Presented at ECOS'98, Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems, July 8-10, 1998, Nancy, France, publ. A. Bejan et al Eds., ISBN 2-905-267-29-1, pp. 235-242.

EXERGY ANALYSIS OF A BACK PRESSURE TURBINE AND A BACK PRESSURE SUPERHEATED STEAM DRYER IN A SAWMILL INDUSTRY

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Abstract This study is an inquiry into sawmills as producers of electricity or dried biomass. Exergy is used to point out possible improvements of the internal energy system in a Swedish sawmill. Exergy is also used to evaluate the consequences of integrating (1) a back pressure superheated steam dryer, (2) a back pressure turbine and a back pressure superheated steam dryer in the sawmill. The study shows that the exergy utilization can be improved if the sawmills enter the energy market.

Key Words: power generation, drying, sawmill, backpressure, exergy, bioenergy

1 Introduction

Exergy is applied to a Swedish sawmill and an integration of a back-pressured superheated steam dryer or a back pressure turbine is evaluated. Entering the energy market and utilizing the by-products of the sawmills might lead to an improvement of the energy system within the mills as well as for the Swedish energy system as a whole.

Sweden has a high amount of potential biofuels from forests and mires. In 1996 48.7 TWh was used by industry and 22.9 TWh for district heating [1]. However the maximum annual supply from the forests for energy production is discussed. Parikka [2] states that 130 TWh can be used in a long-term energy production while the Swedish Environmental Protection Agency [3, p. 23], declares that only 45-50 TWh can be used. The situation is better understood from an exergy diagram of Sweden. [4]

The fellings in Sweden are usually recorded in (m^3 sk)- cubic meter standing volume, which involves the whole tree above stump height, including bark and excluding branches. Sawmills exclude the bark in their records and the consumption of raw material is recorded in round wood without bark (m^3 fub). The relation between these units are 1 m^3 sk = 1.2 m^3 fub.[5, p.141]

The increase in mean annual volume, including growths on felled trees, in the period between 1990-94 was 99.66 Mm^3 sk [5, p. 73].

During 1995 the calculated annual gross fellings were 76.3 Mm^3 sk or 63.6 Mm^3 fub. Additionally, 2.6 Mm^3 sk trees, felled and intact, were left in the forest [5, p. 141].

The sawmills are the most important users of wood, in 1995 they used 34.7 Mm^3 fub, mainly coniferous saw logs, see *figure 1*. The pulp industry and the use of firewood are other main parts. [5, p. 141].

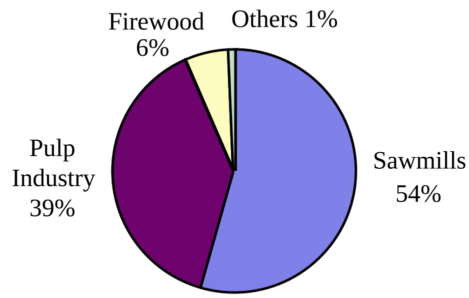

Figure 1 The users of forested wood in 1995

Less than half of the wood input ends up as wood products in the sawmills, see *figure 2*.

[5, p. 174]. Wood chips are used by the pulp industry.
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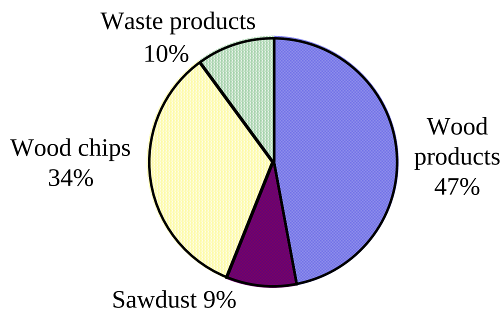

Figure 2 Production yield from sawmills with an annual production of 5000 m^3 or more in 1995.

A lot of the by-products are used in district heating plants which can combust the wet fuel with acceptable efficiency and local environmental impact. These by-products are low priced on the market, whereas processed bio energy is priced much higher.

If sawmills start producing high quality biofuels and/or electricity then bark and wood left in the forest, would become useful resources. If the bark and half of the left wood, are used for energy purposes then the production yield becomes as shown in *figure 3*
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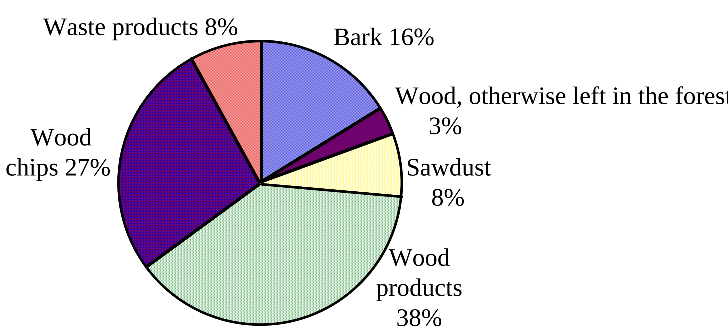

Figure 3 The production of sawmills if the bark and 50% of the wood that today is left in the forest, is utilized for energy production.

When values on density and higher calorific value from [6] is used then the biomass from sawmills suitable for energy production is about 30 TWh, to be compared with the numbers given above, by the Swedish Environmental Protection Agency and Parikka.

Swedish sawmills are suitable for handling these resources. Usually, they have a hot water boiler and a heating system for heating the sawmills and the drying sheds. The heating system can be combined with a back pressure fuel dryer or a back pressure turbine. Thus, they offer an important improvement of the Swedish energy system.

A typical sawmill is selected for this study, Alex' sawmill in the south of Sweden. In 1995 the production was 67,000 m^3. All data are on a yearly basis. The wood products are dried before delivery. In the existing plant heat for the saw house and drying sheds is provided by a hot water boiler at 120°C. Two alternative energy systems will be investigated, (1) a circulating back pressure superheated steam dryer at atmospheric pressure and an inlet temperature of 200°C, and (2) a back pressure turbine at 30 bar and 450°C, and after passing through the turbine the steam is condensed and the condensation heat is led to the same steam dryer as in system number one mentioned above. Temperature and pressure states are set from an economic evaluation, and not from an optimization.

2 Definitions and assumptions

The ambient temperature of the sawmill T_0 is 6°C. Exergy losses, i.e. irreversibility in the process and exergy to environment, are evaluated for subsystems. The sawmill is regarded as a user of heat and a producer of wood products, chips and biofuels. Data are in m^3 wood products.

Usually, biofuel is measured in the lower calorific value. But, if the heat of evaporation can be recovered and cascaded, the higher calorific value would be more relevant, and if work was to be extracted, then exergy content of the flame would be best choice [7]. Here we use the higher calorific value.

The exergy of wood is assumed to be unaffected in the drying process and in the superheated steam dryer.

The exergy factor, i.e. E/Q or exergy/energy, for biofuel is not taken into consideration in this study. The difference between energy and exergy will show up as an irreversibility in the boilers and the irreversibility due to this assumption are the same in all three cases. Under these assumptions exergy calculations will only show up in the following three cases:

1. *A hot and a cold reservoir*, i.e. the temperatures, T and T_0 do not change if heat is transported between the reservoirs. T_0 refers to the environment. The exergy factor is:

$$\frac{E}{Q} = \left| \frac{T - T_0}{T} \right|$$

The equation is used to calculate the exergy losses from buildings to the environment and convective losses in the saw houses and superheated steam dryer and boilers.

2. *A limited system and a reservoir*, i.e. the temperature T of the system will change if heat is added or removed. For a constant heat capacity the exergy factor is:

$$\frac{E}{Q} = \left| 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \right|$$

The equation is used to calculate the exergy when it appears in water, air and exhaust-gases.

3. *Steam*. The specific exergy for steam is:

$$e = h - T_0 s$$

where e, h, and s are the specific exergy, enthalpy, and entropy, respectively. In standard tables 0°C is often used as the reference temperature. Since, T_0 = 6°C in this study, exergy in steam must be adjusted accordingly:

$$e = h - T_0 s - (h_0 - T_0 s_0)$$

where h , s is at 0°C and h_0 and s_0 are the enthalpy and entropy at 6°C respectively. The exergy factor for steam can now be written as

$$\frac{E}{Q} = \frac{h - T_0 s - (h_0 - T_0 s_0)}{h - h_0}$$

Efficiencies in thermodynamic processes are often difficult to define in a way that suits all possible purposes. The exergy efficiency is no exception, and it can be defined in different ways [8]. One definition expresses all the exergy output as utilized, and all exergy input as used exergy.

$$\eta_{ex,1} = \frac{E_{out}}{E_{in}} = \frac{\text{Exergy used in following processes} + \text{Exergy to the environment}}{\text{Exergy input}}$$

However, another definition is to put only the exergy that is used in following processes as utilized.

$$\eta_{ex,2} = \frac{E_{used}}{E_{in}} = \frac{\text{Exergy used in following processes}}{\text{Exergy input}}$$

Both these definitions gives a number between 0 and 1. Since all real processes involve exergy losses the number must be smaller than 1.

When the results from the study is presented it is preferable if (1) the exergy used in following processes, can be separated from, (2) losses due to irreversibility's and (3) losses to the environment. Since the results, see sec 4 and 5. are shown in a Sankey diagram where all three kinds of exergy flows can be shown. $\eta_{\varepsilon\xi,2}$ is considered to be preferable and therefore used in this study.

3 Existing energy system in the sawmill

Wet by-products with about 58% water, e.g. bark, sawdust, and chips, are produced before the wood products are dried. Dry by-products such as chips and shavings are produced after the wood products have been dried.

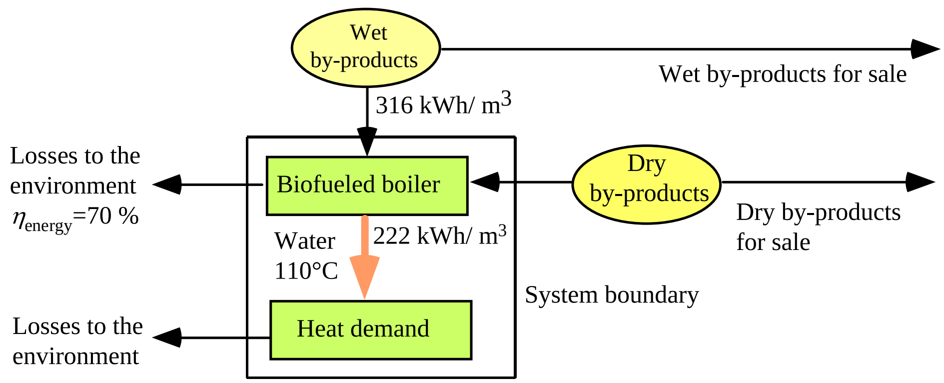

Figure 4 The existing energy system at Alex' sawmill in the south of Sweden.

The system boundary in *figure 4* encloses the hot water boiler and the heat to the drying sheds and to heat the saw houses. These kind of energy systems are the most common in the Swedish sawmilling industries.

In *figure 5* it is found that 89% of the exergy is lost in the hot water boiler from irreversibility, shown as a reduction, and exergy to the environment as exhaust gases. The energy conversions are white boxes. Conversions to heat usually implies large exergy losses. The water temperature after the hot water boiler is much lower then theoretically maximum, so a higher temperature gives a higher exergy efficiency. The heat demand for the drying shed and the saw-house is put together. The heat demand of the drying sheds is 86% of the total heat demand, and the main heat loss is in the ventilation of humid air. The exergy factor is calculated as a limited system and a reservoir. In heating the saw house the convective losses are dominant, exergy factor is calculated as a hot and cold reservoir.

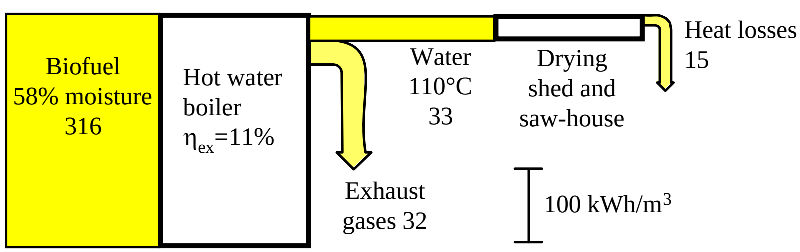

Figure 5 The input and output of exergies for the existing system calculated per unit m^3 of wood products produced.

4 Two alternative systems

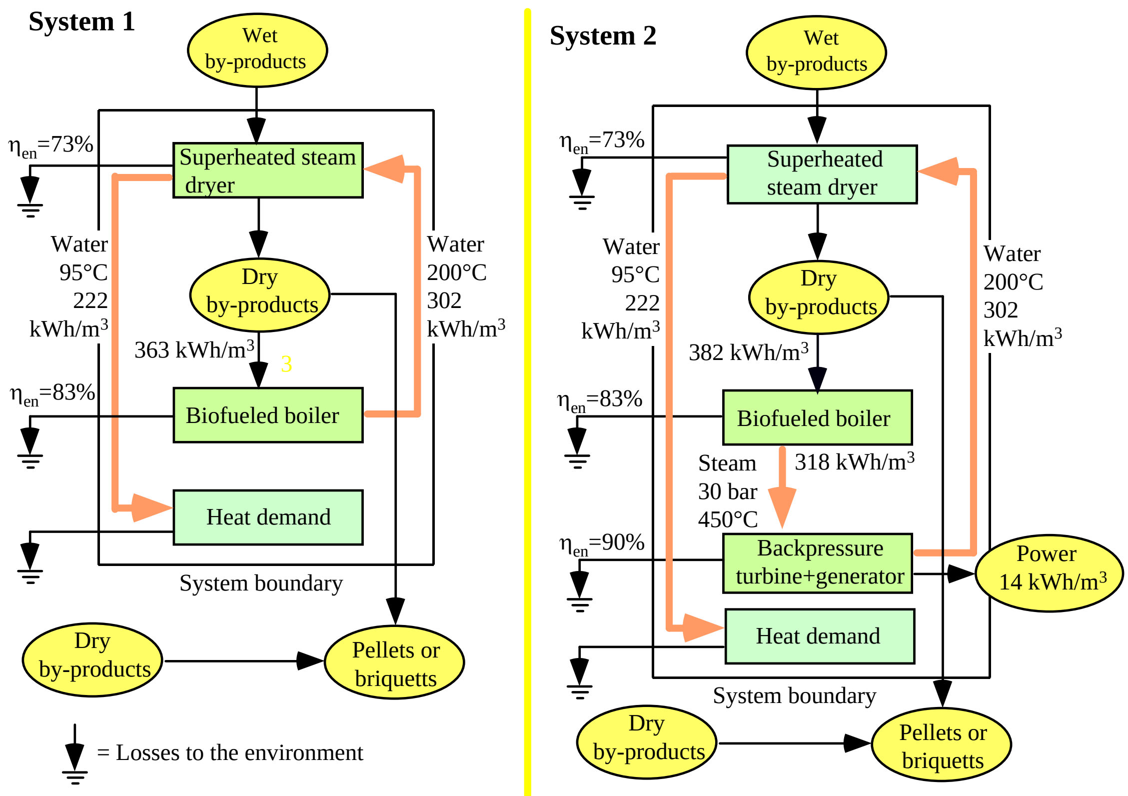

Figure 6 Two alternative systems, (1) with a superheated steam dryer and (2) with a back pressure turbine and a superheated steam dryer.

In *figure 6* two alternative systems are illustrated, (1) an atmospheric back pressure superheated steam dryer and (2) a back pressure turbine and a back pressure superheated steam dryer. The heat demand is calculated as an average on a yearly basis. All by-products are supposed to be dried from 58% to 15%. Dried biofuel is used in the hot water boiler. In system 2 the hot water boiler is replaced by a steam boiler.

The energy efficiency of heat exchangers is usually 100%, which implies no heat, i.e. no energy nor exergy, to the environment. The exergy losses are only due to irreversibility.

The superheated steam dryer improves the system. From *figure 7* we see that the exergy efficiency for the hot water boiler almost doubles, from 11% to 20%, because of a higher temperature of the water output and reduced exhaust gas losses due to less moisture in the fuel.

The steam dryer has an exergy efficiency of 72%, and the exergy losses are mainly to the environment. The energy losses to the environment and the sensible heat losses from the dried biofuel are together estimated to be 15%. Condensed water, 100°C, is assumed to be let into a basin for treatment. The main part of irreversibility losses are found in the condenser. In consequence of the lower temperature the heat demand has a higher exergy efficiency when compared to the existing system.

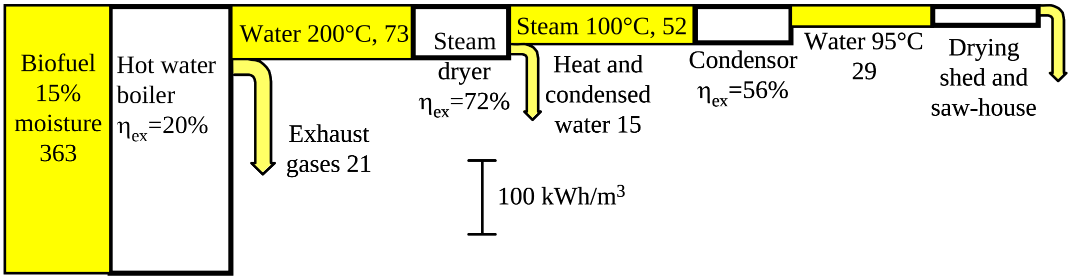

Figure 7 Exergy flow of a system with a superheated steam dryer.

The system in *figure 7* is a combined heat and drying plant. The drying capacity is doubled even though the exergy input is increased by only 15%, from 316 to 363 kWh/m^3.

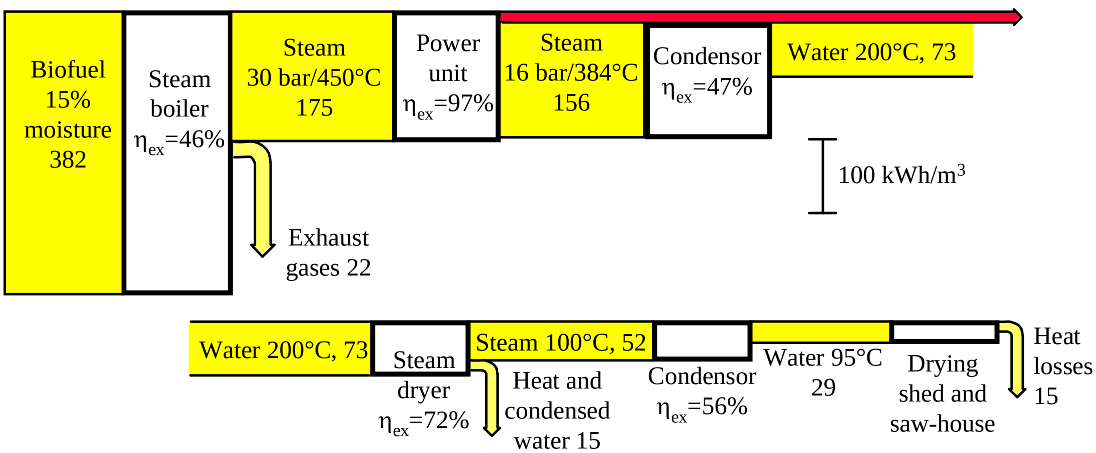

Figure 8 Exergy flow of a system with a superheated steam dryer and a back pressure turbine.

The system in *figure 8* is a combined heat, drying and power plant. The hot water boiler is replaced by a steam boiler at 30 bar 450°C, which improves the exergy efficiency compared to the hot water boiler. The exergy efficiency of the turbine and the generator becomes high, or 97%, because most of the exergy, the transiting exergy, is not involved in the conversion process. This shows the need to sometimes modify the definition of exergy efficiency.

The steam is superheated after the turbine to be used for drying. The operating state is not optimized in this application. Thus, the system could be further improved by applying thermoeconomic optimization.

5 Conclusions

If lower calorific values were used in the study the superheated steam dryer would seem as a creator of exergy, and using the higher calorific values the gain of reducing the moisture in the biofuel is not clearly seen. This exergy study does not give the whole picture. The superheated steam dryer also produces dry biofuel for combustion, which falls outside of the system boundaries for this study and due to this the superheated steam dryer needs a special attention. Biofuel with a water content of 58% is being dried to 15%, i.e. for each m^3 of processed wood product, 500 kg of water is being removed from the biofuel, more or less free of charge.

Less than 25% of the dried biofuel is used in the hot water boiler of the sawmill. Thus, most of the biofuel can be sold as dry biofuel which gives both a better exergy use in those boilers and environmental benefits.

The exergy benefits achieved by using dry biofuel is shown in this study and the environmental benefits achieved by using dry instead of wet biofuel are well known from practice.

Exergy is an effective tool to disclose hidden matters which may lead to improvements of the system. It is shown that the exergy utilization at the sawmills is improved by applying back pressure dryers or back pressure turbines to produce electricity, dried biomass or both. However, the system for wood drying and space heating must work at slightly lower temperatures than today.

In Sweden there is a strong space heating need during winter season. Thus, a study on a monthly basis would be of value for a design to support this need. In the future we would also like to optimize the system by applying thermoeconomics, and also investigate if a Kalina cycle could be an economical improvement.

The study shows that the exergy utilization within the sawmills can be improved if the sawmills enter the energy market by use of back pressure dryers or back pressure turbines. The higher price for processed biofuel then for the wet indicates that the processing is profitable.

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