INNOVATIVE BIOMASS POWER PLANT BASED ON PEBBLE-HEATER TECHNOLOGY AND HOT AIR TURBINE

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Introduction

The use of biomass for combined heat and power (CHP) production becomes increasingly important. On the one hand it substitutes the usage of fossil fuels like coal, oil or natural gas; on the other hand it is neutral regarding the CO_2-emissions into the atmosphere. That is the reason why many countries, especially the EU and the USA have launched very ambitious programs for increasing the usage of biomass, especially for power production.

The European Commission ´s White Paper sets out a Community Strategy and Action Plan to increase RES (regenerative energy sources) market penetration, to reduce energy dependency and to reduce greenhouse gas emissions in order to meet the Kyoto objectives. One of the actions is to install 10,000 MW_{th} of CHP biomass plants till the year 2010. That action will help achieve the objective of 23.5% of electrical power produced from RES. With an estimated annual 14,000 MW of installed power generation capacity worldwide, biomass power is the largest source from non-hydro renewable electricity in the world. Currently, the USA are the greatest bio-power producer with a capacity of 7,000 MW. Approximately 80% of this total are generated in the industrial sector, i.e. in relatively big units in the pulp and paper industry. The US Department of Energy (DoE) has started several programs in order to contribute to a further increase in bio-power (e.g. co-firing, gasification, energy crops etc.). One program deals with the development of small modular systems in the size of 10 to 5,000 kW. Those systems are expected to be attractive with regard to deregulation and the consumers' free choice of who they want to be their power supplier and what they want the contents of the power product to be.

Nevertheless, DoE expects that the biggest markets for biomass power generation worldwide will be the developing countries. China and India are considered to be the prime candidates, followed by Brazil, Malaysia, Philippines and Indonesia. They all meet several criteria, such as rapid economic growth, burgeoning demand for electricity, mounting environmental problems, need for rural electrification and significant agricultural/forestry residues.

How to achieve the target

Very few CHP plants are really competitive in comparison to the classical power plants. There are two main obstacles for a higher competitiveness:

- high specific investment costs
- high expenditure for the logistics of biomass collection and transportation.

In fact, those two are reversely connected: by decreasing the plant capacity the cost of logistics decrease, but the specific investment costs increase and vice versa. Thus, the most successful biomass CHP plants are usually located near a big wood industry. The large amount of waste wood is locally available, so that it is possible to realize a high plant capacity without any additional logistics problems. However, such locations are more or less exhausted. Just with such leftover locations it is surely not possible to achieve the targets posed in the EU and worldwide.

For new biomass projects it is necessary to overcome the two obstacles mentioned. The principal objective is to develop a low cost (low specific investment) CHP plant for small capacities (less than 5 MW_e). Such a facility has to have low maintenance costs, but at the same time a high power to heat ratio and a high thermal efficiency of power production, with the aim of reaching a good economic efficiency. Those goals cannot be achieved with classical technology based on steam or combined steam and gas cycles. These have been developed for fuels (first of all fossil fuels) with high energy concentration. They are not suitable for small and decentralized units and they cannot be fitted well to the possibilities and restrictions of biomass.

This paper deals with an innovative biomass power plant (*Stevanović & Emmel, 2000*) based on Pebble-Heater technology and hot air turbine, suitable especially for small capacities (e.g. 100 kW_e – 3 MW_e). Such a facility should enable an economical exploitation of locally available biomass, without a need for expensive collection and transportation logistics. By using cheap and proven components such as

- Pebble-Heaters as regenerative heat exchangers
- gas turbine in radial design for low pressures and temperatures (e.g. 4 bar, 850°C), and
- classical biomass combustor,

connected in an indirectly fired gas cycle, it would be possible not only to achieve low investment costs, but also a high efficiency of power production (between 30% and 37%). It would enable the economical operation of a plant located directly at the place where the biomass originates (smaller forest regions, fast rotation crops, agricultural waste, food industry waste etc.)

Components of the innovative biomass plant

The main novelty compared to some previous projects dealing with a similar cycle lies in the heat exchanger. Instead of a recuperator, it is proposed to use a newly developed regenerator, the so-called Pebble-Heater with radial fluid flow (*Faßbinder, 1996*), shown in *Figure 1*. The main obstacle to the use of a recuperator were the too high investment costs for a high temperature device. Moreover, biomass combustion gases always contain more or less dust and tar residues (due to the non-homogeneous temperature field). Their deposition in the tubes of a recuperator drastically decrease their efficiency. Due to the required regular cleaning campaigns, the maintenance costs are very high, while the plant operation has to be interrupted.

Beside lower investment costs (bulk material is used as a heat storage mass), this new type of Pebble-Heater enables higher temperatures (800°C – 1,000°C) without any additional costs. The most important advantage of the new Pebble-Heater technology is its very high recuperation efficiency. The recuperation efficiency is defined as:

$$\varepsilon = \frac{m_1(h_{1h} - h_{1c})}{m_2(h_{2h} - h_{1c})}$$

and represents the ratio of recuperated heat towards the maximum possible recuperated heat. The maximum possible recuperated heat is defined by the hot end temperature T_{2h} of the heating fluid (mass flow m_2) and the cold end temperature T_{1c} of the heated fluid (mass flow m_1). In case of constant flow rates ($m_1 = m_2$) and a constant specific heat of two gas streams, the recuperation efficiency is reduced to the more understandable expression:

$$\varepsilon = \frac{T_{1h} - T_{1c}}{T_{2h} - T_{1c}}$$

For the proposed biomass plant it is expected to reach the recuperation efficiency of 95%. In some other applications of the Pebble-Heater technology, extremely high values of up to 98% have been measured *(Stevanović & Faßbinder, 2000)*.

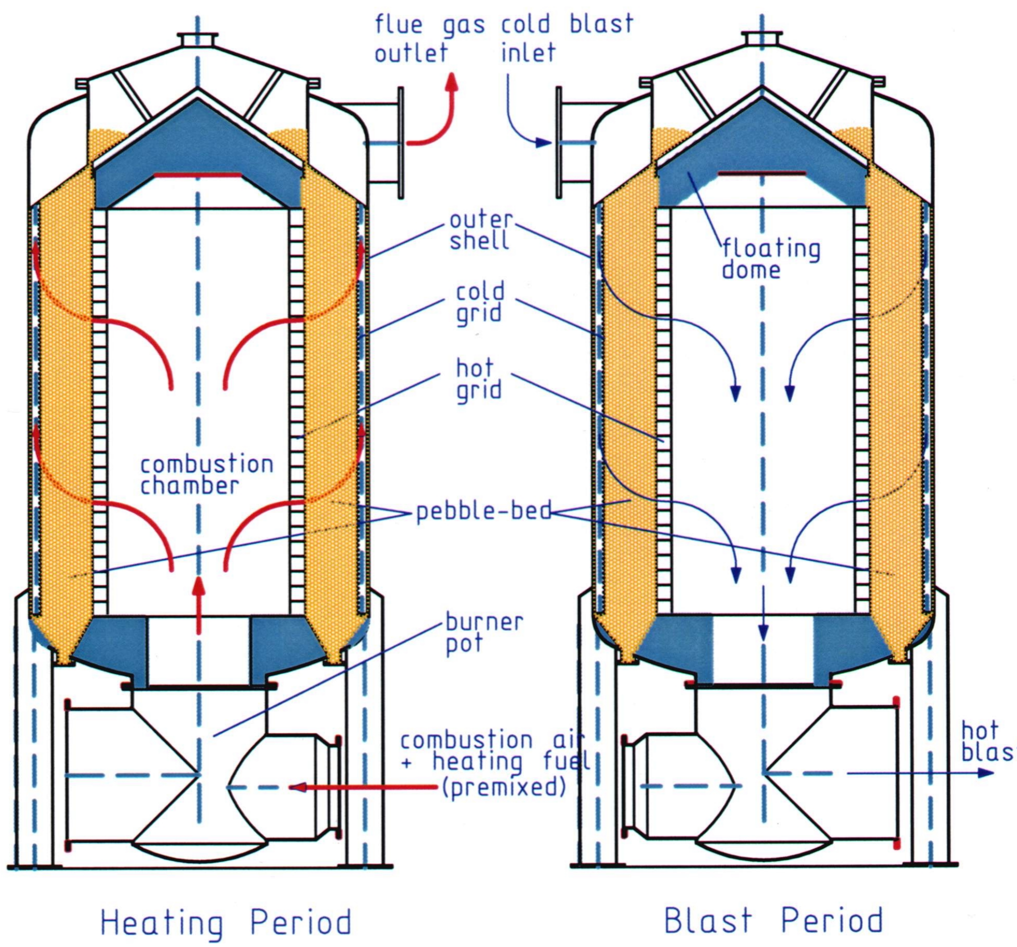

Figure 1: Pebble-Heater with radial fluid flow

Another important advantage of the Pebble-Heater is that bulk material (i.e. heat storage mass) may be taken out easily and cleaned if necessary. Partial recirculation and cleaning may be done pneumatically (with conveying air) even without interrupting the plant operation.

The Pebble-Heater is a regenerative heat exchanger, which means that at least two units, with four valves each, are necessary for a continuous process. For a smooth power plant operation (without disturbances during the switching from one to another unit) a solution with three units is the best one.

The required valves for these operational conditions (4 bar, 900°C) are available on the market. They were proven to be of high reliability in even harsher conditions in some metallurgical processes (e.g. hot wind supply for blast furnace), for which this technology has originally been developed *(Brotzmann & Stevanović, 1998)*.

The best solution for optimal operational conditions of the proposed cycle is to use gas turbine sets in radial design. They are very robust, with low sensitivity towards dust and other impurities. They usually have just one compression and expansion stage. There is no need for fine and cooled blades, as is the case with modern gas turbines for high operational parameters. As a result, they are very robust with low maintenance required. For small capacities (100 kW_e – 500 kW_e) the nowadays famous microturbines with integrated high-speed generators (without mechanical gears) may be used. The thermal efficiency in an open non-recuperated cycle is pretty low, usually less than 16%. This fact is not so important here. Due to the very high recuperation efficiency of the Pebble-Heater, the plant efficiency of power production is over 30%.

For the proposed cycle a more or less standard biomass combustor may be used. The possible solutions are furnaces with classical grates, with conical rotational grates or with fluidized bed combustion. The advantage of combustion on a grate is that a wide variety of biomass fuels may be used. Due to the high preheating of combustion air, it has to be additionally cooled or some additional cold combustion air has to be used, too. That is a disadvantage, because the whole plant efficiency of power production decreases. On the other hand, a fluidized bed combustion is more suitable for the operation with preheated combustion air. However, it has to use a fuel with constant characteristics.

The only big difference to the common biomass combustors lies in a much higher air factor, which in this case is between 6 and 8 (depending on the type of biomass and the required output temperature). It is planned to first have a more or less common combustion process (with air factor 1.5 – 3) at elevated temperature, and afterwards to mix the combustion gases with the rest of the preheated air. That way the outlet temperature may be controlled (to avoid sintering of fly ash, as well as to control the amount of alkali aerosols). Moreover, all impurities (dust, aerosols, tars) will be diluted by a factor of two to four compared to the common biomass combustion.

Description of the plant layout

All the main components are well known, with proven reliability, robustness and low maintenance requirements. They are arranged in a gas cycle with indirect combustion, as presented in *Figure 2*.

The ambient air (15°C) is first compressed to 4.50 bar in a compressor driven by a gas turbine. Due to compression its temperature rises to 205°C. In an after-cooler it is cooled down to 90°C in a recuperative heat exchanger. The available heat may be used for a heat consumer, e.g. as hot water or low temperature steam. Decreasing temperature before entering the first Pebble-Heater (PH1) is important for lowering the stack losses. Lower input temperature at PH1 enables lower outlet temperature at PH2.

After the cooler, the compressed air enters the first Pebble-Heater, where it is heated to 830°C. With that temperature the hot air enters the gas turbine, where it is expanded to almost ambient pressure (1.03 bar) and to a temperature of 542°C. The released expansion work is used for compressor and generator drive.

The most part of the expanded air is used as preheated combustion air for the biomass combustor. The rest may be used for another heat consumer, at a higher temperature level. As it is pure air, it may very well be used for drying processes, even in the food industry. Of course it may be used for drying the input biomass fuel, thus increasing the efficiency of the power production.

Biomass is fueled into the combustion chamber and burnt with preheated (542°C) combustion air. Due to a high air factor, combustion gases have a relatively low temperature of 870°C. That prevents the sintering of flying ash. Depending on the kind of biomass and on its ash characteristics, that temperature may be further decreased (or increased as well). Depending on the ash content, it may be necessary to include a hot gas cleaning system (e.g. a hot gas cyclone or a filter bed) before entering the Pebble-Heater from the hot side (the so-called hot grid), where there is a homogeneous temperature field (870°C). If there are still some tar particles in the gas stream, they will at least be extracted there and certainly burnt. The combustion gases are cooled down to 97°C and exhausted through the stack. This temperature may be controlled (e.g. by the cooled compressed air temperature at PH1 inlet) and adjusted to the type of biomass used, i.e. to the actual sulfur and moisture content, in order to avoid cold-end corrosion.

The cycle with such parameters will result in an electric efficiency of 32.3%. In case the heat from the air after-cooler and from the hot air at the turbine outlet may be used, the total efficiency of the CHP plant will be about 71%. Those results are obtained with the following parameters:

- isentropic efficiency of compressor $\eta_{ic} = 80\%$
- isentropic efficiency of gas turbine $\eta_{iT} = 83.7\%$
- product of mechanical and electrical efficiency at generator $\eta_{mech} \cdot \eta_{el} = 93.5\ \%$
- thermal efficiency of biomass combustor $\eta_{comb.} = 95\%$.

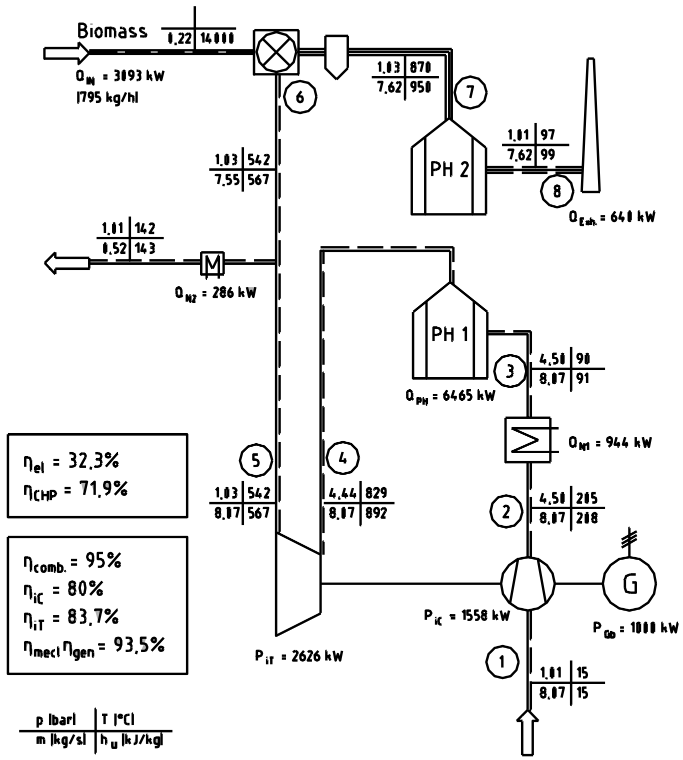

Figure 2: Basic flow-sheet of the innovative biomass CHP plont

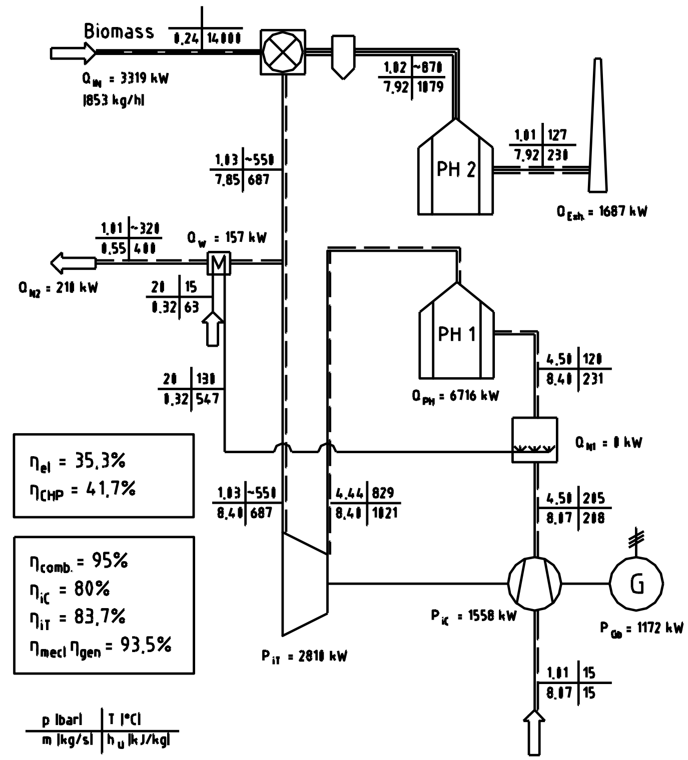

Figure 3: Flow-sheet with water injection

It is clear that a high efficiency of power production is an outstanding characteristic for such small units. The power to heat ratio is also very high, above 80%, which is important for a better economy of the plant. If an even higher electrical efficiency and higher power output are required, the plant may switch to the operational mode presented in *Figure 3*. In that layout, the compressed air is cooled by water evaporation (injector or film evaporator) before entering the first Pebble-Heater PH1. That way, the flow rate through the compressor (and so the compression work) stays constant, while the flow rate through the gas turbine is increased. The increased expansion work released in the turbine is used to increase the power output. To increase the amount of evaporated water, it may be preheated, using the heat of the hot air at the turbine outlet. That way the heat available for a consumer is further reduced, but the power output and the efficiency of power production are increased.

In the presented case the power output rises by 17.2% and the efficiency of power production rises to 35.3%. Due to a very small heat production, the total efficiency drops to 41.7%. In principle, it is possible to use all the available heat for water preheating and to further increase the amount of evaporated water in the air after-cooler. In that case the electrical efficiency will rise further towards 37% !

That operational mode may be used to adapt to the daily or even seasonal change in heat consumption. The thermal load of the gas turbine stays the same, as its output is increased just due to the increase in the flow rate, not the temperature.

For a smooth operation and stable power output the best solution is to use three Pebble-Heaters, as presented in *Figure 4*. The required valves, at least four per PH, are presented, too. The valves in closed position are given in black. During normal operation one PH is in air phase (here PH1) and two are in combustion gas phase. That way the difference in volumetric flow rates (due to different pressures) will be partially compensated and the pressure drops will be similar (e.g. some 20 mbar) through all three units. After a while (e.g. 15 minutes), the heat stored in PH1 will be exhausted and it will have to change to combustion phase. To enable a smooth switching, the valves (27) and (21) will be closed first and PH3 will be pressurized. During that time, only the PH2 will stay in combustion phase, while PH3 will enter into air phase, by opening the valves (30) and (24). Then, the PH1 will go out of air phase by closing the valves (32) and (26). After its depressurization, it will join the PH3 in combustion phase, by opening the valves (29) and (23). After another 15 minutes, PH3 will go to air phase and PH2 again to combustion phase, and so on.

The by-pass line (17) and the by-pass valve (18) are used to control and precisely adjust the air temperature at the turbine outlet. The first objective is to maintain its constant value, but that may be used for small and fast temperature changes and thus for load control, too.

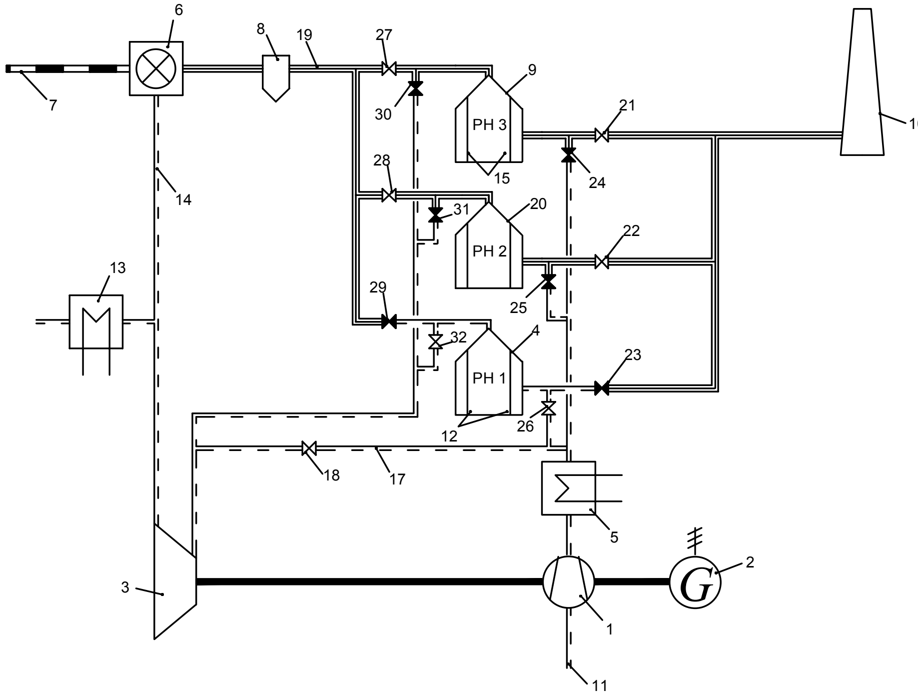

Figure 4: Real layout with 3 Pebble-Heaters and required valves

Thermodynamical background

How is it possible to achieve efficiencies over 30% with a gas turbine which reaches less than 16% in a simple open cycle? The answer lies in indirect combustion and heat recuperation.

It is well known that heat recuperation drastically increases the cycle efficiency (*Stojanović 1973, Haselbacher 1989, etc*). That effect is more important for turbines with higher heat losses at the turbine exit, i.e. for turbines with a lower pressure ratio. For a given inlet temperature there is an optimal pressure ratio. It has one value for a simple cycle and a different, much smaller value for a recuperated cycle. In fact, the latter is also dependent on the recuperation efficiency (previously defined): by increasing the recuperation efficiency, the optimum pressure ratio decreases. E.g. for 95% recuperation efficiency the optimum pressure ratio is about 2.7 (for 900°C input). That means there is a big difference between the gas turbines for a simple and for a recuperated cycle. The highly sophisticated modern turbines for high temperature and pressure will have very good performance in a simple cycle, but the performance will increase very little (if at all) in case of recuperation. It is quite the opposite with turbines for low pressure ratios: they do very poorly in a simple cycle, but with recuperation the cycle efficiency increases dramatically! This is clearly presented on the diagram in *Figure 5 (Watts, 1998).* At pressure ratio 4 the recuperation with 90% recuperation efficiency increases the cycle efficiency by more than 15% points (depending on temperature). At pressure ratio 3 it is already by 20% points and more. From pressure ratio 11 on, the overall cycle efficiency may even decrease! The reason lies in higher gas (air) temperature at the compressor outlet, which becomes higher than the turbine outlet temperature.

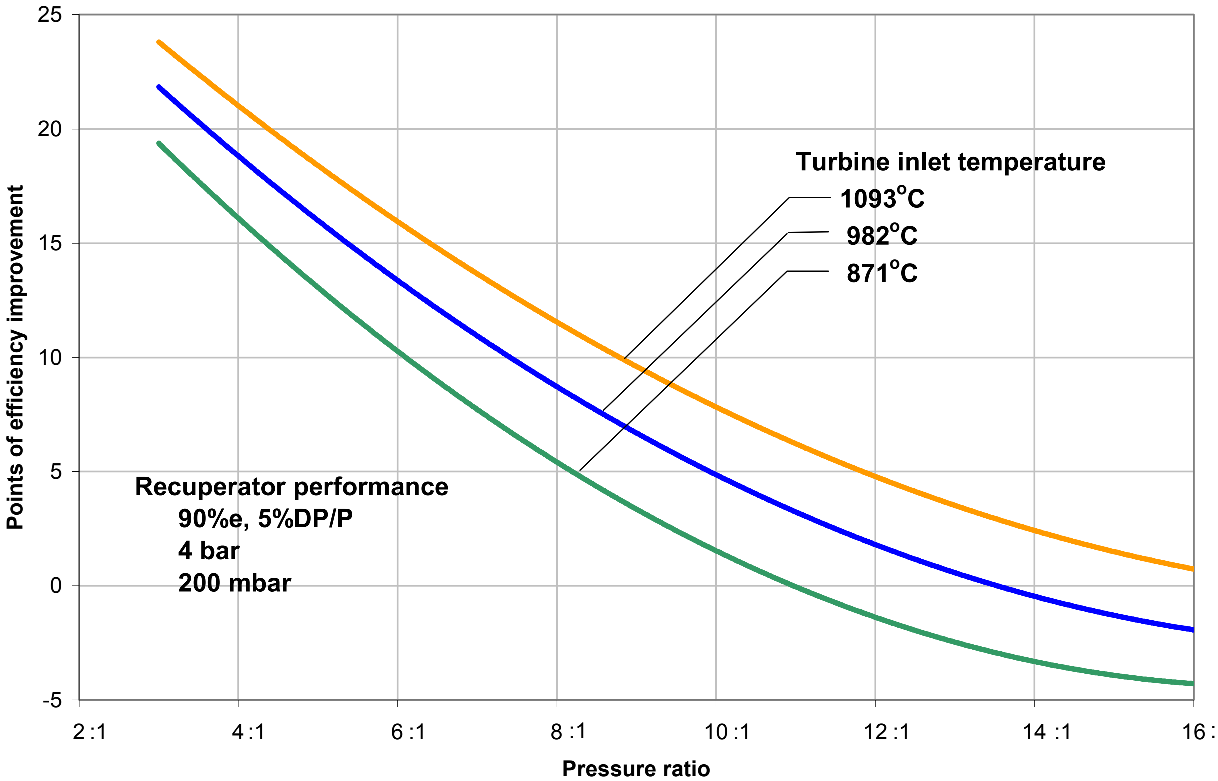

Figure 5: Impact of recuperation on simple cycle gas turbine engines *(Watts, 1998)*

That means a turbine with pressure ratio 4 and simple cycle efficiency of 16% may reach more than 31% in a recuperated cycle. Is it therefore not more attractive to have simple turbines in a recuperative cycle than to develop more sophisticated high pressure, high temperature multistage turbines with cooled blades made of ceramics?

The problem lies in the heat exchanger. Even for a 85% recuperation efficiency it is very expensive and limited in maximum temperature to 800 – 900°C. Technologically it is possible to achieve a higher recuperation efficiency, but each per cent in addition is very expensive – its price rises exponentially. Simultaneously rises the pressure drop, decreasing the effect of higher recuperation efficiency.

An indirectly fired cycle is in fact also a kind of recuperated cycle. The difference is in the amount of heat that has to be recuperated. It is not just the exit heat at the turbine outlet, but the complete heat contained in the combustion gases. *Figure 6* shows the $h - s$ diagram for the proposed indirectly fired cycle. The state points correspond to *Figure 2*. The whole amount of heat between points 7 and 8 has to be accumulated in a Pebble-Heater and later regenerated to increase the temperature of compressed air from point 3 to point 4. That means that the question of the heat exchanger is even more decisive for such cycles.

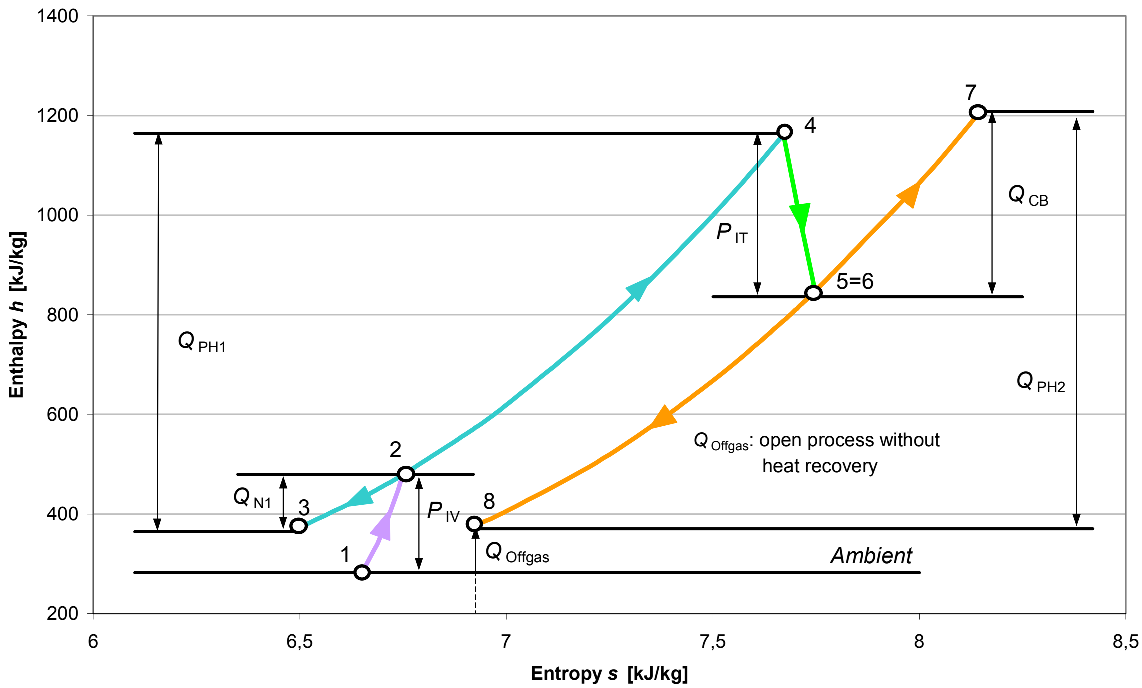

Figure 6: *h* – *s* Diagram

The next steps

It is planned to first develop two more or less standardized units:

- 2 MW electrical output and
- 250 kW electrical output, based on microturbine technology.

For the 2 MW plant a worldwide operating international concern has begun with the preparation activities. The aim is to start the construction of the first demonstration facility during the year 2001. The unit (3D view presented in *Figure 7*) will be commissioned during 2002. Several months are planned for testing the critical issues of dust deposition and removal. The equipment will be adjusted to achieve the optimum reliability for a given biomass.

For the smaller unit a consortium of different European companies and organizations has been formed with the objective to develop, test, demonstrate and finally commercialize it. A support from the EU is expected for a project for which a proposal has been recently submitted. For that unit there is a great interest on the part of farmers and smaller industries all around Europe. It should help the farmers to partially switch from food to energy production. The specific investment costs of the first units are expected to be in the range of 2,500 €/kW_e. Later, at an increased number of installed standardized units per year, the goal is to achieve 1,700 €/$kW_{e.}$

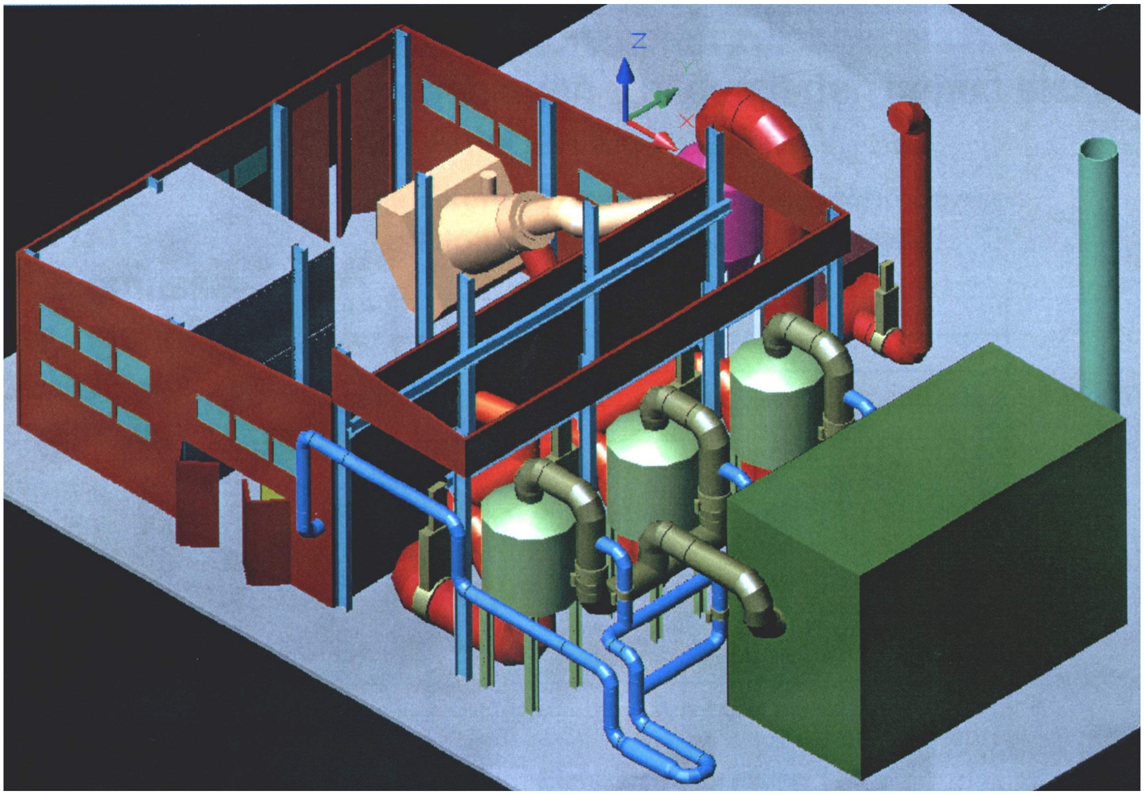

Figure 7: 3-D View of the future biomass CHP plant of 2 MWe (*courtesy of SIEMENS AG*)

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