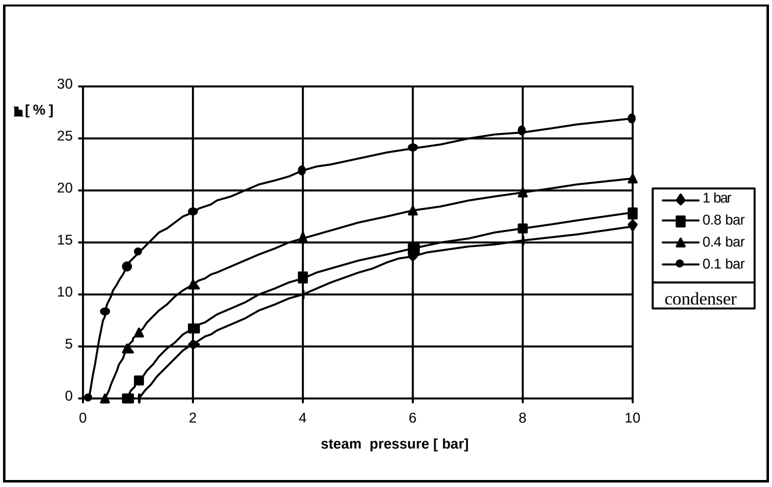

Figure 2: Thermodynamic efficiency of the steam engine

The photovoltaic is the main supply for electrical energy in periods of high insolation whereas the combined heat and power system has the priority during heating periods. A great advantage in the usage of steam for energy transfer is the possibility to use fuels from renewable resources.

Because of the external combustion there is a maximum degree of freedom in choice. Predestined for a possible fuel for the steam generator is *biomass*'. In comparison to the usual production of electrical energy with the usual efficiency of nearly 35% independent of the season, this hybridsystem could reduce the CO_2-emissions drastically. A grid-connected version is also possible because this would be a simplification.

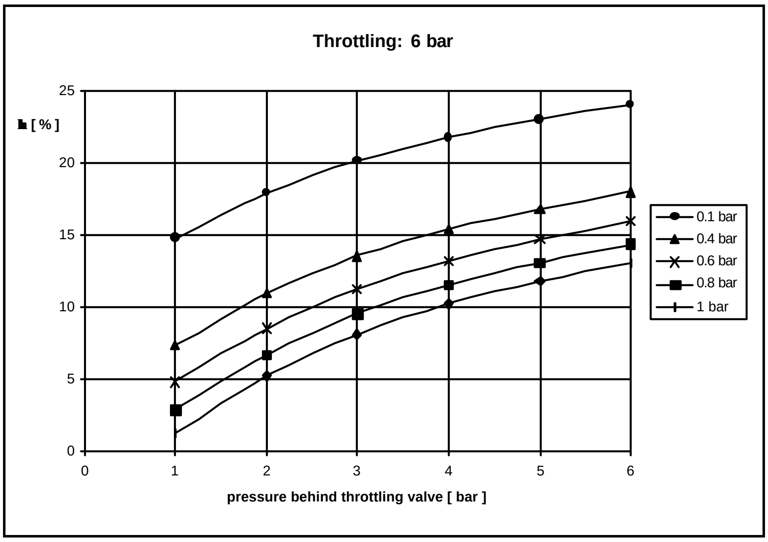

Figure 3:Influence of throttling on thermodynamic efficiency

To demonstrate the principal correlation (figure 3 and 4) between mechanical power, heat and efficiency, we choose as an example saturated steam with a pressure of 6 bar, which would be throttled by valve V1 as shown in figure 6, to control the rotation frequency of the engine shaft.
(e.g. X200 normalised mechanical power for 6 bar and 200 1/min → figure 5)

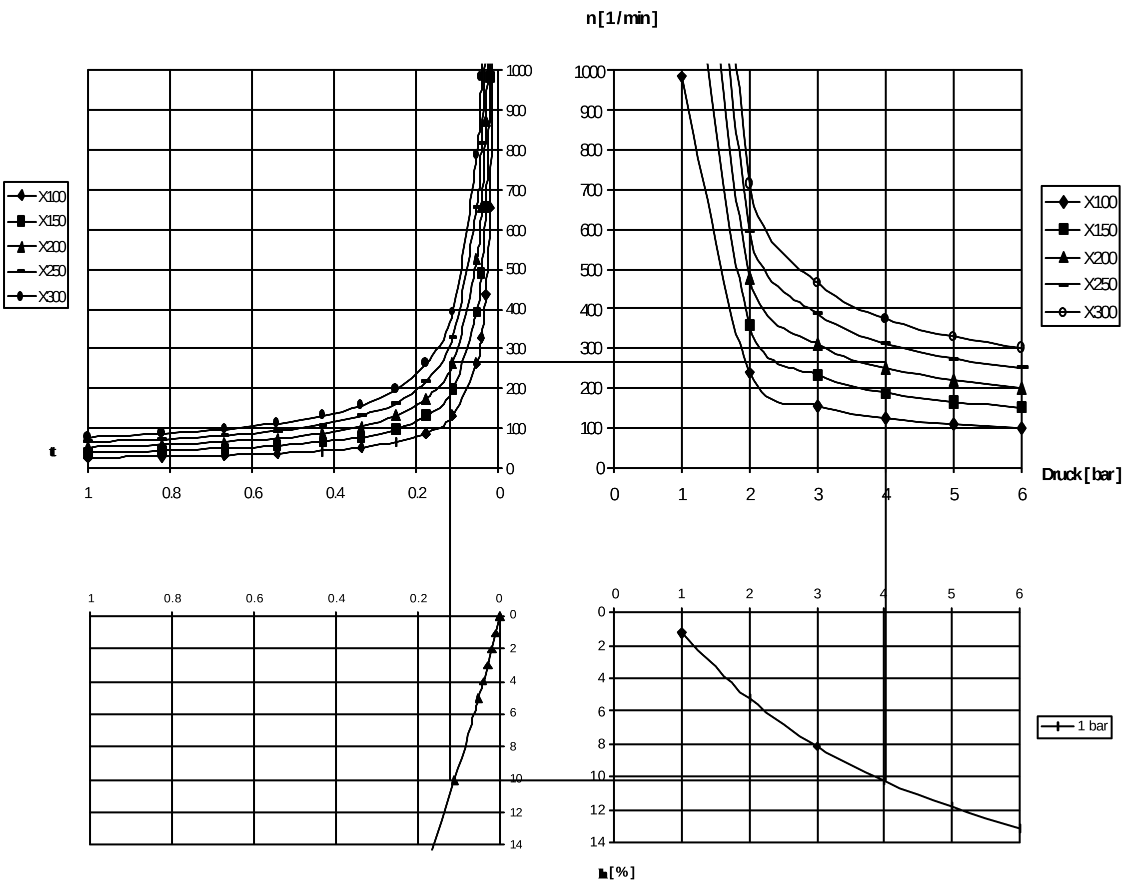

Figure 4: Diagram to determine the theoretical working conditions for the steam engine, p_D = 6 bar saturated steam

An important fact to achieve a minimum primary energy consumption for this hybridsystem is the ability of the controlsystem, to give priority to the PV-plant for the electrical energy supply.
Due to the momentary insolation the controlsystem decides whether the machine works or not. This has to be coordinated closely together with the charge control of the batteries.

$$X \equiv \frac{P_{mech}}{V_p}\ , \qquad V_p \equiv \text{piston steam-inlet-volume}$$

$$\dot{Q}_{WT} = \dot{Q}_W - \frac{1-h}{h} \cdot P_{mech}$$

$$\dot{Q}_{WT} \geq 0 \quad \Rightarrow \quad t \leq \frac{h}{1-h}\ , \quad t := \frac{P_{mech}}{\dot{Q}_W}$$

$$n[1/\min] = \frac{30 \cdot X}{r_{st} \cdot (h_3 - h_1)} \cdot \frac{1+t}{t}\ ,$$

$$(h_3 - h_1) = \text{specific heat input}\ , \quad r_{st} = \text{inlet-steam density}$$

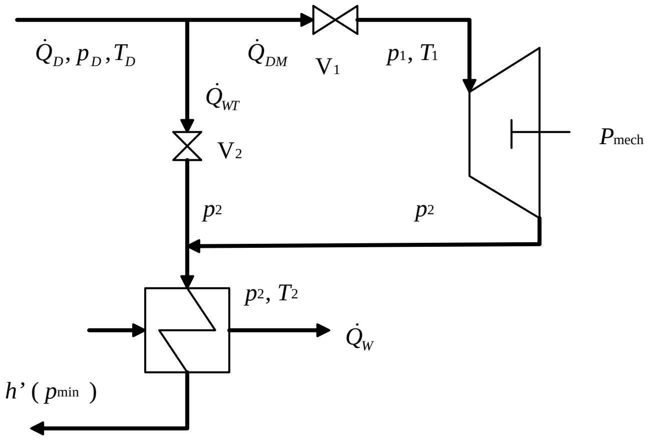

Figure 5: Exemplary results Figure 6: Main controlcircuit for combined heat and power

The presented results for the efficiencies are for a reversible process, therefore a correction with respect to the experimental mechanical efficiency is necessary. But this depends on the mechanical engineering facts due to the construction of the steam engine, and we have no '*modern*' machine, especially not up to 5 kW. There would be a lot to develop to gain a steam engine regarding modern aspects of mechanical engineering.

If the heat consumption surmounts the amount of the heat passed through the steam engine, the bypass valve V2 as shown in figure 6 would be opened by the controlsystem with respect to the condenser temperature.
For the contrary case, if there passes to much heat through the machine, a storage container would be able to equalise the energy balance.

The steam generator allows an individual freedom for the choice of the fuel with respect to the availability. It is desirable to use fuels from renewable resources. In comparison to a combined heat and power with an internal-combustion engine a great advantage of such a steam engine is also the nearly noiseless mode of operation. Extensive measurements and investigations were made and are still necessary to optimise this system. Summarised it can be established, that this hybridsystem shows a good nature behaviour.

Preview:

Nowadays the production of electrical power and thermal heat is usually separated especially for private households. The greatest part of electrical power is supplied by conventional central power plants based on coal, oil and gas or nuclear energy. A further part comes from hydroelectric power and only a very small contribution is left for the exploitation of renewable energy with wind energy converters, photovoltaic plants or biomass power plants. The supply with thermal energy especially for heating and hot water ensues with oil, gas, coal or electrical power.
The combined production and consumption of heat and power leads to an efficient exploitation of the primary energy and to an increase of the total efficiency.
The usage of decentralised systems has become more important during the last 10-20 years. Except of wind energy converters we find this for PV-plants up to 10 kWp and small combined heat and power units up to 10 kW_{el}. The combination of the principles of combined heat and power with the advantages of

a PV-plant to a hybidsystem as described above, with respect to summer and winter, would be a further increase of the total efficiency.
To realise this system for the practical usage in private households or interdepartmental industrial consumers many details are still left for further research and development.
In contrast to the PV-plant a modern piston-type steam engine for this power range seams to be not available on market. Therefore the main endeavours would be necessary to develop a steam engine with respect to the progress in modern mechanical engineering.
Aim of this research project of the Chair of Electrical Power Engineering from the FernUniversität Hagen, is to work out all physical and technical facts which would be necessary for a professional manufacturing of such a system.

Conclusion:

A hybridsystem consisting of a PV-plant and a combined heat and power unit to provide a completely self-sufficient energy-supply system is presented. This work shows the basic physical properties of such a hybridsystem especially with respect to the piston-type steam engine for the combined heat and power.

References:

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