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OPTIMIZATION OF THE BARK DRYING PROCESS IN COMBINED HEAT AND POWER PRODUCTION OF PULP AND PAPER MILL

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ABSTRACT

Solid biofuels, such as bark, forest residues, sawdust, and wood chips are important mill fuels in the forest industry. They are combusted in combined heat and power plants (CHP-plants) to generate heat and electricity for pulp and paper making processes. Biofuels usually have high moisture content. The high moisture content decreases the effective heating value of fuel and makes the operation of the boiler more difficult. Until now, biofuels have not been dried before combustion in Finland; however, the forest industry is currently highly interested in biofuel drying. The designer of the drying process should be able to determine the final fuel moisture, drying temperature, and degree of energy efficiency of the dryer, thereby maximizing earnings from the drying. This paper presents a calculation model for answering these questions. Earnings are determined using net present value. The calculation model is created for a continuous cross-flow dryer, in which air is aspirated through a fixed bark bed. The highest possible drying temperature depends on the heat source used for the heating of the drying air. The most suitable heat sources in pulp and paper mills are secondary heat flows, backpressure steam, and extraction steam. Using current energy prices, and the economic lifetime of 10 years with an interest rate of 5%, the optimally designed dryer uses only secondary heat for the heating of drying air, consists of two drying stages and dries the fuel/bark flow to final moisture, which is in the order of $0.3 kg/kg_{dm}$.

INTRODUCTION

The heat needed for the manufacturing processes of the mill is produced at the combined heat and power plant (CHP-plant) of the pulp and paper mill. Electricity is produced as a “by-product” for the mill or electricity markets. The most important mill fuels at industrial CHP-plants are black liquor and solid biofuels, such as bark, forest residues, and sawdust. In addition to black liquor and solid biofuels, fossil fuels are usually needed as marginal fuels to cover the heat production for all heat loads. Black liquor is burnt in a recovery boiler. The recovery boiler generates high-pressure steam and regenerates used cooking chemicals [1]. Solid biofuels are usually combusted in fluidized bed boilers. The most important solid biofuel is bark, which is obtained as a by-product from a debarking plant. Figure 1 shows energy and material flows in and out of the control region at a typical industrial CHP-plant.

Bark has a high moisture content, typically between 55-65 % (water per total mass) [2]. The moisture content and its variation depend on weather, season, and type of bark (pine, spruce etc.). The high moisture content decreases considerably the effective heating value of bark. The occasional variation of moisture content also makes the operation of the boiler more difficult. Bark and other biofuels are not dried before combustion today despite clear disadvantages. The main reasons for this are the negative experiences of flue gas drying in the 1970's and an intensive development of fluidized bed boiler technology. Fluidized boiler technology enables the combustion of moist biofuel. In spite of this development, biofuel drying has been researched quite intensively at universities and research centers in Finland. At the moment, the forest industry is showing an increasing interest in biofuel drying. Pilot-dryer projects are planned and one mill has already decided to build a biofuel dryer.

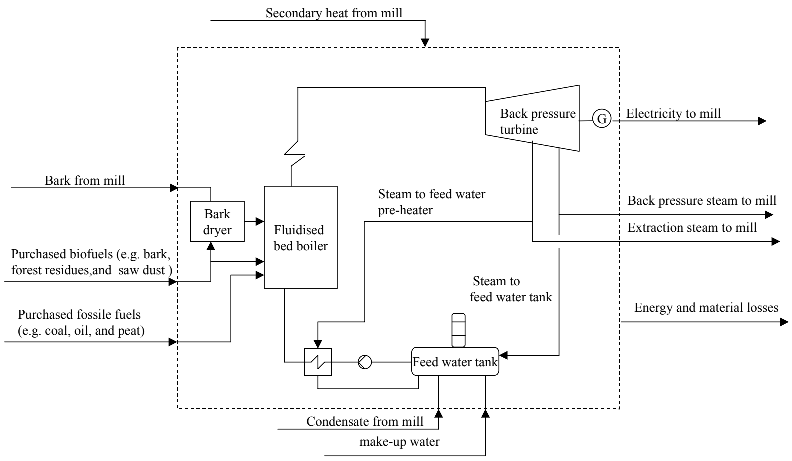


Figure 1. Energy and material flows in and out of control region at an industrial CHP-plant

The dryer type with great potential for biofuel/bark drying is a continuous fixed bed dryer, which uses warm air as drying gas. In cross-flow drying, air is blown or aspirated through a fixed fuel bed that moves forward by means of a mechanical conveyor. Use of a counter- or co-current dryer is also possible. The energy flows with the greatest potential for the heating of drying air in a pulp and paper mill are secondary heat flows (hot water in the temperature range of 50-90^{o}C), backpressure steam (typical pressure level 3-5bar) and extraction steam (typical pressure level 10-12 bar). Secondary heat (also known as waste heat) is heat recovered to a heat recovery system from energy flows leaving the manufacturing processes. The recovered heat can be returned back to the CHP-plant from the mill.

When a biofuel dryer is going to be built at the CHP-plant of pulp and paper mill, the designer of drying process should be able to answer the following questions:

1. What is the final fuel moisture that maximizes earnings of the drying?
2. What heat sources should be used for the heating of drying air? Should we use only a low temperature secondary heat, or could it be more profitable to use both secondary heat and steam or only steam?
3. How energy-efficient a drying system should we build? In other words, is it more profitable to build a less energy-efficient drying system with low investment costs (e.g. single-stage dryer with once-through air flow heating) or more energy-efficient system with higher investment costs (e.g. a multi-stage dryer or single-stage dryer with partial recycle of spent air)?

The target of this paper is to present a calculation model for answering questions 1-3 and apply it in a case study. The calculation model is presented for a continuous fixed bed dryer in which air is aspirated through a fixed fuel bed. The fuel to be dried is bark. The energy efficiency of the drying system is taken into account by making the calculation model for 1-, 2- and 3-stage drying systems. Other ways to improve the energy efficiency are not discussed in this paper.

DESCRIPTION OF DRYING SYSTEM

Figure 2a shows a flow sheet for a 2-stage drying system. Figure 2b illustrates the states of the drying air on an enthalpy-humidity chart diagram. A drying stage consists of the heating and drying period. The drying air in each drying stage is heated using first secondary heat, then backpressure steam, and finally extraction steam, if all heat sources are used for heating. Adding drying stages decreases heat consumption in drying, because the air temperature is clearly higher before the second than the first drying stage (see Figure 2b) [3] . Adding the drying stages also decreases the air demand in drying, if all drying stages operate at the same temperature level. The reason for this is the higher outlet air moisture, which is achieved as a result of several drying stages (see. Figure 2b). Although the air demand decreases, the dryer dimension do not become smaller because the drying air must pass through several drying stages. Heating the drying air successively in three heat exchangers does not decrease the specific heat consumption but decreases the consumption of steam, which is more expensive energy than secondary heat flows.

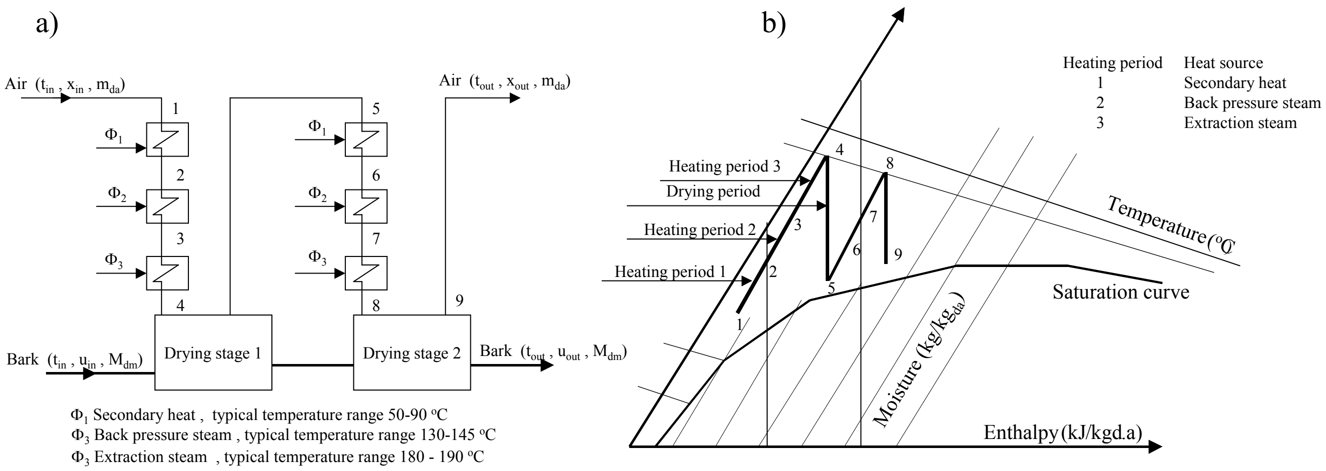


Figure 2. Two-stage drying system a) Flow sheet b) The states of the drying air on an enthalpy-humidity chart

CALCULATION MODEL

The efficiency of the CHP-plant is defined as follows:

$$\eta = \frac{P + \Phi_h}{Q_f} \tag{1}$$

where P is the power generation, Φ_h the generated process heat in the form of steam, and Q_f the fuel input into the fluidized bed boiler. An important term in CHP-production is power-to-process heat ratio:

$$\alpha = \frac{P}{\Phi_h} \tag{2}$$

The power-to-process heat ratio and efficiency are known parameters for each CHP-plant. The main target of the CHP-plant is to produce enough steam to cover the heat consumption at all times. This means that the fuel input must be in balance with the heat consumption. The fuel consumption can easily be calculated from equations (1) and (2) as the heat consumption is known.

Drying increases the effective heating value of the biofuel. As a result of the improved heating value, marginal fuel can be replaced with biofuel. Savings in marginal fuel consumption represent a positive cash flow for a company. If steam is used as drying energy, primary heat consumption increases, and fuel input into the boiler may increase, too. This increases power production. If the dryer uses secondary heat, backpressure and extraction steam, the net income (NI) of drying in a time unit is calculated as follows:

$$\begin{aligned} NI = \dot{M}_{dm}(u_{in} - u_{out})l_v b_{mf} - \Phi_{sh} b_{sh} - \frac{(\Phi_{bs} + \alpha_{bs}\Phi_{bs})}{\eta} b_{mf} + \alpha_{bs}\Phi_{bs} b_e - \\ \frac{(\Phi_{es} + \alpha_{es}\Phi_{es})}{\eta} b_{mf} + \alpha_{es}\Phi_{es} b_e - \frac{\dot{m}_{da}\Delta p}{\rho_{da}\eta_{fan}} b_e \end{aligned} \tag{3}$$

The dryer heat consumption Φ for a certain heat source (e.g. secondary heat) is determined as follows:

$$\Phi = \dot{m}_{da}(\Delta h_1 + \Delta h_2 + ..\Delta h_n) = \dot{m}_{da}(c_{pda} + x c_{pv})(\Delta t_{db1} + \Delta t_{db2} + ..\Delta t_{dbn}) \tag{4}$$

where n is the number of drying stages, Δh the enthalpy difference and Δt the temperature difference over the heat exchanger. The earnings of the drying are calculated using net present value (NPV), which takes into account all cash flows over the economic lifetime of the dryer. Taking investment costs and maintenance costs as negative cash flows, the net present value for the dryer becomes [4]:

$$NPV = \sum_{\tau=0}^{\tau=k} \frac{(NI\tau_{op} - C_{maintenance})}{(1+i)^{\tau}} - C_{investment} \tag{5}$$

where k is the total number of years over which cash flows occur and τ_{op} the annual operating hours of the dryer. Investment costs are expressed as a function of suitable capacity factor. For a continuous cross flow dryer a suitable capacity factor is the air mass flow, in which case $IC = f(\dot{m}_{da})$. In some cases, the function describing the investment costs may be only a rough estimate of actual investment costs. If the drying time for a certain fuel moisture decrease u_{in}-u_{out} is known, the air mass flow in continuous cross-flow drying may be determined as follows [5]:

$$\dot{m}_{da} = \frac{v_a \rho_{da} \dot{M}_{dm}}{Z(1-\varepsilon)\rho_{dm}} \tau_{dry} \tag{6}$$

where τ_{dry} is the drying time from an initial fuel u_{in} moisture to a desired final fuel moisture u_{out}. In the case of cross-flow drying, the drying time can be experimentally determined in a small-scale batch-reactor (see Figure 4c). The measured drying curve is analogous to a drying curve of a continuous cross-flow dryer. Choices of optimal bed height and air velocity are discussed in [5]. To take into account the effect of inlet air moisture on drying time, we assume that drying time is proportional to the temperature difference between dry-bulb and wet-bulb temperature. As a result of this assumption, we can determine experimentally drying curves for various inlet air temperatures using only one inlet air moisture. The dry bulb temperature as a function of wet-bulb temperature may be given approximately as follows [6]:

$$t_{db} = t_{wb} + \frac{x'(t_{wb}) - x}{c_{pa}} l_v(t_{wb}) \tag{7a}$$

$$x'(t_{wb}) = 0.622 \frac{10^5 e^{\frac{11.78(t_{wb}-99.64)}{(t_{wb}+230)}}}{p_o - 10^5 e^{\frac{11.78(t_{wb}-99.64)}{(t_{wb}+230)}}} \tag{7b}$$

$$l_v(t_{wb}) = 2501000-2340t_{wb} \tag{7c}$$

The saturated air moisture $x'(t_{wb})$ in Equation (7b) is expressed using a approximation correlation for saturated vapor pressure. By measuring drying curves for several temperature differences (t_{db}-t_{wb}), a regression curve giving the correlation between drying time and the temperature difference t_{db}-t_{wb} can be determined. The correlation is determined for a certain fuel moisture decrease u_{in}-u_{out}, and is expressed as in this paper follows:

$$\tau_{dry} = A\ln(t_{db}-t_{wb}) + B \tag{8}$$

In 2- and 3-stage drying, the final fuel moisture u_{out} is achieved after the last drying stage, and the fuel moisture after the previous drying stages is somewhere between u_{in}-u_{out} (see Figure 2). This means that the regression curve should tell how the outlet fuel moisture dependences on drying time and the temperature difference t_{db}-t_{wb}. To also use the correlation (8) in 2-, and 3-stage-drying, we share the fuel flow between each drying stage as shown in Figure 3. The moisture decrease for the shared flow in each drying stage is u_{in}-u_{out}, and correlation (8) can be used for 2-, and 3-stage-drying, too. We emphasize that sharing the fuel flow is only a computational action, and there is no reason to share the fuel flow in a real dryer.

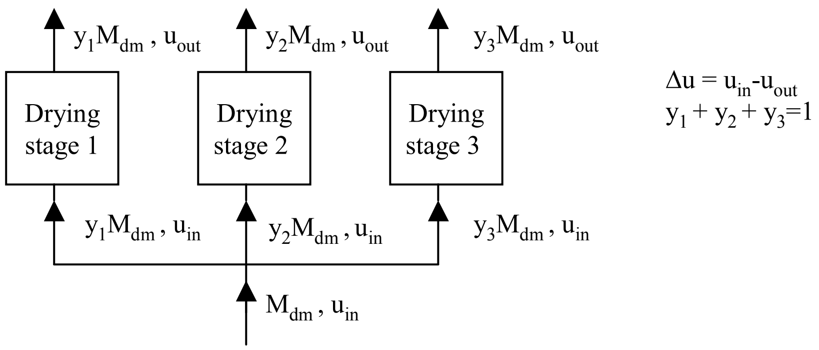


Figure 3. Sharing the fuel flow between drying stages in 3-stage drying

The outlet air moisture after the drying chamber is obtained from the mass balance of chamber [7]:

$$x_{out} = x_{in} + \frac{\dot{M}_{dm}}{\dot{m}_{da}}(u_{in} - u_{out}) \tag{9}$$

The outlet air temperature after the drying chamber is determined approximately by assuming that the enthalpy of the air remains constant in the dryer (h_{in}=h_{out}). In this case, the outlet air temperature becomes

$$t_{out} = \frac{c_{pda}t_{in} + x_{in}(c_{pv}t_{in} + 2501) - 2501x_{out}}{c_{pda} + c_{pv}x_{out}} \tag{10}$$

The air density may be expressed using perfect the gas equation

$$\rho = \frac{p_{da} M_{da}}{R(t + 273.15)} \tag{11}$$

All necessary equations needed for the calculation of net present value are now determined. Substituting Equations (3-4) and (6-8) in Equation (5), net present value is expressed as a function of t_{wbi} and y_j. If the number of drying stages is higher than 1, the outlet air temperature and moisture of the previous drying stage are new inlet values for the next stage. For n drying stages, the number of t_{wbi} is 3n and the number of y_j is n. Now, we present boundary conditions for a 2-stage dryer. Numbers in subscripts refer to Figure 2.

Initial values: x_1, t_1, u_{in}, u_{out}, M_{dm}, v_a, Z, b_{sh}, b_e, b_{mf}, i, k, Δp,τ_{op}, α_{bs}, α_{es}, η,η_{fan}
Variables: t_{wb2}, t_{wb3}, t_{wb4}, t_{wb6}, t_{wb7}, t_{wb8}, y_1, y_2

$$\tau_{dry1} = A\ln(t_{db2}-t_{wb2} + t_{db3}-t_{wb3}-t_{db2} + t_{wb2} + t_{db4}-t_{wb4}-t_{db3} + t_{wb3}) + B \tag{12a}$$
$$\tau_{dry2} = A\ln(t_{db6}-t_{wb6} + t_{db7}-t_{wb7}-t_{db6} + t_{wb6} + t_{db8}-t_{wb8}-t_{db7} + t_{wb7}) + B \tag{12b}$$
$$t_{db2} \geq t_{db1}\ ,\ t_{db3} \geq t_{db2}\ ,\ t_{db4} \geq t_{db3}\ ,\ t_{db6} \geq t_{db5}\ ,\ t_{db7} \geq t_{db6}\ ,\ t_{db8} \geq t_{db7} \tag{12c}$$
$$t_{db2} \leq t_{db2,max}\ ,\ t_{db3} \leq t_{db3,max}\ ,\ t_{db4} \leq t_{db4,max} \tag{12d}$$
$$t_{db6} \leq t_{db6,max}\ ,\ t_{db7} \leq t_{db7,max}\ ,\ t_{db8} \leq t_{db8,max} \tag{12e}$$
$$t_{db5} \geq t_{db5}'\ ,\ \ t_{db9} \geq t_{db9}' \tag{12f}$$

$$y_1 \frac{v_a \rho_{da} \dot{M}_{dm}}{Z(1-\varepsilon)\rho_{dm}} \tau_{dry1} = y_2 \frac{v_a \rho_{da} \dot{M}_{dm}}{Z(1-\varepsilon)\rho_{dm}} \tau_{dry2} \qquad , y_1 + y_2 = 1 \tag{12g}$$

The model calculates the drying temperature(s), heat consumptions, and air mass flow maximizing the NPV in a case where the final fuel moisture u_{out} and the number of drying stages are given. To determine the final fuel moisture maximizing the NPV, the calculation must be made for different values of u_{out}. On the basis of these values, NPV can be drawn as a function of $u_{out,}$ and the optimal final fuel moisture is found graphically (see Figure 5).

RESULTS AND DISCUSSION

The model is applied in a case study to answer the questions 1-3 mentioned in the introduction. The material to be dried is soft wood bark. Drying curves giving the correlation between the bark moisture and the temperature difference t_{db}-t_{wb} are shown in Figure 4a. Drying curves are measured in a fixed-bed reactor shown in figure 4c. Figure 4b shows a few examples of the regression curves determined on the basis of drying curves.

The drying system is assumed to consist of conveyor, heat exchangers, air ducts, covering, and fan. Cost functions as a function of air mass flow or cross-sectional area of the dryer, also dependent on air mass flow, are shown in Table 1. Cost functions are taken from [5], in which they are also explained in more detail. To take into account costs such as instrumentation, lagging etc., the sum of the cost functions is multiplied by a factor of 1.6. The factor is also taken from [5] and is originally based on information obtained from [4].

We will first calculate the NPV as a function of final bark moisture using energy prices corresponding to present price levels in Finland. The economic lifetime of the dryer is 10 years and interest 5%. Maintenance costs are assumed to be 3 per cent of investment costs. The initial bark moisture, bark flow and temperature levels of secondary heat, backpressure steam and extraction steam correspond roughly to a CHP-plant situated in a Finnish pulp and paper mill. Power-to-heat ratios and plant efficiency correspond to this CHP-plant, too. Table 2 shows a summary of all initial values used in the calculations. Figures 5 shows the calculation results for 1-, 2- and 3-stage drying systems.

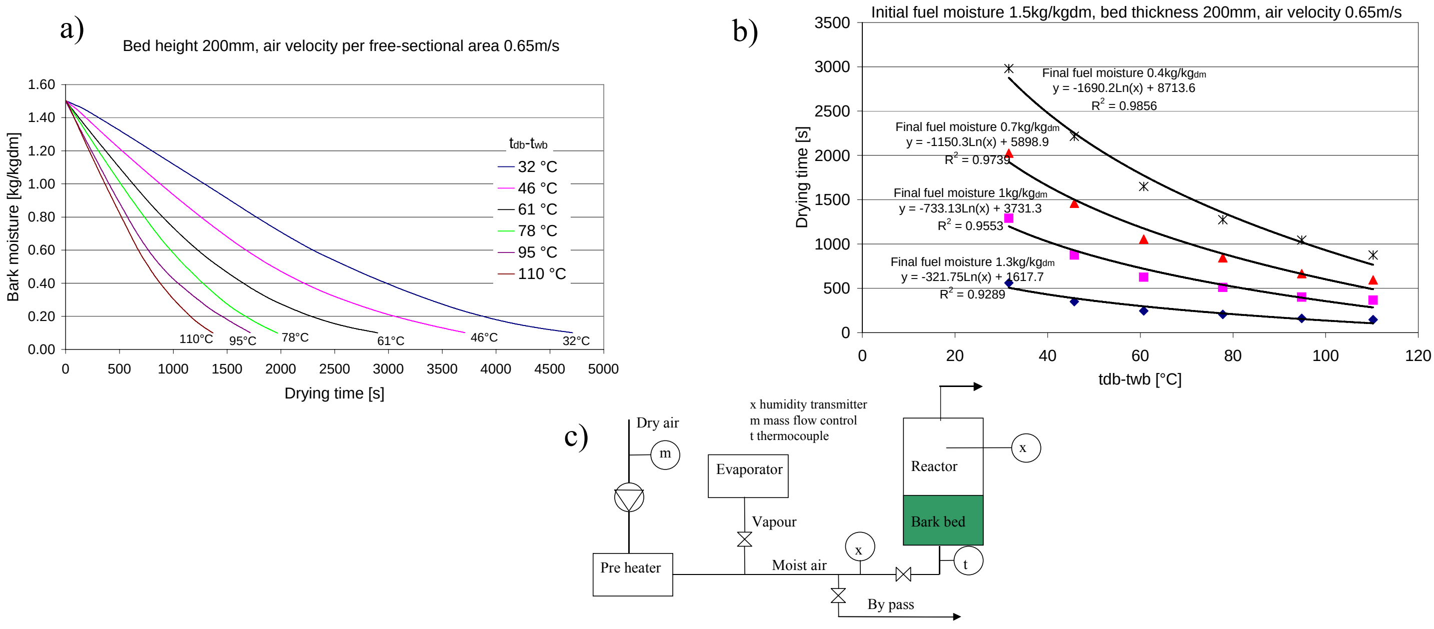


Figure 4. a) Experimentally determined drying curves for various temperature differences t_{db}-t_{wb} b) Four examples of regression curves used in the calculations c) Test rig used for the determination of drying curves

Table 1. Cost functions for main components of the dryer [5]

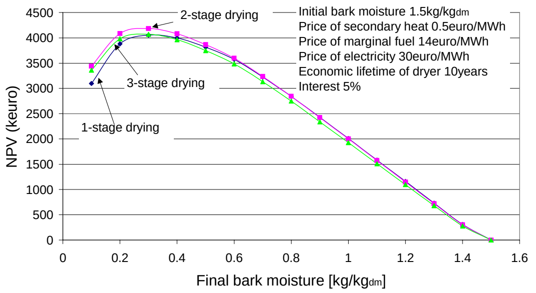
Equipment	Relationship	Capacity parameter Y	Additional parameter
Conveyor	2700Y	Cross-sectional area	
Air-water heat exchanger	$9\Delta tY^{0.9}$	Air mass flow	Δt is temperature increase in heat exchanger
Air-steam heat exchanger	$18\Delta tY^{0.9}$	Air mass flow	Δt is temperature increase in heat exchanger
Air duct	$3770Y^{0.5}$	Air mass flow	
Fan	$0.9\Delta pY^{0.7}$	Air mass flow	Δp is pressure drop of drying stage
Covering	$1200Y^{0.5}$	Cross-sectional area	

Table 2. Initial values for calculation cases. Temperatures in parentheses refer to Figure 2a.

Parameter	Value	Parameter	Value
Highest drying temperature when secondary heat is used (t_2,t_6)	70°C	Initial bark moisture	1.5kg/kg_{dm}
Highest drying temperature when backpressure steam is used (t_3, t_7)	120°C	Bulk density of dry bark	85kg/m^3
Highest drying temperature when extraction steam is used (t_4 , t_8)	150°C	Dry mass flow of bark	4kg/s
Annual operating time of dryer	8400h	Price of electricity	30euro/MWh
Air velocity per free-sectional area of dryer	0.65m/s	Price of secondary heat	0.5euro/MWh
Power to heat ratio in extraction steam production	0.271	[1]Price of marginal fuel	14euro/MWh
Power to heat ratio in backpressure steam production	0.336	Economic life of dryer	10years
Efficiency of CHP-plant (equation (1))	0.87	Interest rate	5%
Pressure drop of each drying stage (estimated)	400Pa	Outdoor temperature (t_1)	5°C
Bed thickness	200mm	Outdoor moisture (x_1)	0.004kg/kg_{da}

[1] Marginal fuel is assumed to be peat and the price includes cost of emission trade

In the next cases, we assess how the length of the economic lifetime and prices of marginal fuel, electricity and secondary heat affect the final bark moisture, drying temperatures, and number of drying stages maximizing the NPV. In each case, one parameter (e.g. price of marginal fuel) is changed and other parameters have the same value as in table 2. The following values are used in the calculations: length of economic life 1-20 years, price of marginal fuel 6-20euro/MWh, price of electricity 20-70euro/MWh and price of secondary heat 0-3euro/MWh. Figures 7-8 show the results for these cases. Results are calculated in a way similar to that shown in Figure 6; only the best case is shown in Figures 7-8. If the drying temperature is higher than 70°C, steam must be used for the heating of drying air in addition to secondary heat. However, in some cases, it may be more profitable to use only steam, not secondary heat, in the dryer. These cases are marked separately in Figures 6-7.



Calculation results at global optimum

Number of drying stages	Optimal drying temperature [°C]	Optimal final bark moisture [kg/kg_{dm}]	Specific heat consumption [kJ/kg_{H2O}]	Investment costs [keuro]	Maximum net present value [keuro]
1	70	0.3	5860	4300	4053
2	70	0.3	4360	4520	4185
3	70	0.3	3890	4725	4071

Figure 5. Net present values as a function of final bark moisture and calculation results at global optimum maximizing the net present value

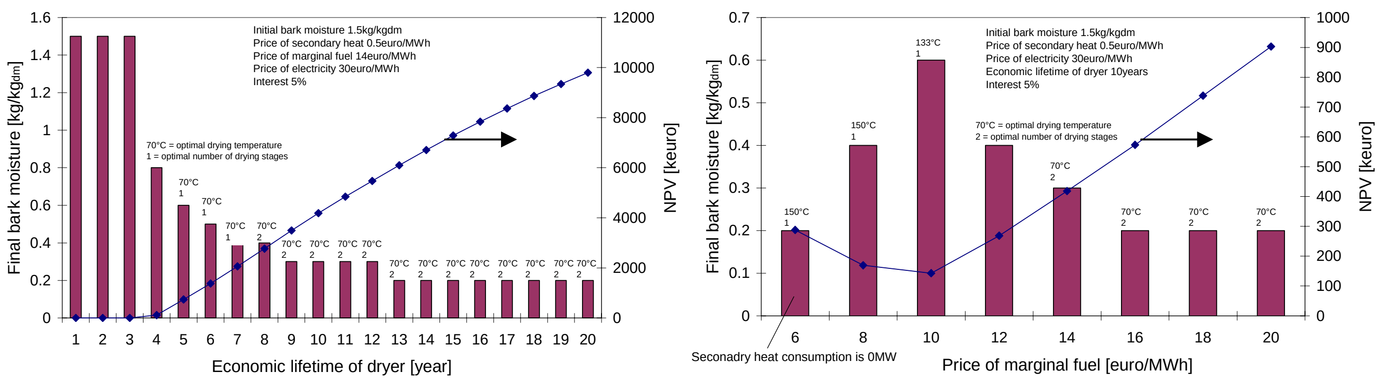


Figure 6. Net present value and optimal final bark moisture, drying temperature and number of drying stages as a function of economic lifetime and price of marginal fuel. Columns show optimal final bark moisture and line maximum net present value in each case.

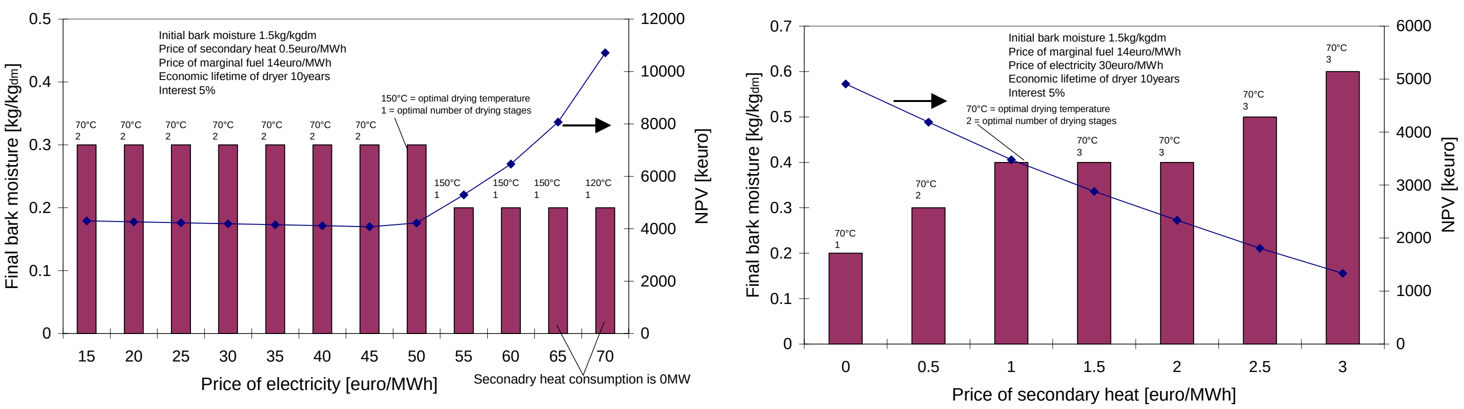


Figure 7. Net present value and optimal final bark moisture, drying temperature and number of drying stages as a function of price of electricity and price of secondary heat. Columns show optimal final bark moisture and line maximum net present value in each case.

Figures 6 and 7 show that the optimal drying temperature is in most cases either 70°C or 150°C. There are only two cases where the optimal temperature differs from these values. Results also show that optimal drying temperatures are always similar in each drying stage in the case of 2- and 3-stage drying. The production cost of steam depends on the prices of marginal fuel and electricity. If the economic lifetime or the price of secondary heat is changed, the production costs of backpressure and extraction steams become so expensive that it is never economical to produce them for the heating of drying air. In these cases, the optimal drying temperature is always 70°C, which is achieved using only secondary heat in drying. If the price of marginal fuel is 6euro/MWh or the price of electricity 65 or 70 euro/MWh, the production costs of steams are negative. The more steam produced the more money gained; therefore, secondary heat is not used in the dryer. However, these prices differ significantly from current prices and are therefore unrealistic cases. It is also important to remember that drying is not the only way to increase the steam and electricity production. Alternative ways are, for example, an auxiliary condenser or condensate turbine. On the other hand, drying is the only way to homogenize the fuel quality, which may be important in some cases. If the price of marginal fuel is 8-10 euro/MWh or the price of electricity 55-60 euro/MWh, the dryer uses both steams and secondary heat. In these cases, production costs of steams become so low that it is more profitable to build a small dryer with a high drying temperature than a large dryer with low drying temperature.

The optimal final bark moisture is in most cases between 0.2 and 0.4kg/kg$_{dm}$, which is fairly low. Bark has quite a small particle size as well as slightly different material properties (e.g., diffusion factors and density) from some other biofuels, which may explain the relatively low value for optimal final moisture. It is probable that the optimal final moisture is higher for biofuels with larger particle size and different material properties (e.g. forest residues). If the economic lifetime of the dryer is less than 4 years, the dryer investment is unprofitable.

Figure 5 shows that the heat consumption decreases considerably when the number of drying stages is added from 1 to 2. If the number of drying stages is 3 instead of 2, the heat consumption does not decrease as much. It is also important to notice that the number of drying stages only has an influence on secondary heat consumption, not steam consumption. The heating system is built in such a way that the drying air can always be heated to 70°C before the steam consumption begins (see Figure 2a). When the price of secondary heat is kept constant at 0.5euro/MWh, a 2-stgae dryer is a better choice than a 1-stage in most cases. Compared to that of a 1-stage dryer, the secondary heat consumption of a 2-stgae dryer decreases so much that savings cover the increased investment costs. However, a 1-stage dryer is always the best choice if steam is used in the dryer (drying temperature is over 70°C). This is an obvious result. Adding the drying stages does not reduce the steam consumption in cases, where secondary heat is used. On the other hand, as a 1-stage dryer always consumes more steam than 2- or 3-stage-dryer, it will always be more profitable to use only steam for the heating of drying air. A dryer with three drying stages becomes competitive when the price of secondary heat is over 1.5 euro/MWh. The more expensive price of secondary heat also means a higher value for optimal final moisture. However, secondary heat is usually not so expensive, which makes these cases less interesting.

It is probable that fossil marginal fuels in particular will be expensive in the future because of the emission trade, for example. Secondary heat will also have a certain price (probably quite low) in the future. In Nordic Countries, the behavior of electricity price is strongly dependent on annual precipitation due to the large capacity of hydropower. In addition, winter temperatures affect the annual price level. Because of these factors, it is more difficult to estimate the behavior of the future electricity price. On the other hand, results show that the electricity price has not any influence on optimal design parameters until the price exceeds 45euro/MWh. During the last four years, the annual average price of electricity has varied between 23 and 36 euro/MWh in Nordic electricity markets [8].

CONCLUSIONS

Using current energy prices, and the economic lifetime of 10 years with an interest rate of 5%, the optimally designed dryer uses only secondary heat for the heating of drying air, consists of two drying stages and dries the fuel/bark flow to final moisture, which is in the order of 0.3kg/kg_{dm}. If future energy prices behave, as we have speculated in the discussion above, the optimal design parameters will be very similar to those calculated using current price levels.

NOTATION

b	Price of energy [euro/MWh]
c_p	Specific heat capacity [kJ/kgK]
C	Cost [euro]
h	Enthalpy [kJ/kg]
i	Interest [%]
k	Economic lifetime [year]
l_v	Vaporization heat of water [J/kg]
$\dot{m}_{da}$	Dry mass flow of air [kg/s]
$\dot{M}_{dm}$	Dry mass flow of fuel [kg/s]
M_{da}	Molecule mass of dry air=0.0288kg/mol
NI	Net income [euro/h]
NPV	Net present value [euro]
p	pressure [Pa]
P	Power generation [W]
Q_f	Fuel input [W]
R	Gas constant = 8.314 J/molK
t	Temperature [^{o}C]
u	Fuel moisture [kg_{H2O}/kg_{dm}]
v	Air velocity [m/s]
x	Air moisture [kg_{H2O}/kg_{da}]
Z	Bed height [m]

Greeks

α	Power to heat ratio [-]
ε	Volume fraction of air in fuel bed [-]
Φ	Heat generation/consumption [W]
η	Efficiency
ρ	Density [kg/m^3]
τ_{dry}	Drying time [s]
τ_{op}	Annual operating time of dryer [h]

Subscripts

a	Air
bs	Backpressure steam
da	Dry air
db	Dry bulb
dm	Dry mass
e	Electricity
es	Extraction steam
in	Inlet
mf	Marginal fuel
out	Outlet
sh	Secondary heat
v	Vapor
wb	Wet bulb

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